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Contents:

6 White Papers

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Generous financial support for the event was provided by the U.S. NOAA, the U.K. Met Office and the U.K. Natural Environment Research Council and COAPEC. It was hosted by the Centre for Global Atmospheric Modelling in the Department of Meteorology at the University of Reading.

1. Introduction

Efforts to improve climate prediction are at the heart of CLIVAR. In TOGA, and in the first phase of CLIVAR, much attention was focused on the problem of forecasting ENSO and its climate impacts, particularly those in the Indo-Pacific region. Rather less attention has been addressed to forecasting the climate of the Atlantic region, although research has clearly indicated potential predictability, especially in the tropical Atlantic. It was recognition of the need to ensure that research progress is translated into progress in climate prediction that led to the CLIVAR Workshop on Atlantic Climate Predictability.

The workshop was held at the University of Reading, UK, from 19-22nd April 2004. It brought together scientists from operational forecasting agencies with academics and others involved in more basic research. Over 50 scientists (see Appendix I for full list of participants) from North and South America, Africa and Europe met to assess the current state of the art in predicting the climate of the continents that surround the Atlantic Ocean, and to make recommendations for future priorities. The focus was on climate predictions for time horizons of seasons to decades ahead.

The workshop was organised by the CLIVAR Atlantic panel in collaboration with WGSIP. The organising committee were:

Rowan Sutton, Yochanan Kushnir, Chris Reason, David Marshall (members of the CLIVAR Atlantic panel), Tim Stockdale, Paulo Nobre (members of WGSIP), Lisa Goddard (IRI)

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2. Aims of the Workshop

The specific aims of the workshop were:

- To provide an up to date assessment of the state of knowledge concerning the predictability of climate in the Atlantic Sector, with particular emphasis on the role of the Atlantic Ocean.
- To improve communication between the operational prediction centres and regional fora and the research community concerning the predictability of Atlantic Sector climate.
- To identify gaps in knowledge, and in observing systems, required for the further development of systems for forecasting Atlantic Sector climate.
- To recommend priorities for future research, observational programmes and development of prediction systems.

3. Agenda

The workshop was divided into two main sessions. The first session focused on reports from the operational centres and similar organisations involved in routine climate forecasting. In the second session a series of 9 “White Papers” was presented. The purpose of these papers was to review the current state of the art and highlight important issues. The papers broke into three groups (see Table 1). First were two papers on the physical basis for climate prediction in the Atlantic Sector. Second were two papers on the infrastructure for climate prediction: on the observing system and the climate prediction systems themselves. Third were five papers each of which focused on a particular region: West Africa, Southern Africa, North America, South America and Europe. In addition to the two main sessions the workshop programme was significantly enhanced by a lively poster session and two guest lectures. Dr Tim Palmer (of ECMWF) discussed “Developments and future prospects in understanding predictability”. Dr Neil Ward (of IRI) discussed “Merging forecasts with applications”.

Following the presentations, discussions were held to identify priorities for the future. These discussions involved break groups followed by a plenary session. The full agenda for the workshop is included in Appendix II

Table 1: Subjects and lead authors of White Papers

	Subject	**Lead Author**
1	The physical basis for prediction of Atlantic sector climate on seasonal-to-interannual timescales.	Yochanan Kushnir
2	The physical basis for prediction of Atlantic sector climate on decadal timescales [to include THC and climate change]	Mojib Latif
3	The climate observing system for the Atlantic sector	Tony Busalacchi
4	Coupled prediction systems for Atlantic Sector climate	Tim Stockdale
5	Seasonal-to-decadal predictability and prediction of West African climate	Neil Ward
6	Seasonal-to-decadal predictability and prediction of Southern African climate	Chris Reason
7	Seasonal-to-decadal predictability and prediction of North American climate [to focus primarily on the Atlantic influence]	Huug van den Dool
8	Seasonal-to-decadal predictability and prediction of South American climate	Paulo Nobre
9	Seasonal-to-decadal predictability and prediction of European climate	Mark Rodwell and Francisco Doblas-Reyes

4. Summary of Working Group Discussions and Recommendations

The aim of the break out groups was to generate recommendations for future priorities in a) research b) the observing system c) development of prediction systems. As indicated in the table below two groups were formed. These groups were designed to provide a broader perspective than the regional white papers, while still retaining some focus. The working groups were followed by a plenary discussion.

	Focus	**Chair**	**Rapporteur**
A	South America and Africa (to include the tropics, South Atlantic and surrounding continents)	Richard Washington	Jose Marengo
B	North America and Europe	David Anderson	Mat Collins

Rather than summarising the discussions of the working groups separately, the following is an attempt to synthesise the main issues that were highlighted by both groups, whilst also taking into account issues raised in the White Papers. The issues are loosely organised into “basic research", concerned with understanding sources of predictability, and more applied research and development, concerned with the prediction systems, including the network of observations. It should be acknowledged that the discussions were more fruitful in their identification of priority issues than in providing detailed recommendations of how to address these issues. We hope, however, that highlighting of key issues will help to focus future efforts in the field. Note that references are omitted in this section since comprehensive references are provided in the White Papers.

4.1 Understanding sources of predictability

a) Seasonal Timescales
There is evidence of seasonal climate predictability on all the continents that surround the Atlantic basin. As elsewhere on the planet this predictability arises primarily from the influence of slowly changing oceanic and land surface conditions, and is generally higher in the tropics than in the extratropics. However, many issues regarding the detailed mechanisms that govern predictability are poorly understood. Advancing understanding of these mechanisms is a key challenge.

Capitalizing on advances in ENSO prediction and extending them to the Atlantic Basin is of primary importance. ENSO directly impacts the Atlantic Sector, most strongly in the tropics but also in the northern and southern extratropics. The most robust features of these impacts have been characterised, but there is a need to better understand: a) the origin of the differences between individual ENSO events and the extent of their predictability, b) the role of Atlantic ocean conditions in modifying the direct ENSO influence (particularly in the tropics – see below), c) the impacts of ENSO on the South Atlantic region; d) decadal variability of the ENSO teleconnections to Atlantic Sector climate.

Within the Atlantic, the best prospects for advancing climate prediction on seasonal-to-interannual time scales lie in the tropics. Here the sensitivity of the climate (particularly the ITCZ related rainfall) to boundary forcing is significant and the potential benefits to society large. In particular, a skilful prediction of tropical SST can yield a reliable prediction of rainfall anomalies in the semi-arid regions of northeast Brazil and West Africa. The major stumbling point is the accurate prediction of SST. Both statistical and dynamical models have difficulties in this area, and this partly reflects an incomplete understanding of the processes that govern SST evolution.

In the tropical Southeast Atlantic, there is some evidence that large warm / cool events (Benguela Ninos / Ninas) may have potential predictability. These events have large sub-surface expression in the equatorial region and manifest significant SST anomalies near the Angola – Benguela frontal zone. There is evidence of a linkage between tradewind anomalies over the western equatorial Atlantic and the generation of Benguela Ninos/Ninas 2-3 months later. There may also be a connection with Atlantic ENSO-like equatorial warming events. The challenge is to better understand the relationships between equatorial and Benguela events and to explain why equatorial wind modulations do not always lead to significant SST anomalies off Angola. There is a related need for advances in understanding the basic processes that control the climate of the region. Key issues include: a) The interaction between the diabatic heat sources in the Congo and Amazon basins; what factors control the strength of these heat sources and how does their interaction shape regional climate? b) What factors control the South Atlantic Convergence Zone (SACZ), the subtropical anticyclone and related climate impacts? c) What controls SST, and its persistence, in the tropical South Atlantic?

In the extratropical North Atlantic there is evidence from observational and model studies of some predictability in the NAO. NAO persistence is somewhat greater than that expected for a first order autoregressive process, and there is weak but statistically significant persistence from winter-to-winter. The origin of this persistence is not clear although oceanic processes, both local and remote, as well as the land surface, could play a role. Downward influence from the stratosphere is potentially important on intraseasonal timescales. There is a need to extend current modelling work to the coupled system to investigate, for example, the role of reduced thermal damping and re-emergence in influencing the NAO. There is also a need for further work to understand the subtle influence of Atlantic Ocean conditions on European and North American climate in seasons other than winter. The influence of coastal SST is significant locally and merits further investigation. Variations in sea ice are also important locally and may have more far-reaching impacts. The predictability of sea ice and coastal SST needs to be investigated. In addition, it appears that much can be gained in seasonal-to-interannual prediction from better resolving and understanding decadal variability and trends.

The influence of land surface processes on climate predictability has for some time been identified as an important, and under researched, issue. This is certainly true for the Atlantic Sector. Soil moisture is a key variable in the hydrological cycle with a potentially large impact on, e.g., intensity of droughts and heat waves. Research to better understand the role of soil moisture is hampered by systematic errors in models and by a lack of observational data. Other aspects of the land surface such as snow cover, snow depth, and vegetation characteristics can also influence seasonal climate, and research is needed into the predictability of these factors and their impacts. As with the oceanic influence, coupled model studies are preferable to prescribed anomaly experiments. The land surface is also an important source of aerosols in the form of Saharan dust and black carbon emissions from natural and anthropogenic biomass burning. The impacts of dust and other aerosols on Atlantic sector climate are poorly understood, and research is required to understand and quantify these impacts and their importance for climate predictability. (Some evidence of the impact of aerosols from biomass burning in the Amazon Basin has started to emerge from research derived from the LBA experiment.)

b) Decadal and Longer Timescales

In the North Atlantic the primary (internal) source of predictability on decadal timescales is the Atlantic Meridional Overturning Circulation (MOC). There is evidence of predictability of ocean fields such as SST and deeper thermal structure for lead times up to several decades but there is as yet no consensus concerning the detailed mechanisms that determine predictability. Moreover, it is not clear how much of that predictability can be carried over to atmospheric fields such as air temperature over the adjacent continents. There is need for a much more detailed understanding of which aspects of ocean conditions most constrain the future behaviour of the MOC and related aspects of climate. The roles of air-sea exchanges, convective mixing, overflows, boundary waves and advective processes in setting the timescale and predictability of changes in the MOC have to be clarified.

Changes in the MOC may also be a significant factor for decadal variability and predictability in the South Atlantic. However, at least for Southern Africa, ENSO-like decadal variability with its origins in the Pacific may be a more important factor. Thus a challenge in the South Atlantic region is to better understand potentially competing influences on decadal timescales.

Changing external forcings, whether natural or anthropogenic, also influence climate on decadal (and indeed shorter, e.g. volcanoes) timescales and are a further source of potential predictability. Many of the issues are global but there is a clear need to improve understanding of the factors that determine climate change at a regional scale. In the Atlantic Sector, understanding potential changes in the principal diabatic heat sources over South America and Africa, and in the North Atlantic Storm track, and the knock-on consequences of such changes are natural priorities. The impact of external forcings on the stratospheric polar vortex, and the consequences for tropospheric climate, must also be better understood. Lastly, of great importance for climate prediction is the interaction between initial conditions (notably in the MOC) and the effect of changing forcings. For predictions with lead times in the range 1-30 years both factors are likely to be important.

4.2 Development of coupled prediction systems

a) The Observing Network and Estimation of the Initial Conditions
Although the Atlantic Ocean has historically been the best observed of the world's oceans, the lack of sufficient subsurface data is a major issue for the initialisation of hindcasts used to develop and test coupled prediction systems. Recently (with, for example, the PIRATA array, satellite altimetry and ARGO) there has been significant progress. However many gaps remain, especially in the South Atlantic, and the supply of data for the tropical Atlantic does not come close to that available from the TAO array in the Pacific. The proposed extensions to PIRATA in the NE, SE and SW Atlantic offer a very valuable enhancement of the existing observational network, as does the new AMMA programme. More detailed recommendations to enhance observations in the South Atlantic were made at the recent SACOS (South Atlantic Climate Observing System) workshop.

Given the limited ocean data, the best use of this data, through intelligent assimilation schemes, is a major issue. The treatment of salinity –which plays a more important role than in the Pacific– is a particular challenge. Another challenge is how to make best use, for (decadal) prediction purposes, of the data that will become available from major new projects designed to monitor the MOC (e.g. UK "RAPID" project). Lastly, the initialisation of the land surface can have a significant impact on seasonal predictions and should not be neglected.

There is also a lack of atmospheric observations. In some regions, such as southern Africa and tropical South America, there has been a severe decline in the (already sparse) network of atmospheric observations, both of surface and upper air parameters. These trends are a major concern for climate monitoring and prediction. There is also a need for "data rescue" efforts to make past observations available to the scientific community.

b) Model Systematic Error
The coupled models used to make seasonal and longer timescale predictions suffer from significant biases in the Atlantic Sector, and especially in the tropical Atlantic (e.g. the zonal gradient of SST on the equator frequently has the wrong sign). These biases cause problems for assimilation schemes and also compromise forecasts directly. Arguably there has been less attention paid to the resolution of these problems than to addressing similar problems over the Pacific Ocean. Progress in the prediction of Atlantic Sector climate requires that the reduction of biases over the Atlantic is prioritised. Higher resolution models of both the atmosphere and ocean may be a pre-requisite, and improvements to the parameterisation of sub-grid-scale processes are also required. Also essential is better understanding of the physical processes that determine regional climate. The new observations and research expected with the African Monsoon Multidisciplinary Analysis (AMMA) should make a significant contribution in this area. The upper air observations collected during the recent CLIVAR-SALLJEX field experiments are also of considerable importance.

Faced by the difficulties of reducing coupled model biases in the Atlantic region, one approach (favoured, for example, at the IRI) is to adopt a two-tier prediction strategy. In this case a high quality SST prediction is paramount. At present SST predictions for the tropical Atlantic, whether generated by statistical or dynamical methods, have many weaknesses especially south of the Equator. Achieving better SST predictions for this region is therefore a key challenge.

c) Generic Issues
Beyond the issues outlined above, there are many other challenges in the development of seasonal and longer-term predictions. However these challenges are more generic rather than featuring a distinctive Atlantic perspective. The issues include: a) how to handle model uncertainty through, for example, multi-model or "perturbed physics" methods; b) how to meaningfully quantify and verify probabilities (rather than merely ranges); c) how to develop forecast products that provide the maximum value for specific users; d) how to develop

"seamless" prediction systems that provide continuous information for all lead times from days to decades.

There is an ongoing need for extended hindcasts that can be used to quantify forecast skill over many realisations, and to compare results (using standard metrics) from different forecasting systems, including new versions of existing systems. The European DEMETER project is an example of such a study but, as with other such projects, much more attention has been paid to the Pacific than the Atlantic. The Atlantic now merits a similar degree of attention. Relatedly, it has been suggested that a process similar to IPCC be instigated for the regular review of progress in seasonal-decadal prediction. Such a process could be of considerable value in focussing community attention.

4.3 Overarching Challenges

The preceding discussion identified a wide range of specific issues. However, focussing of effort may most readily be achieved if there is agreement on major priorities. In this context we recognise two overarching challenges for Atlantic climate prediction over the next 5-10 years:

1) To realise fully the potential of seasonal predictions for the tropical Atlantic region
The potential skill and value of seasonal forecasts is highest in the tropical Atlantic. The challenge is to build a seasonal climate prediction system for the tropical Atlantic region that is comparable (in terms of data coverage, model fidelity, and –subject to physical limits– forecast skill) to that in the tropical Pacific. This will entail:

- Significant enhancement of sustained observations in the tropical Atlantic region, in the ocean, at the land surface, and in the free troposphere
- Major effort to reduce the systematic errors in simulation of tropical Atlantic climate in models used for seasonal prediction
- Research to better understand the fundamental ocean-atmosphere-land processes that control the climate of the tropical Atlantic region, its variability and predictability, including the statistics of sub-seasonal variability
- Improvement of data assimilation systems for the Atlantic Ocean (especially the treatment of salinity)
- Development of reliable methodologies for making seasonal forecasts relevant and useful to decision makers.

2) To take a lead in the development of systems for decadal climate prediction
The development of useful decadal climate predictions, incorporating both initial condition constraints and transient boundary forcings, is a "grand challenge" whose importance is increasingly recognised. Because of the key role played by the Atlantic Ocean in the global overturning circulation, the Atlantic climate community is naturally placed to take a lead in this area. A number of specific challenges may be identified, for example:

- Development of an observational system for monitoring the MOC (already in progress)
- Understanding the limits of predictability in the MOC and the mechanisms that determine predictability
- Identifying which aspects of the oceanic initial conditions most constrain the future behaviour of the MOC
- Development of data assimilation methods for initialisation of decadal MOC forecasts
- Understanding how initial conditions and changing external forcings combine to determine climate evolution on decadal timescales, and (relatedly) development of suitable ensemble techniques for sampling forecast uncertainty
- Understanding and quantifying the regional climate impacts of MOC change and the predictability of these impacts.

5. Summaries of Ongoing Prediction Activities

5.1 Seasonal Forecasting of Atlantic Sector Climate at IRI

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Introduction

The mission of the International Research Institute for Climate Prediction (IRI) is to make seasonal climate predictions that can be harnessed to aid decision-making in societal applications, especially in developing countries. The main current regions of interest in the Atlantic sector are NE Brazil, and western and southern Africa. Specific applications include water resource and agricultural planning in NE Brazil, and early warning of malaria and other vector-borne diseases over West Africa.

Global seasonal forecasts are produced every month at IRI, for 3-month averages of precipitation and near-surface temperature (Goddard et al. 2003). These forecasts are disseminated via the IRI web site: http://iri.columbia.edu. A two-tiered system is used, whereby the global SST field is predicted first. This short paper focuses on some of the challenges faced in (a) seasonal prediction of SST over the tropical Atlantic, and (b) the performance of the atmospheric GCM (AGCM) simulations of precipitation over Africa, given observed and predicted SST.

Atlantic sector seasonal predictions

The SST prediction over the tropical Atlantic at IRI is currently based on the statistical model of Repelli and Nobre (2004), or on a damped persistence forecast, depending on the season. The former is a canonical correlation analysis (CCA) based scheme that uses the observed SST field over the tropical Pacific and Atlantic oceans as a predictor. A damped persistence forecast is used poleward of 30^o in all seasons.

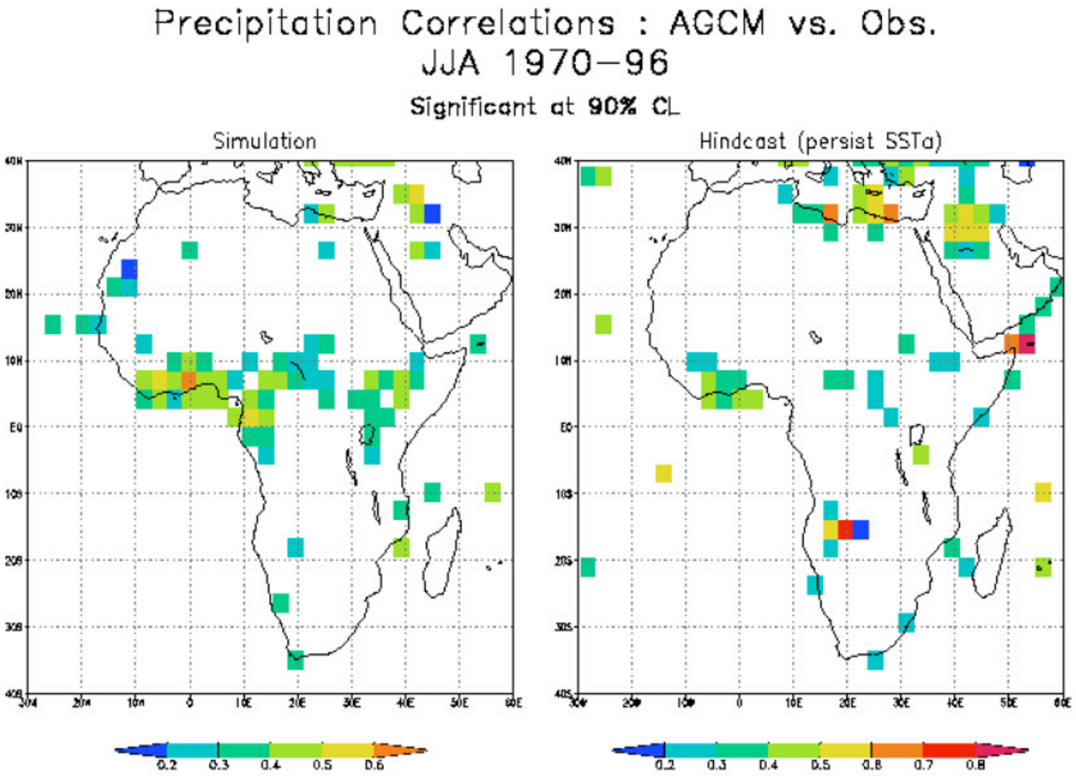

Figure 1: Anomaly correlation skill of seasonal JJA precipitation AGCM simulations 1970–96, with SSTs prescribed from (a) observations, and (b) one-month persistence forecasts. Only correlations significant at the 90% confidence level are shown.

The key seasons for rainfall prediction for NE Brazil are February–May, and June–September for West Africa. Maps of lag-correlations between station rainfall and SST (not shown) indicate potential predictability from the South Atlantic ocean, for a one-season lag over for West Africa, and up to 3–4 seasons for NE Brazil. Precipitation over the latter region is closely tied to ENSO, but significantly modulated by the state of the Atlantic (Giannini et al. 2004), especially on longer timescales. The Repelli and Nobre (2004) CCA scheme is relatively skilful at capturing the predictability of SST over the tropical North Atlantic during March–May, associated with these processes, and is considerably more skilful than the persistence forecast.

The June–September season, most relevant to West African rainfall, is considerably more challenging, because the relationship with ENSO is much weaker. The IRI two-tier system currently relies on the damped persistence forecast for this season.

Figure 1 shows the June–August (JJA) precipitation skill of the ECHAM3 model over Africa using (a) observed SSTs and (b) the persistence forecast of SST, both in terms of the ensemble mean computed from 10 ensemble members. The skill over the Guinea Coast drops markedly when persisted SSTs are prescribed, indicating the importance of improving the SST forecast. Even using observed SSTs, the skill only reaches moderate levels, indicating limitations in the second tier of the forecast system. These errors reflect biases in the atmospheric GCM, together with atmospheric chaos. Errors in rainfall observations and SST observations may also play a role. Goddard and Mason (2002) examined the relationship between the difference in the SST fields (between observed and persisted SSTs) and the difference in the resultant AGCM simulations. The dominant patterns of the errors, plotted in Fig. 2, make clear the importance of improving predictions of SST over the equatorial and SE Atlantic during boreal summer.

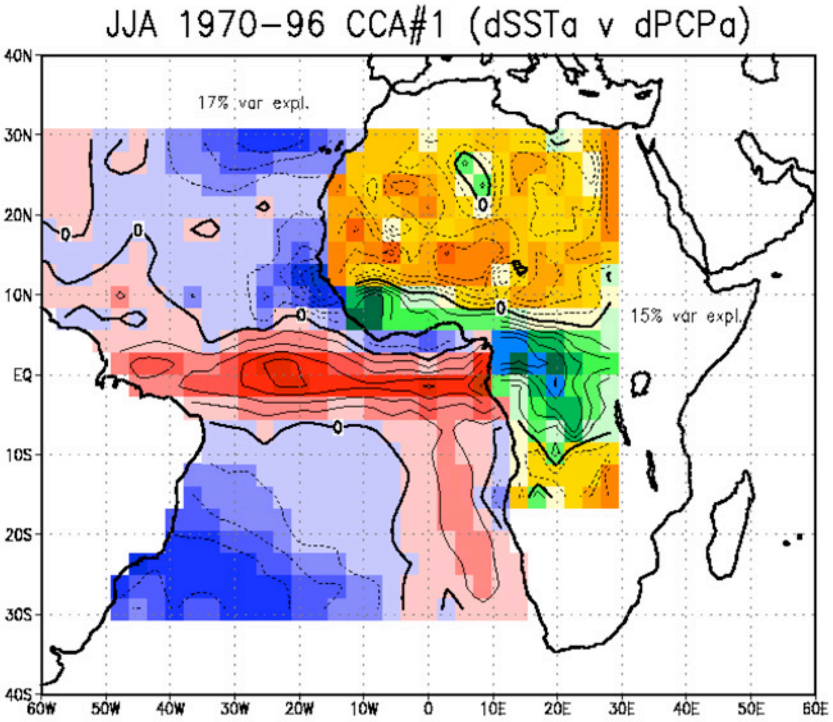

Figure 2: First mode of canonical correlation analysis showing the dominant pattern of precipitation errors (over land) generated by the dominant pattern of SST anomaly (SSTA) error for JJA 1970–1996 over the tropical Atlantic/western Africa region. dSSTA = observed JJA SSTA – persisted May SSTA; dPCPA = simulated PCPA – hindcast PCPA. Maps are invariant to change in overall sign. Contour interval is 0.1 for both patterns in relative (normalized) units. From Goddard and Mason (2002).

Coupled GCM predictions

Experimental predictions of global SST are being carried out at IRI using the ECHAM4 model coupled to the MOM3 ocean GCM, with ocean data assimilation from the GFDL variational optimal interpolation system.

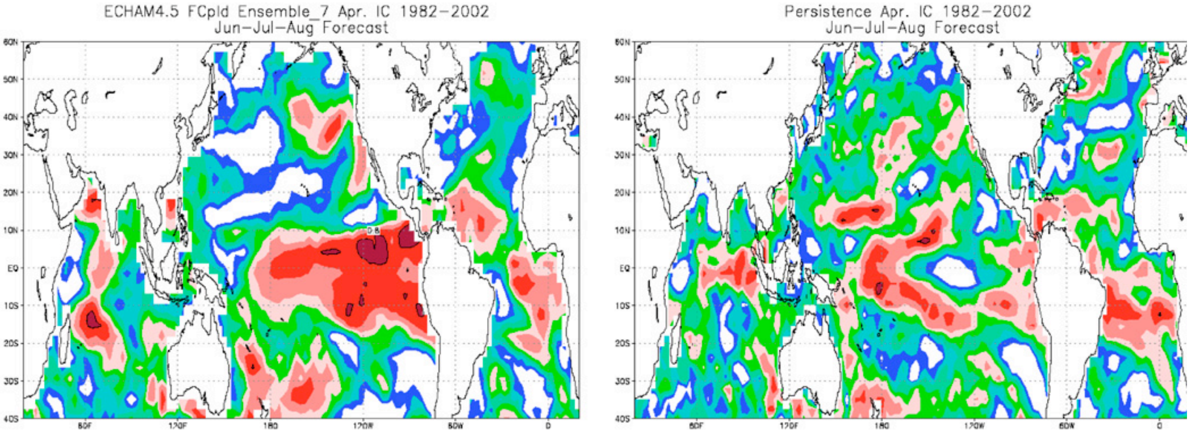

Figure 3: Anomaly correlation skill of SST forecasts for JJA made with (a) the coupled GCM, and (b) by persisting the SST from April 15. The coupled GCM forecasts are formed from the ensemble mean of 7 simulations made from April 1 ocean initial conditions. Contour interval: 0.2.

Figure 3 illustrates the anomaly correlation skill during JJA for forecasts made from April 1 initial conditions, using (a) the coupled GCM, and (b) a persistence SST forecast (from April 15). The coupled GCM forecasts were evaluated from the ensemble mean of 7 members, over the period 1982–2002. The coupled model exhibits anomaly correlations exceeding 0.4 over most of the eastern equatorial Atlantic between just north of the equator and 10°S, outperforming the persistence forecast, except near 10°S. According to Fig. 2, this largely coincides with the region in which SST errors are most critical for simulating rainfall anomalies over West Africa. The coupled GCM's own precipitation skill over West Africa lies in between the two maps in Fig. 1 (not shown).

Conclusions

The results presented here underline the need for progress in predicting SST over the tropical Atlantic, particularly in the equatorial band and the Gulf of Guinea. In addition, experiments in a two-tier framework suggest that even with a "perfect" SST forecast, serious deficiencies in seasonal rainfall simulation skill will remain over tropical land areas, such as West Africa, due to AGCM biases and atmospheric noise. A second challenge is to reduce these AGCM biases to a minimum. Our multi-AGCM ensembles go some way toward improving precipitation skill over West Africa in summer (not shown). One-tier coupled GCM forecast experiments exhibit some skill in SST over the equatorial Atlantic, and the rainfall forecast skill over West Africa falls in between the observed and persisted SST experiments shown in Fig. 1. A third challenge concerns the lack of land-surface initialization in the results presented.

Acknowledgements

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5.2 Seasonal Prediction over the Atlantic by the French Weather Service

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Abstract

Operational seasonal forecasts at Météo-France have certainly some skill in winter in the Atlantic-Europe region. In summer, this is probably not the case. However, robust estimates of the skill need a long experiment like DEMETER. The skill of 850 hPa temperature is presented here, with comparison with non-coupled forecasts. Results show a superiority of the coupled approach. This superiority is confirmed when large-scale indices like North Atlantic Oscillation or Northern Annular Mode are considered. A perfect model approach shows that the both indices have indeed a good predictability potential.

Introduction

Since 1999, Météo-France produces each month an ensemble of 9 forecasts with the climate version of the ARPEGE-IFS forecast model. The results of an earlier version of this model in the European project PROVOST (Doblas Reyes et al., 2000) have proved that an atmosphere model forced by observed SSTs is not just a climate generator, once the 10- to 20-day limit for deterministic forecast is reached. As observed SST are not available in real time, but slowly evolving in the tropics in the first months, a statistical technique was introduced in order to prepare a set of SST for the 4 forthcoming months, before the forecast starts. A simple technique based on order-1 autoregression of the first 20 EOFs was used, then an order-2 autoregression with variance inflation (to avoid a too rapid return to climatology at month 2) was introduced. A 20-year reforecasting (1979-present) experiment with this scheme was run each month to evaluate at a time the mean model state (to produce model anomalies) and the mean scores (to convince potential users).

Then came DEMETER (Palmer et al., 2004). This European project offers a few features compared to his predecessor PROVOST, e.g. using much more models or extending from 4 to 6 months the forecast range, but the essential features are:

- the use of coupled models (the score are no more potential scores)
- the triplication of the length of the experiment (from 15 to 44 years, better stability of the scores)

Just after the end of the project (October 2003), a decision was taken to continue DEMETER in real time (DEMETER is based on ERA40) with ECMWF, Met Office and Météo-France. The first two partners have already started the production, and Météo-France will join in 2004.

In this study we will examine the actual and potential predictability over Europe and Atlantic with our model in DEMETER and peri-DEMETER experiments, restricting to the winter cases and the first 4 months. In section 2, we examine 850 hPa temperature. The results are related in section 3 to the NAO index, and, in section 4, to the NAM index. Section 5 concludes the study.

850 hPa Temperature

When large-scale, monthly mean anomalies are considered, in particular in winter, 850 hPa temperatures can be used in the place of near surface (2m) temperatures to identify warm or cold events. A good prediction system will be able to produce more hits in predicting these events than a random or systematic prediction like persistence. The question is then to measure how good a system is over a small (with regard to the globe) area like Europe. PROVOST was the first long re-forecasting exercise. It was based on ERA15.

With DEMETER, based on ERA40, we can re-forecast 44 years in a homogeneous way. This has been done with ARPEGE-Climate.3/OPA.8 model (see Clark and Déqué, 2003, for a few details and further references). We consider here 44 forecasts with 9 members, starting at 1 November 1958 through 2001. We concentrate on the first 4 months (NDJF) of the forecast. When the mean correlation for western Europe is calculated with the first 15 years, the DJF score is 0.24. With the next 15 years, it is 0.06, and the last 15 years 0.19. This result shows that a 15-year validation period is too short, as far as regional skill is concerned. Similar results can be obtained with midlatitude indices like PNA or NAO. In the following, we will not use results from the verification phase of the operational forecast, but from DEMETER and peri-DEMETER experiments.

Three additional forecast experiments have been performed with the atmospheric component alone:

- PROVOST, consists here of using the same model and dates, but monthly observed SST
- 2-tier SST, consists of using monthly SST from DEMETER to force the atmosphere, once the SST bias is removed
- Statistical SST, consists of using a statistical scheme to predict SST

We have 9 members in each case, except the last one, for which 36 members are available. This last experiment was essentially designed for probability forecasting. The deterministic scores are a little worse than in the Météo-France operational scheme, since the statistical method used here introduces diverging errors in the SST forecast (see Déqué, 2001 for details on the method). For the sake of equity, all scores will be calculated with 9 members, the scores for the last case being calculated by 200 random drawings and then averaged.

There is a risk of overestimating temperature scores over a long period. The calculation of the correlation coefficient assumes that the statistics of the distribution is stationary. This is not the case: since 1960, Europe has experienced a warming. Temperatures in the beginning of the period tend to be colder than temperatures in the end, both for the verification and the observation. This tends to increase correlation score. We want to measure seasonal predictability, not climate change. So the data have been detrended by removing a 15-year moving average instead of the full 44-year average to produce the anomalies.

Figure 1 shows the DJF correlations for our 4 experiments. It appears that DEMETER is the best over western Europe, even better than PROVOST. Global correlation maps (not shown) prove that in fact PROVOST is the best over most areas, but in our small domain this is not the case. This feature is model-dependent (have a look at the DEMETER Web page at www.ecmwf.int) and possibly period dependent (wait for ERA80).

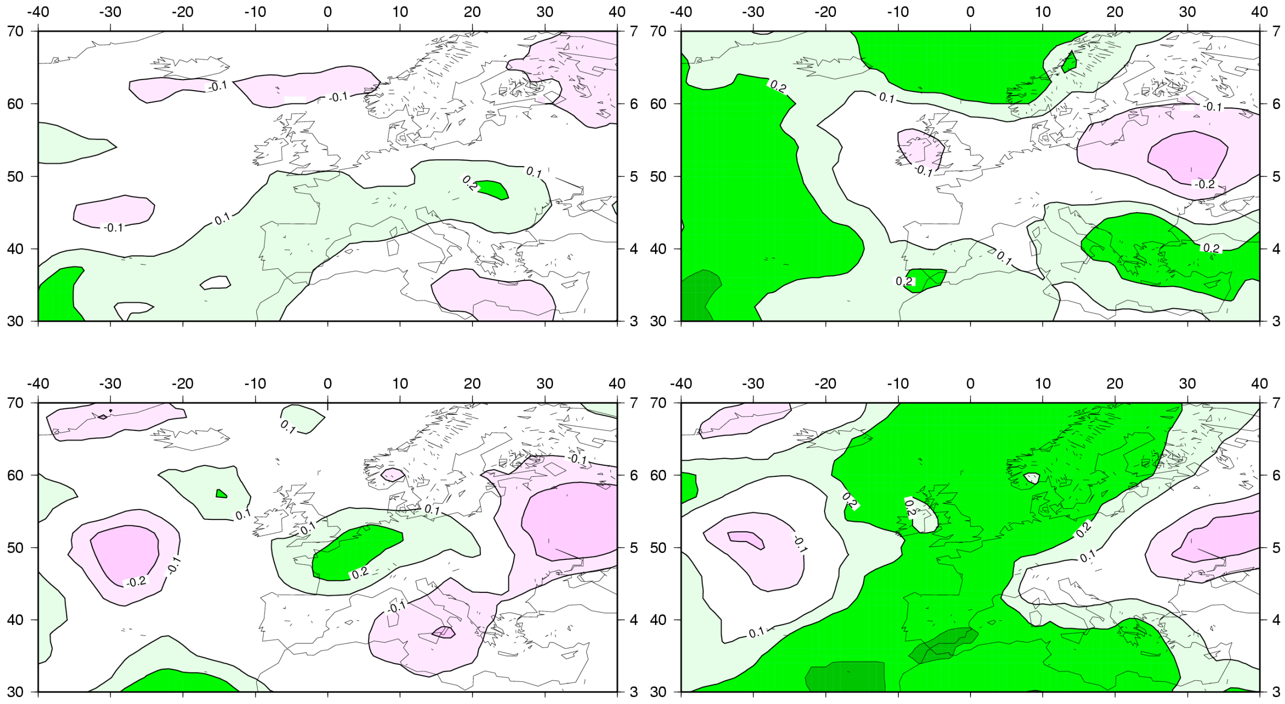

Figure 1: Correlation for winter seasonal forecast: Statistical SST (top left), PROVOST (top right), 2-tier SST (bottom left) and DEMETER (bottom right); contours ±0.1, ±0.2 and 0.3.

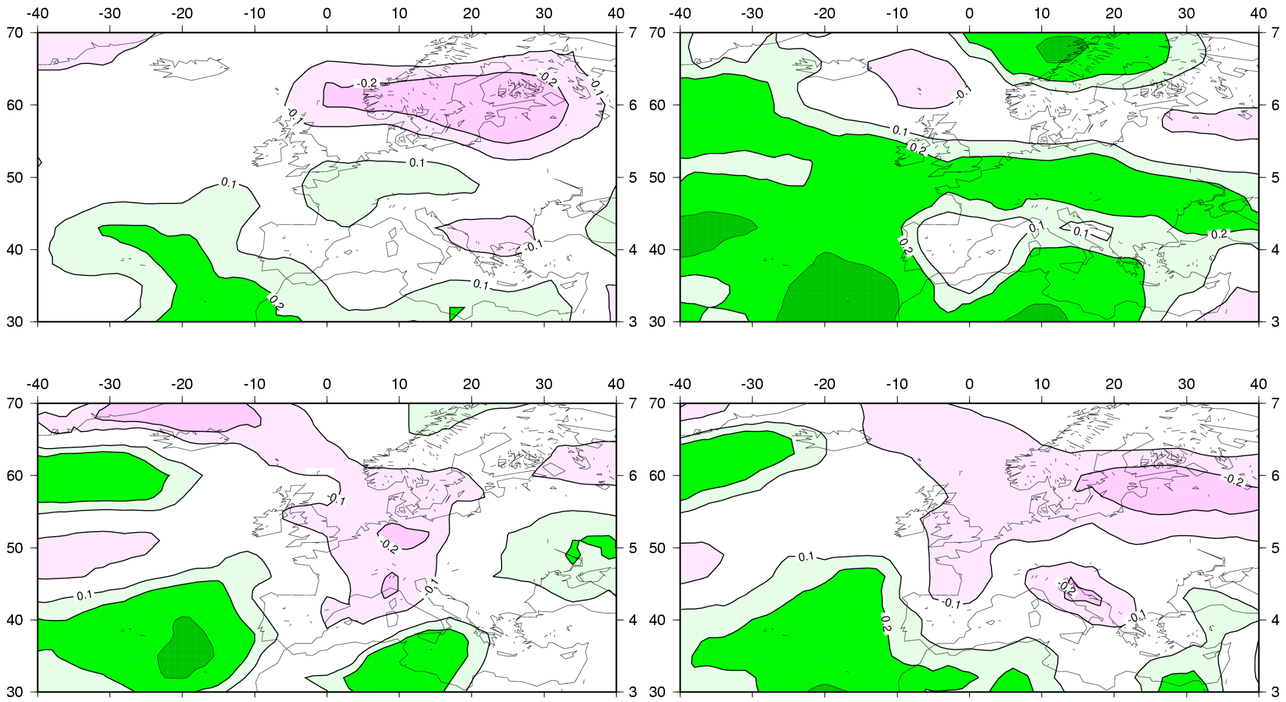

Figure 2: As Figure 1 for summer (JJA).

The DEMETER scores are even greater, when the standard correlation is calculated (i.e. no trend removal), but the impact of the climate drift on the scores is less obvious in the other 3 experiments.

Figure 2 is just here to explain why the heat wave of summer 2003 was not announced by National Meteorological Services. Only PROVOST does a reasonable job. But PROVOST is not compatible with an operational forecast.

North Atlantic Oscillation

We shall try here to generalize the results shown for temperature over Europe. Danish sailors have remarked in the past centuries that cold winter in Greenland (a Danish colony) corresponded often with mild winters in northern Europe and vice-versa. The Greenland Seasaw (van Loon and Rogers, 1978) is one of the ancestors of the NAO. If we want a robust index for temperature, rather than using an average temperature over the whole domain, which has little interannual variability and therefore little predictability, a circulation index over a wider domain is a better choice.

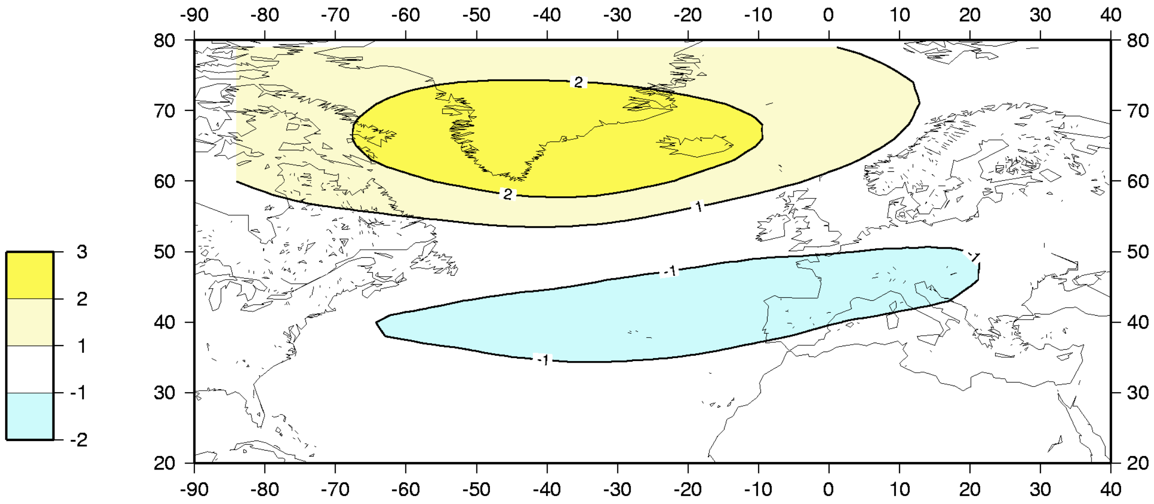

Figure 3: First EOF of winter monthly means of ERA40 for Z500.Non-dimensional units.

There is no need to present this famous index of the circulation over the northern Atlantic and Europe (Wallace and Gutzler, 1981). It is calculated here as the first EOF of an analysis in the domain 85°W-30°E, 25°N-80°N of monthly 500 hPa geopotential for the 44 winters (DJF) of ERA40. The first EOF (Figure 3) explains 33 % of the variance. The bimodal pattern is typical of a North-South gradient with a slight NW-SE shift of the NAO.

The forecast scores, measured by the correlation coefficient between observed and predicted NAO series, is given in Table1. The predicted NAO is just the projection of the monthly mean onto the above pattern. As we consider only correlation coefficients, there is no need to center or unbias the series. In the case of statistical SSTs, 200 estimates are calculated with 9 members selected at random each year, and the average is presented. A simple statistical test is done. The 44 years are scrambled in the verification series, which gives an estimate of a no-skill correlation. The operation is repeated 200 times, the correlations are sorted by ascending order, and the 190th value is compared with the actual correlation: when the latter is greater than this 95%-threshold, the correlation is said to be significant. This method cannot be applied to the statistical SST, as the correlation in this case is already an average of 200 estimates. The test has been applied to the first 9 members of the ensemble: if this partial result is not significant, the result for the full 200-estimate average is declared as not significant. The correlations compare with those of Doblas-Reyes et al. (2003).

One can see that for month 1, any method provides the same skill. The role of SST variability at this range is thus negligible. Beyond end of November, the PROVOST method provides the best results, as expected, which shows the role played by the SST. However DEMETER results confirm the results of section 2: coupling with the ocean plays a role.

	Statistical SST	PROVOST	2-tier SST	DEMETER
November	0.45	0.44	0.43	0.42
December	NS	NS	NS	NS
January	0.09	0.30	NS	NS
February	0.09	NS	NS	NS
DJF	NS	0.25	NS	0.22

Table 1: Correlation of the NAO index for the 4 types of forecast. Non-significant (NS) values are not shown.

Although perfect model scores are not a measure of the maximum score modellers can expect to reach by improving their model, this approach is a good indicator of the potential predictability, when it is used to compare different models, different areas or different ranges. It can be seen also as measure of the ensemble spread by a correlation coefficient instead of a variance. Using a correlation coefficient is necessary to compare variables that do not have the same scale.

	Statistical SST	PROVOST	2-tier SST	DEMETER
November	0.88	0.89	0.89	0.83
December	0.24	0.30	0.26	0.28
January	0.12	0.24	0.28	0.17
February	0.08	0.18	0.15	0.11
DJF	0.20	0.31	0.33	0.29

Table 2: As Table 1 for perfect model approach. No significance test is applied.

For each of the 44 years, one member was selected as the verification and eight members (the remaining eight, except in the case of statistical SST) as the forecast ensemble. The operation was repeated 200 times, and the average was calculated. As we use here an average, simple scrambling tests cannot be applied, and we will simply assume that our results are significant. Indeed, they are all above 0.10. Table 2 shows the huge difference between the first month and the others. The scores decrease with time (which is another indication they are significant). The predictability of DJF is comparable to that of December. As far as DJF is concerned, PROVOST is at the same level as DEMETER and 2-tier SST (the fact that observed SSTs are used in PROVOST are no more an advantage in this perfect model approach). The statistical SST is poorer, which can be explained by the fact that the “verification” may have a very different SST from the “forecast”.

Northern Annular Mode

To get an even more stable tool to verify our result, we need to go to the hemispheric scale. The NAO is coarsely a North-South seesaw. When statistical analyses are extended in the stratospheric levels and to the northern hemisphere, the mode corresponding to NAO becomes more and more zonally symmetric, and is named Arctic Oscillation (AO, Ambaum et al., 2001). Another solution to filter out the non-zonal effect due to the land-sea and orography contrasts, is to work directly with zonal averages. The Northern Annular Mode (NAM, Thompson and Wallace, 2000) is simply the leading EOF of an analysis performed on 44x3 monthly means of ERA40 500 hPa geopotential zonal averages. It explains 51 % of the variance. Figure 4 shows that it corresponds to a contrast between the pole and 40°N.
Table 3 shows the scores (correlation coefficients) for the monthly means and the seasonal mean. In November, the scores are less than the NAO. This is somewhat strange, as NAM is larger scale that NAO and is expected to be more predictable. In fact this predictability is revealed at longer lags. Beyond December NAM has better scores than NAO. In PROVOST approach, December and January scores are even greater than the November one. This is not a “return of skill”: in PROVOST observed SST is injected each month in the model; this is just an annual cycle effect. Similarly to NAO, the coupled forecast (DEMETER) has the second position in predictability after PROVOST, better than the 2-tier approach. This shows that NAM predictability is not just an answer to SST forcing, since SST in the 2-tier method is better than in DEMETER. But SST forcing plays a role anyway, since PROVOST is a forced experiment.

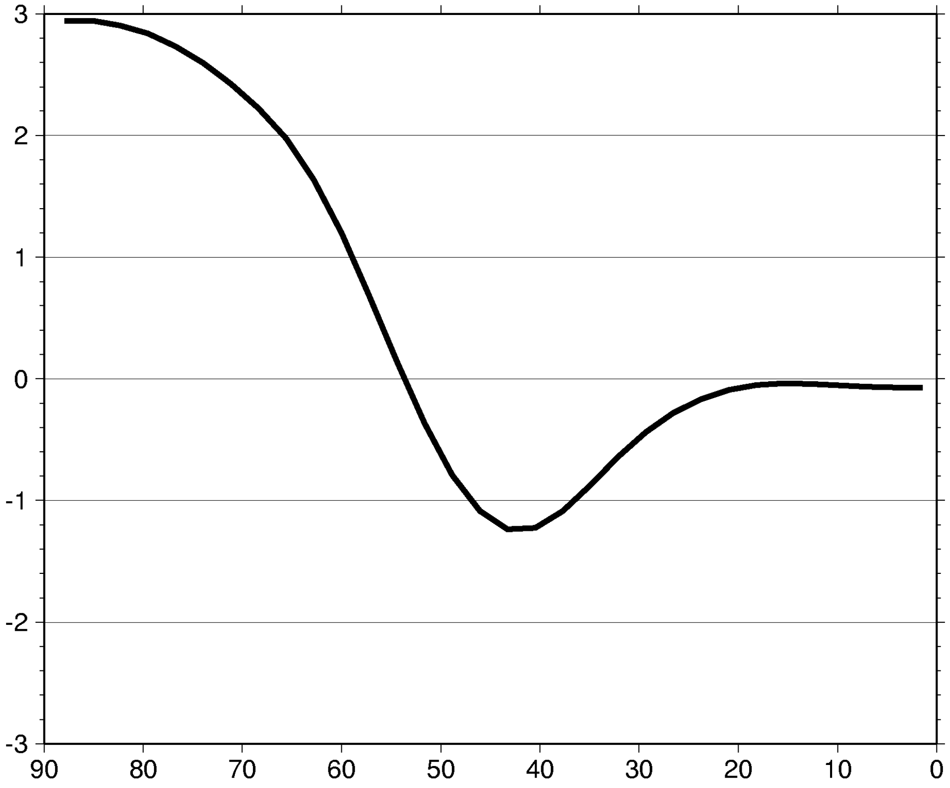

Figure 4: First EOF of winter monthly means of ERA40 for Z500 zonal averages. Non-dimensional units.

The perfect model approach is applied to the NAM. In fact Table 4 is very similar to Table 2. The predictability of the NAM is similar to that of the NAO: excellent for month 1, weak but potentially useful for the seasonal range, except with statistical SST. It is interesting to note that the DJF correlation in PROVOST is 0.50 with the actual model, and only 0.36 with the perfect model. There is no reason why, and simple examples can be constructed to illustrate this, perfect model scores should be always greater than actual scores.

	Statistical SST	PROVOST	2-tier SST	DEMETER
November	0.34	0.39	0.35	0.34
December	0.28	0.52	NS	0.29
January	NS	0.41	NS	NS
February	NS	0.24	0.29	NS
DJF	NS	0.50	0.31	0.39

Table 3: Correlation of the NAM index for the 4 types of forecast. Non-significant (NS) values are not shown.

	Statistical SST	PROVOST	2-tier SST	DEMETER
November	0.88	0.89	0.91	0.86
December	0.18	0.26	0.05	0.27
January	0.08	0.23	0.18	0.20
February	0.06	0.36	0.03	0.00
DJF	0.14	0.36	0.28	0.27

Table 4: As Table 3 for perfect model approach. No significance test is applied.

Conclusion

There is some predictability for DJF temperature over Europe. This justifies partly the operational use of numerical model in National Meteorological Services like France, although the main reason is the tropical predictability (parts of France are located in the tropics, and France develops a strong cooperation with African countries). The predictability is tiny, and 44 years for a validation are not excessive.

Among the various approaches, if we exclude the use of observed SST, which is obviously the best way to get good scores, ocean coupling seems to be the best strategy. If we remove the biases, but cut the atmosphere to ocean feedbacks, the scores are less. The multimodel strategy defined at ECMWF with the Met Office, based on coupled models, is thus fully justified.

In order to verify this behaviour on more stable predictands, we have considered forecasts of the NAO and of the NAM. The NAO is good at month 1, but the predictability does not survive a lot after a few months. On the contrary, the NAM is better adapted to the month 2-month 4 range.

The perfect model approach has been applied to the two indices. Although they have a rather different predictability in actual forecasts, the NAM and NAO potential predictability are very similar. This potential predictability expresses that the spread of an ensemble of forecasts (due to variability in initial conditions) is smaller than the interannual variability (due to variability in external forcings).

All these results are certainly model dependent. The conclusions drawn here are related to the version of ARPEGE used in DEMETER. One non-negligible outcome of the multimodel approach is to explore the variety of behaviour amongst a panel of model. This will be exploited in the forthcoming ENSEMBLES European project.

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5.3 Operational Seasonal Forecasting at the South African Weather Service

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Introduction

The South African Weather Service (SAWS) has been issuing seasonal rainfall and temperature forecasts since June 1994. For the first few years forecasts were based primarily on the output from a canonical correlation analysis (CCA) model (Klopper et al. 1998; Landman and Mason 1999) and expressed as a deterministic expectation of three equi-probable categories of below-normal, near-normal and above-normal. Since 1997, forecasts have been presented as probabilities of the three categories. These forecasts are a result of the subjective interpretation and combination of forecasts produced by a variety of forecast models, both empirical and dynamical, and are verified using a standard verification system.

The SAWS as Forecast Producer

The SAWS is a Regional Specialised Meteorological Centre and has a geographical responsibility. The SAWS is involved in the Southern African Development Community (SADC) through training workshops on seasonal to interannual climate variability and predictability, and also participates actively in the Southern Africa Regional Climate Outlook Forums (SARCOF).

The Global Forecasting Centre for Southern Africa (GFCSA) was established in 2003. The prime function of the GFCSA is to operate and maintain an operational long-range forecasting (LRF - from 30 days up to 2 years) system for the globe from where Regional Climate Centres and National Meteorological and Hydrological Services within SADC, as well as the international research community involved in the development of long-range forecasts, can obtain relevant global LRF products. Global forecast fields are available at www.gfcsa.net.

Currently the GFCSA consists of three institutions, based in South Africa: the Laboratory for Research and Training in Atmospheric Modelling based at the University of Pretoria, the Long-Range Forecasting Group of the SAWS and the Climate Systems Analysis Group based at the University of Cape Town. Each institution is involved in the production and dissemination of long-range forecasts and the GFCSA website serves as one focal point for such activities. The forecasts made available on this site are also used in the compilation of the SAWS consensus forecasts.

SAWS Forecast Models

The forecast models that are being run operationally at the SAWS include both dynamical and empirical forecasting systems. The COLA T30 GCM (Kirtman et al. 1997) is the operational dynamical model and forecasts of rainfall and temperature fields, both deterministic (ensemble mean) and probabilistic, are produced up to six months ahead. The boundary forcing sea-surface temperature (SST) fields are respectively persisted and forecast anomalies. Initial conditions from the most recent month (using NCEP data) are used to produce an ensemble of 10 members.

The forecast SST anomalies that are used to force the COLA GCM are produced every month by a CCA model (Landman and Mason 2001). CCA is also used to make rainfall and temperature forecasts for South Africa. These models use evolutionary features of the global oceans as predictors. The rainfall and temperature models make predictions for 3-month seasons, while the SST forecast model produces SST anomalies for individual months. Figure 1 shows the skill of the CCA model predicting the Niño3.4 region's SST anomalies. Significant skill levels are also obtained for the equatorial Indian Ocean, but almost no useable skill for the basin wide equatorial Atlantic Ocean (6° south to 6° north) is found. Moreover, most of the forecast skill is limited to the tropics.

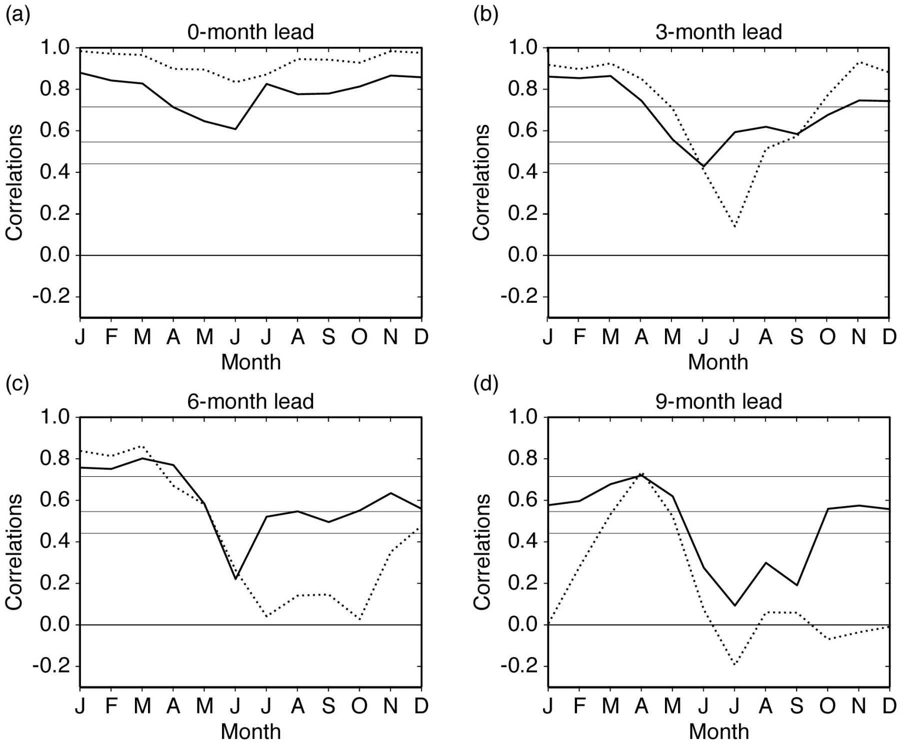

Figure 1. Correlation between predicted and observed (solid line) and persisted and observed (dashed line) eastern equatorial Pacific Ocean SST anomalies over the 18-year independent period 1982/83-1999/2000 at various lead-times. The horizontal lines represent the 90%, 95% and 99% confidence levels.

Empirical forecasting and downscaling techniques are used to make operational forecasts for a number of homogeneous rainfall regions in southern Africa. The latest downscaling technique is based on the model output statistics (MOS) approach (Wilks 1995; Landman and Goddard 2002), combined with the perfect prognosis (PP) approach (Wilks 1995; Landman et al. 2001). This MOS-PP technique uses GCM rainfall fields obtained from an ensemble of 24 members of the ECHAM4.5 GCM. These fields are provided by the International Research Institute for Climate Prediction (IRI), and are a result of forcing the GCM with simultaneously observed SST fields (i.e., DJF SSTs for a DJF simulation). MOS equations are constructed using this simulation set for all 3-month seasons. ECHAM4.5 forecast rainfall fields at various lead-times are subsequently used in these MOS equations to produce recalibrated forecasts. This part of the process is reminiscent of the PP approach, except that the forecast equations are based on the GCM's simulation data and not observed data. Figure 2 is a MOS-PP forecast produced in 2003.

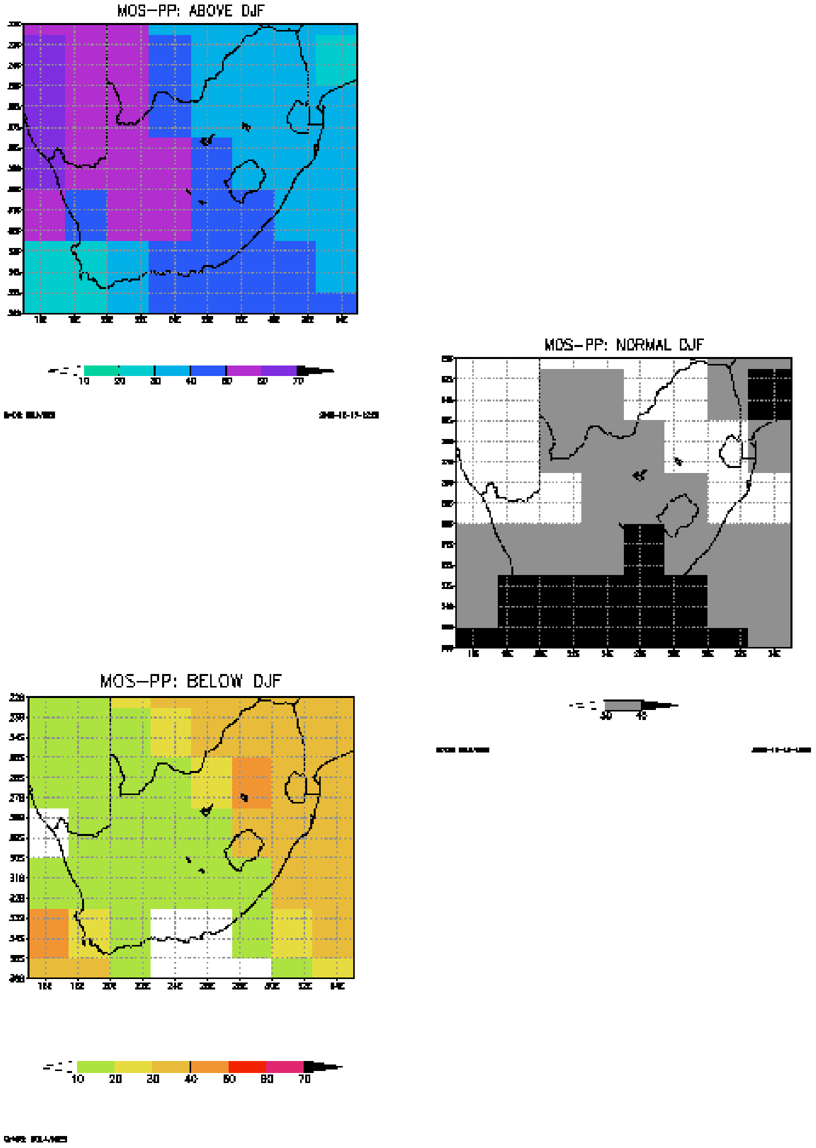

Figure 2. MOS-PP forecast for DJF 2003/04. Forecasts are expressed in terms of probabilities for three categories of below-normal, near-normal and above-normal.

Compiling the Official Forecasts

In addition to the statistical, dynamical and downscaled forecasts produced at the SAWS every month, the centres currently contributing to the official consensus forecasts are the University of Cape Town (HadAM3 (Pope et al. 2000) forecasts), the International Research Institute for Climate Prediction (ECHAM4.5 data (Roeckner et al. 1996) and forecast maps from their website), the UK Met Office and the European Centre for Medium-Range Weather Forecasts (forecast maps from their respective websites). The various forecasts are subjectively combined through consensus forecast discussions by SAWS forecasters. Probability forecast maps of rainfall and temperature, similar to the one shown in Figure 3, are subsequently produced. The logos of the contributing centres appear on the forecast maps.

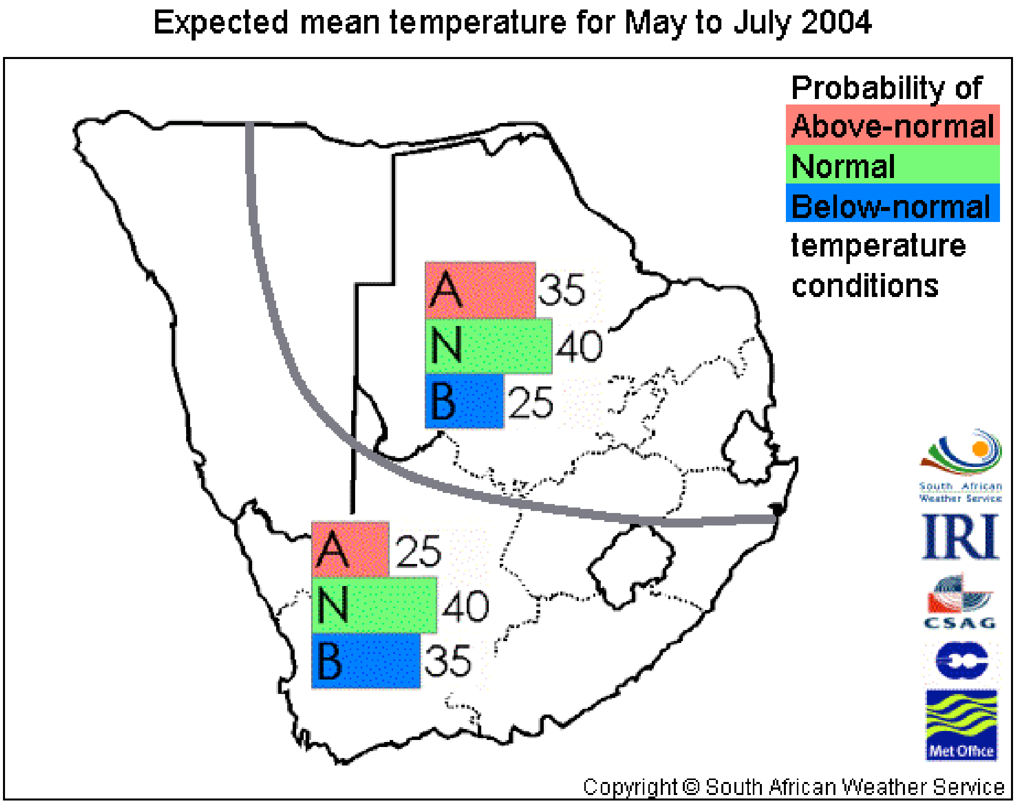

Figure 3. Consensus probability temperature forecast for May-June-July 2004, issued by the SAWS.

Verifying the Official Forecasts

A verification system to verify the consensus probability forecasts has recently been implemented at the SAWS by Dr Simon Mason of the IRI. Verification statistics are available for the probability forecasts from 1998 to present. Figure 4 shows ranked probability skill scores (RPSS) (Wilks 1995) of the September to November (SON), December to February (DJF) and February to April (FMA) seasonal forecasts at a 1-month lead-time as calculated over a number of consecutive years. The larger part of the country, with the exception of the southwestern Cape region, receives austral summer rainfall from about September to April.

Summary and Future Plans

The SAWS issues seasonal probability rainfall and temperature forecasts every month. These forecasts are based on a variety of different forecast models from which the forecast fields (probabilistic and deterministic) are subjectively combined through a consensus discussion forum. A standard verification system verifies these forecasts.

Further development of the forecasting system is taking place. Operational forecasts will in the near future involve the use of regional climate models. The objective combination of post-processed multi-model forecasts, including forecasts from both GCM and regional models, should further add to the operational forecast skill of the region. In fact, simply averaging post-processed (MOS) forecasts from five simulation GCM runs, has produced skill levels higher than those of the best GCM-MOS model. These downscaling schemes are also currently tested for the predictability of streamflow of some of the major catchments of South Africa.

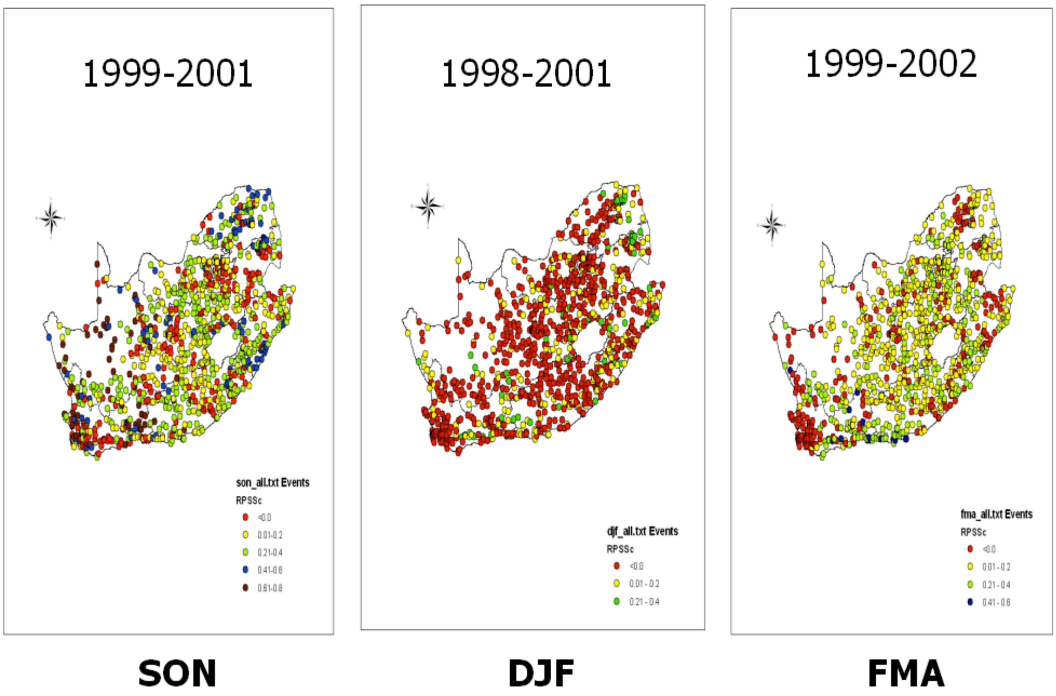

Figure 4. Ranked probability skill scores of the 1-month lead-time SAWS consensus probability forecasts for the seasons indicated.

Significant forecast skill has already been found in predicting for five instead of the usual three categories, suggesting that there is useful skill in predicting extreme seasons. In addition to predicting very wet or dry seasons, efforts are currently ongoing to assess the predictability of intra-seasonal characteristics (Tennant and Hewitson 2002), as well as the influence land-surface characteristics may have on seasonal rainfall and temperature forecast skill over the region. The Conformal-Cubic Atmospheric Model (CCAM) (McGregor and Dix 2001) is currently being configured at the University of Pretoria for this purpose.

The seasonal predictability of tropical cyclones over the southwestern Indian Ocean is underway. Very little proof has as yet been found that using the GCM fields available to the SAWS can provide useful seasonal predictability of tropical cyclone characteristics over the southwestern Indian Ocean. However, regional model simulations have provided evidence that a properly defined model domain should improve on the predictability of seasonal characteristics of tropical cyclone occurrence over that part of the Indian Ocean (Landman et al. 2004).

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5.4 Dynamical and statistical seasonal climate forecasts at CPTEC

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Introduction

The Center for Weather Prediction and Climate Studies (CPTEC) of the National Institute for Space Research (INPE), located in Cachoeira Paulista, São Paulo, Brazil, develops, produces and disseminates real time weather forecasts, as well as seasonal climate forecasts since early 1995. This Center is part of the research network of the Ministry of Science and Technology (MCT) of Brazil. CPTEC is a leader in operational meteorology and climate research and forecasts in South America. Its focus is numerical seasonal climate forecasts for Brazil and the rest of the South American continent. Currently, the main users of CPTEC weather and climate products are research groups, universities, federal and state government agencies, civil defence, meteorological and hydrological services, the media (TV, radio, newspaper), hydropower, agricultural, industry and tourism sectors, as well as the private sector not only from Brazil but also from the rest of the South American countries.

Long-range forecasts (LRF) are being issued from CPTEC since 1995 and made available for the public domain. Forecasts for specific regions may differ substantially at times, due to the inherent limited skill of long-range forecast systems. This LRF can be Monthly outlook, or three-month or 90-day outlook (Seasonal outlook) or interannual. CPTEC issues Deterministic Long-Range Forecasts presented as maps of anomalies (non categorical forecasts) and Probabilistic categorical forecasts (equiprobable terciles). Deterministic dynamic LRF is produced from the ensemble mean from all the members of an Ensemble Prediction System (EPS) from the CPTEC AGCM. The seasonal forecast issued one month before the beginning of the validity period is said to be of one-month lead. Statistical forecast is made for rainfall in Northeast and southern Brazil.

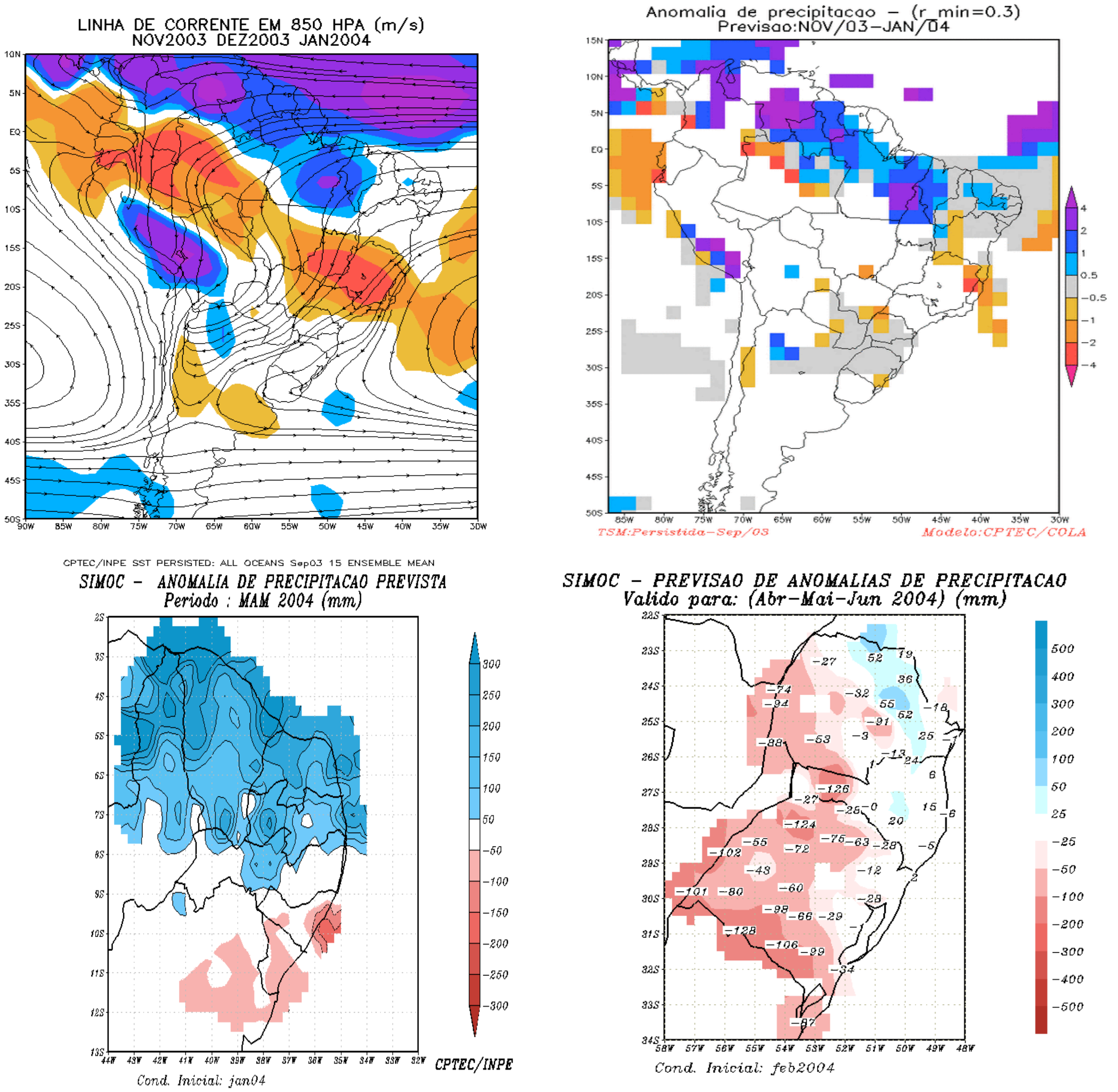

Fig. 1. (a) Dynamical seasonal rainfall and 850 hPa wind forecast from the CPTEC/COLA AGC for ND2003-J2004. (b) Seasonal rainfall forecast for the same season using an statistical mask considering anomaly correlation coefficients above +0.3 or below -0.3. (c) rainfall anomalies for MAM 2004 for Northeast Brazil and (d) southern Brazil both derived from the SIMOC model.

CPTEC also provides tailored specialized products to service users in particular areas, such as trajectories or dispersion of pollutants in case of environmental emergencies, information on prolonged adverse weather conditions, including drought monitoring. It also carries out verification and intercomparison of products and arrange regional workshops and seminars on centre's products and their use in national weather forecasting.

Research and development in LRF specialized data processing

Seasonal climate forecasts are presented as seasonal (3-month) anomaly maps based from a 10-year 9-member ensemble climatology from the CPTEC AGCM forced with observed SST anomalies during the 1982-91 period. Indices of skill and confidence levels were assessed based on this 10-year climatology. Together with the rainfall anomaly maps from the ensemble mean, maps of masked rainfall anomalies, with correlations larger than 0.3, are also presented (Fig. 1a, b). In addition, *seasonal maps of probabilities of rainfall categories above normal, near normal and below normal, as well as a "rebuilt " forecast are presented for South America, based on the 1982-91 climatology of the CPTEC AGCM*. This is for the most recent seasonal climate forecast issued by CPTEC for the season ND2003-J2004. All these statistics will be re-made using the 1949-2000 CPTEC-AGCM new climatology that has been recently completed at CPTEC.

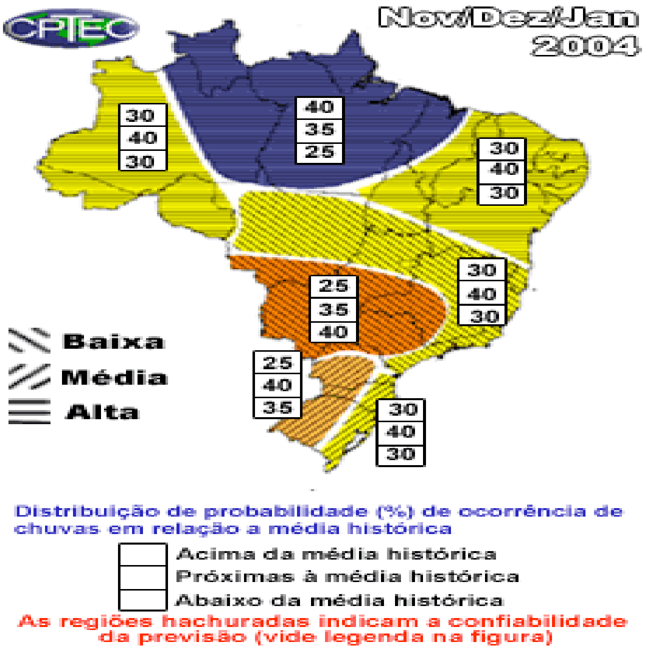

Figure 2. Seasonal (Nov Dec 2003-Jan 2004) probabilistic rainfall forecast for Brazil as produced by CPTEC. Numbers represent probabilities of having rainfall above normal/ nearby normal/below normal. Hatching represents the levels of confidence. (www.cptec.inpe.br/clima/)

Forecasts are made for the whole continents, but are shown for Brazil only, as indicated on the Climate Portal at the CPTEC web site (www.cptec.inpe.br). Seasonal rainfall forecasts are presented to the public in the form of categorical forecasts, for the entire country and considering forecasts made by CPTEC dynamic and statistical models, as well as the UK Met Office, IRI, JA, NCEP and other world meteorological centres. Fig. 2 shows the categorical (consensus) forecasts, indicating probabilities of above the normal/near normal/below the normal rainfall, as well as the level of confidence of there forecasts. Regional Eta/CPTEC seasonal forecasts are presented as total rainfall and temperature maps, since the regional model climatology is not yet known for South America we still do not have a complete analysis of predictability and skill of the regional eta CPTEC model.

Outstanding Research and development activities related to LRF specialized analyses forecasts system in operational use

CPTEC has two NEC supercomputers: the SX4 (peak performance of 16 GFlops) and the recently purchased SX-6 (peak performance of 256 GFlops). Currently, the SX-6 operates with 32 processors, 128 Gbytes of memory and disk capacity of 4 Tbytes). The SX6 cluster will grow to 96 processors and 768 Glops towards end of 2003. This improvement in the computer capability makes possible the application of a larger number of integrations for weather and climate prediction experiments, using the ensemble technique for weather and climate forecasts.

Numerical Weather Prediction is carried out using the CPTEC Atmospheric General Circulation Model (AGCM), which was originally derived from the NCEP model by COLA. Global analyses from NCEP are used as initial conditions. The current resolutions are T62L28 and T126L28, with the SX6 we started to run the model with a T170L42 (~70 km) and later with T254L42 (~50 km).. The model climatology and an analysis of regional and global predictability based on a 10-year climatology of the CPTEC COLA AGCM can be found in Cavalcanti et al. (2002) and Marengo et al (2003).
Seasonal dynamical climate predictions are made using the same CPTEC AGCM T62L28 model. The seasonal forecasting system comprises a 30-member ensemble run for 6 months, in which 15 members use persisted sea surface temperature (SST) anomaly and 15 members use

predicted SST anomaly. Since 2002, the Eta regional model, with 40 km horizontal resolution, is run on a monthly basis to produce seasonal forecasts for the whole South American. The Eta/CPTEC model runs with the boundary conditions provided by the CPTEC AGCM.

A coupled ocean-atmosphere global model from COLA was implemented at CPTEC and is being tested. Assimilation of oceanic surface and subsurface data from PIRATA array is being planned as well as numerical experiments in seasonal climate forecasts using the coupled model. CPTEC has developed also a statistical model, the SIMOC or Sistema de Modelagem Estatística dos Oceanos (Pezzi et al. 2002).. It is based on canonical correlations using Pacific and Atlantic SST's as predictors of seasonal rainfall anomalies for many areas of South America (Northeast Brazil, Southeastern South America-Repelli and Nobre 2004). Another module of the SIMOC model also produces forecasts of SST anomalies over the tropical Atlantic. These predicted anomalies are input to the CPTEC AGCM as lower boundary conditions. The SIMOC model outputs can be made available to any center in the world. Fig. 1c, d show the statistical rainfall prediction at CPTEC for Northeast and southern Brazil, respectively. Rainfall anomalies as re shown in blue (positive) and red (negative).

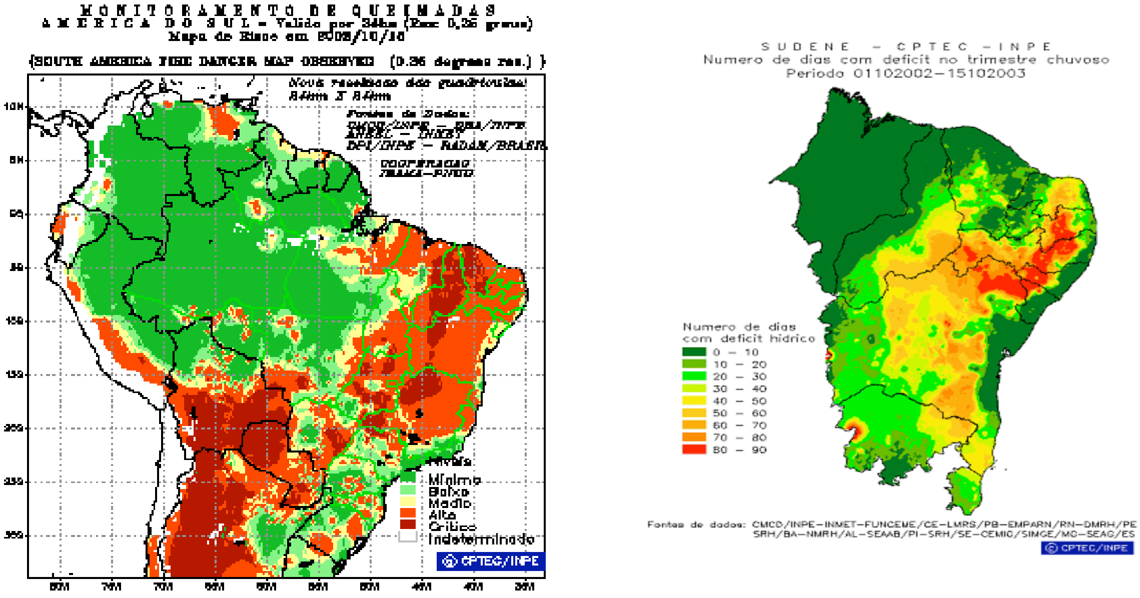

Fig. 3 (a) Map of risk of fire in South America for October 18 2003, based on Eta/CPTEC forecasts. (b) number of successive days with no rain during October 1 2002 until October 15 2003.

CPTEC is currently developing Hydrological seasonal forecasts, using seasonal climate forecasts from regional and global models for agriculture and hydroelectric generation purposes. Experiences from CPTEC show some use of modeled rainfall from a global model for seasonal river discharge prediction in southern Brazil (region with high-medium predictability). On this region (as well as in the Amazon basin), the model systematically underestimates rainfall and corrections can be made using statistical adjustments (linear regression type) to obtain a "corrected" rainfall in order to obtain "corrected" streamflow values.
Fifteen climate researchers are involved in studies related to climate variability and effects on South America, mainly Brazil. The main studies are focused on Northeast and South American Regions, Amazonia (LBA project), Southeast and Central West Regions (South Atlantic Convergence Zone variability), El Nino, and La Nina influences. Teleconnection patterns in the Southern Hemisphere are also investigated to identify remote forcings that affect South America. The studies have been conducted using results from model simulations, observations and NCEP or ECMWF reanalyses data.

The main lines of investigation by the climate research group at CPTEC can be summarized as:

- Seasonal climate forecasts for Brazil and the rest of South America (dynamical), and for Northeast Brazil and southern Brazil and the South-Southeast of South America (statistical)
- Sensitivity of climate to changes in land use, SST anomalies, and greenhouse gases/aerosols.
- Climate variability (intraseasonal, interannual, interdecadal) and climate change with emphasis in tropical regions and South America, via observational studies and downscaling of IPCC SRES climate projection scenarios for the XXI Century.
- Monitoring of climate hazards or prolonged adverse conditions (drought, floods, forest fires).
- Land surface-atmosphere interactions
- Macro and basin hydrological scale modelling
- Atmosphere, ocean and coupled atmosphere-ocean modelling
- Global and regional climate modelling
- Aerosol transport and trajectories of smoke and other gases due to biomass burning and pollution
- Verification of model results and intercomparison of model products from other centers

Results of research are disseminated through specialized literature and a list of recent publications is presented in Part VI.

Two examples of environmental monitoring and modeling applications are the PROARCO Program (Fig. 3a) for forest fire and the PROCLIMA (Fig. 3b) Program for hydrometeorological conditions in Northeast Brazil. PROARCO is an effort between CPTEC and the Brazilian Institute for the Environment (IBAMA) and consists of weather forecasting and monitoring to calculate forest fire risk for the entire country, but with a main focus on the region called “Deforestation Arc”, that includes the southern boundaries of the Amazonian tropical forests and the transition zones to the savanna (cerrado) to the south. A model implemented by INPE is used in order to process observations (conventional, satellite) and to feed a model that produces a map of forest fire risk. This model also feeds other ecological models. Deforestation and forest degradation due to selective logging has led to a situation where large areas of forest became vulnerable to fires. Seasonal climate predictions are being used to give early warning of forest areas which could become too dry during the dry season, thus sensitive to fire risk.

PROCLIMA is a joint effort between CPTEC and the Agency for Development of Northeast Brazil (SUDENE), and consists of calculations of soil moisture produced by a water balance model, with the input of more than 1000 rainfall stations, soil and vegetation conditions from RADAM BRASIL, and information from the automatic weather and hydrological stations, as well as from satellite, implemented on a GIS framework for Nordeste. The level of detail goes from the entire region to the local level. The maps of soil moisture plus the numerical seasonal predictions are taken into account in the monitoring of the Nordeste rainy season.

Plans for future research and development activities related to improvement of LRF oriented operational system

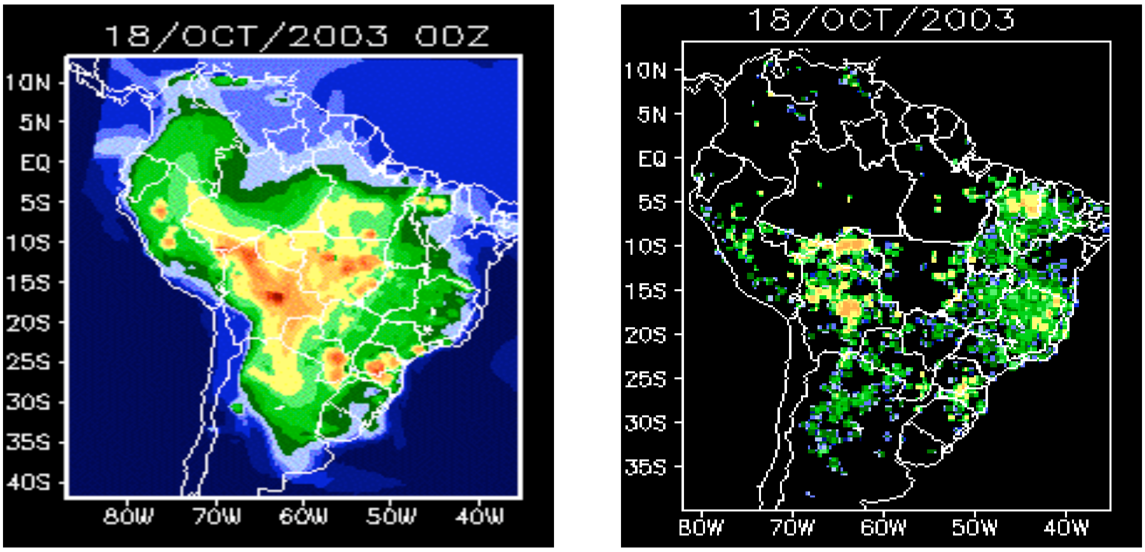

Fig. 4. (a) Concentration of CO as forecasted by CPTEC for October 18.2003; (b) Total emission of CO released by forest fires and biomass burning during October 10 2883.

We have identified the following topics that are matter of outgoing research activities for future operational applications

1. Implementation of *"environmental forecasts"* activities at CPTEC (air quality, dispersion of air pollutants, risk of fire, UV), as well ad seasonal soil moisture content and soil moisture storage; and Seasonal river streamflow forecasts. These activities are been developed regionally in Brazil and still on resting model, and should be made operational by the beginning of next year. Fig 4 shows some of these experimental products.
2. *Stratification according to the state of ENSO* should be made based on reasonably representative model climatology. This has been done at CPTEC for a 10-year 9-member ensemble (1982-91) as discussed in several papers (Cavalcanti et al. 2002, Marengo et al. 2003….). Currently a new run for 50-years model climatology (1949-2000) has been finished and is under analyses. This will allow for a better stratification since sufficient ENSO events are contained within this hind cast period. Scores are to be provided for each of three categories: All hind cast seasons, Seasons with El Niño active, Seasons with La Niña active. IRI has done this for the model it runs, and it would be great for them to share experiences and software with other centers.
3. Perform studies on the *"optimum size of the ensemble"* for seasonal climate forecasts on global and regional basis. CPTEC runs 25 realizations for two sets of SST anomalies. Studies developed by CPTEC have shown that for regions with higher climate predictability (e.g. Northeast Brazil) a smaller size ensemble can be enough, while for regions such as Southeastern South America, a region with lower climate predictability and where the most important cities in South America are located (São Paulo, Buenos Aires, Rio de Janeiro) even with a ensemble size larger than 25 members, the models do show skill in predicting regional rainfall anomalies.

Some research activities are being implemented and or current development at CPTEC regarding model improvement, changes in boundary conditions, use of field experiment data for model validation and physical assimilation, mainly directed to:

1. *To improve the boundary conditions in AGCMs*: SST prediction in the tropical Pacific Ocean, Tropical Pacific and Indian Oceans: SST anomalies in the tropical Pacific all year long is generated by the NCEP coupled model and provided by NCEP; SST anomalies in the tropical Atlantic Ocean during the period November to May generated by the SIMOC statistical model and provided by CPTEC; SST anomalies in the Indian Ocean generated by an statistical model and is provided by IRI. CPTEC's SIMOC

model is made available to many numerical centres, and we suggest that IRI provides the Indian Ocean SST model to other centres.

2. *To exchange parameterisation schemes from different models*, in order to improve the models performance. Example, the CPTEC AGCM and several other models exhibits a systematic underestimation of rainfall in the Amazon basin during the rainy season. Several experiments using different parameterisation schemes (clouds, convection, land surface processes, Planetary Boundary layer, among others) should be tested to improve the seasonal climate prediction.
3. *To propose and develop methodologies in order to study climate extremes* (dry spells, days with intense rainfall using) global and regional models, for composites of ENSO (El Niño and La Niña years) and for normal years.
4. To propose and explore the benefits (usefulness and limitations) of *dynamical and statistical downscaling in seasonal climate prediction,* including assessments of skill of the model, for both seasonal climate prediction and projections of climate change scenarios. Successful experiences in Northeast Brazil: under the collaboration CPTEC-IRI-FUNCEME are described in Quiang et al. (2000).
5. To develop and test *physical data assimilation* schemes using the PSAS scheme developed by NASA-DAO for regional and global models at CPTEC, and using data from field experiments performed during the last 3 years in South America, part of the IAI, GEWEX and CLIVAR programs.
6. *To exchange information on seasonal prediction activities among the different numerical (operational and research) centres.*. This will provide new information and new insight on methodologies to study and assess predictability in subtropical and extra tropical regions. INPE has a collaboration project with ECMWF in seasonal prediction, and this allows for exchange of experiences, interaction among researchers of both centres and collaborative studies. Collaboration agreements also exist between INPE and IRI in seasonal prediction and with INMET. Informal or formal agreements can be done with other centres in order to exchange seasonal prediction experiences.
7. *To make available global digital results of several models* to perform a multi-model ensemble similar to those from IRI. We envision a *global multimodel ensemble* including all models used by the IRI plus from other centres (ECMWF, JMA, UK Met Office, BMRC, CPTEC and other centres that do not have models run at IRI) to be implemented either by IRI or any other institution with support from WMO. We expect that one the 50-year climatology of the CPTEC/COLA AGCM is implemented, seasonal forecasts from this model will be submitted to IRI so our model will joint the suite of AGCM run by IRI to implement the global multimodel ensemble.

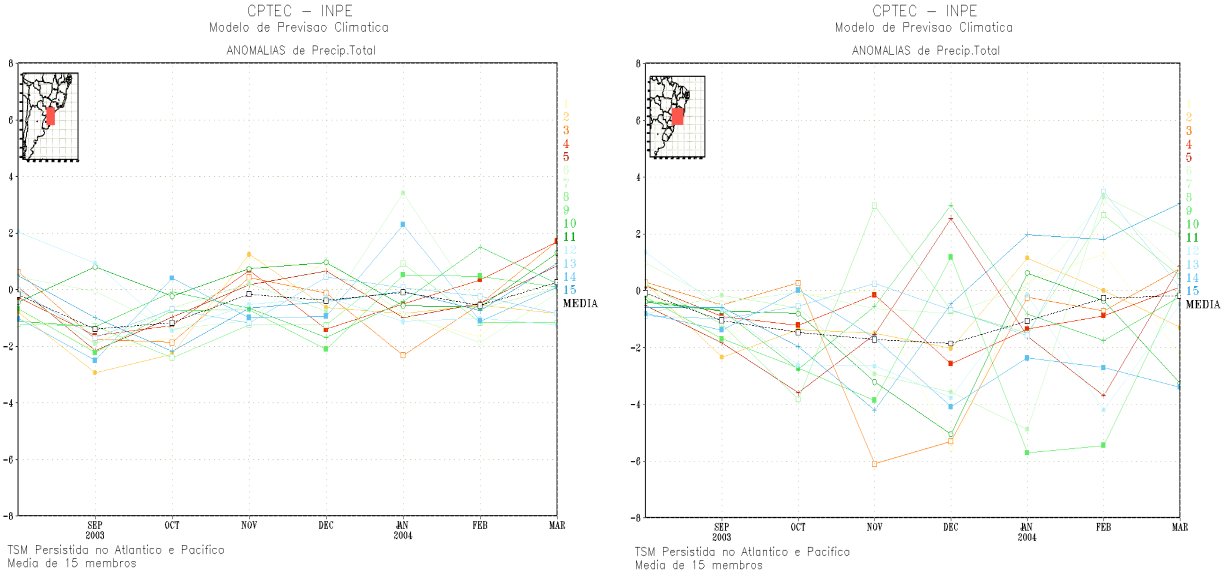

Fig. 5. Inter member ensemble for the ND2002-J2004 rainfall forecast for a) Southern Brazil, b) southeast Brazil. Each thin line represent one realization, and the broken line is the ensemble mean of all members.

Development and verification procedures including performance statistics

CPTEC has used for the validation of the CPTEC COLA AGC the following "observational" data sets":

- NCEP/NCAR reanalyses for circulation, humidity and air temperatures.
- Xie-Arkin –CMAP and CRU for Precipitation anomaly.
- Precipitation and temperature from different Brazilian institutions (INMET, regional meteorological centres, private electric companies, etc)
- OLR data sets from NCEP

CPTEC's seasonal climate and "environmental" products at global and regional scale include:

- Seasonal (up to 6 months) global and regional climate forecasts, based on the CPTEC AGCM-T62L28, for rainfall and 2 meter air temperature anomalies.
- Seasonal (up to 3 months) regional climate forecasts, based on the 40-km Eta/CPTEC regional model, forecasts of rainfall and 2 meter air temperature.
- Seasonal statistical rainfall anomalies in Northeast Brazil and Southern Brazil using the SIMOC statistical model.
- Seasonal statistical SST anomalies over Tropical Atlantic Ocean
- Seasonal forecasts of risks of fire in South America (derived from the global and regional seasonal climate forecasts.
- Seasonal soil moisture content and soil moisture storage (experimental for the Northeast Brazil, soon to be extended to South America using the CPTEC AGCM T62L28 and the 40-km Eta/CPTEC models.
- Seasonal river streamflow forecasts (experimental for the La Plata River Basin in southern Brazil-Argentina-Uruguay) for generation of hydroelectricity activities (based on CPTEC AGCM T62L28 and the 40-km Eta/CPTEC models.

Measurements of model skill used at CPTEC include the

(a) Anomaly correlation,
(b) Relative Operating Characteristics ROC,
(c) Brier skill score,
(d) Bias score, and
(e) Root Mean Square Error (RMSE).

These diagnostics permit direct intercomparison of results across different geographical regions, forecast ranges, etc. For these verifications, we have used the CMAP-Xie/Arkin rainfall data sets as "rainfall observations", and are using the CRU-Hulme/New data sets for rainfall and air temperature data sets for future studies. Regarding climate predictability and model skill, studies performed at CPTEC using the CPTEC AGCM, and other models has shown that region such as southern Brazil, northern Brazil-Central Amazonia and Northeast Brazil exhibit high-medium climate predictability, while southeast and central Brazil exhibit lower climate predictability and poor model skill. Fig 1b shows those regions in blank, meaning that the observed and simulated rainfall anomalies are of opposite tendency. This can also be observed in the spread among the members of the ensemble in Fig. 5a, b, where 5a shows the rainfall anomalies for southern Brazil and 5b shows similar variable but for southeast Brazil. In summary, CPTEC is an operational and research centre in Brazil funded by the federal government. It is the only center in Latin America that issues regularly weather and seasonal climate forecasts based on dynamical and statistical models. All meteorological services in South America access CPTEC forecasts. Currently, it has several monitoring activities (water balance, hydrometeorology, air pollution, Antarctica, oceanic waves, UV, fire risks), and also regional experiments and research programs (LBA, mirror site in Portuguese/Spanish of IPCC DDC, SALLJEX). With the arrival of more nodes of the NEC SX-6 Sypercomputer, CPTEC is starting new model activities: coupled ocean atmospheric, paleoclimate, dynamic vegetation model, future climate change scenarios using global and regional models. At the end, CPTEC is heading towards environmental prediction activities: weather, climate, fire risk, SST, waves, streamflow, UV, air pollution and trajectories, soil moisture and water balance

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Seasonal and Monthly Forecasting at ECMWF

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Arthur Vidard, Frederic Vitart, Paco Doblas-Reyes and Alberto Troccoli.
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At ECMWF, a seasonal forecast system has been operating for several years. This system is described and some results presented. More recently, a monthly forecast system is being prepared for operational use. In both cases, the forecasts are made by fully coupled atmosphere ocean models. The models are global and so include the Atlantic sector. Skill there is contrasted with the Pacific sector.

A multi-model forecast system is well advanced and results should be available by early next year. The multi-model approach avoids to some degree the tendency for individual models to be too confident in their predictions. Model error is still a major issue and requires considerable effort to improve the models. It is also the case that maximum information is not being extracted from the ocean observing system.

Introduction

For several years now ECMWF has been running, first quasi-operationally and then fully operationally, a seasonal forecast suite. This consists of an ocean data assimilation system to provide initial conditions for the forecast, a fully coupled ocean-atmosphere model and a post processing procedure to generate forecast products. A subset of these products is then made available on the web but data can also be extracted from the ECMWF MARS archive for those users who want to generate their own tailor-made products. In this section we will consider the three components of the forecasting system and different developments over the years.

Largely as a result of the TOGA programme which highlighted ENSO as a major source of atmospheric variability and possible predictability, seasonal forecasting was perceived as an area of potential interest to ECMWF. As a result a small group was formed in 1996 to develop a forecast system. The results of the PROVOST programme later showed that given reasonable SSTs, atmospheric models were capable of simulating much of the interannual variability in the tropics at least, and that a multi-model approach was beneficial.

The ECMWF strategy was to go for a single suite to predict the SSTs and the more interesting and relevant atmospheric variability. This is the so-called one-tier approach. Others have tried a two-tier system, to first predict SST and then calculate the atmospheric response to these SSTs. While the latter may have some short-term advantages in that it avoids, to some degree, climate drift, we felt it unlikely to be a good long-term strategy. However, this is a relatively new endeavour and experience may tell which approach is best. We will return to the potentially flawed strategy of two-tier forecasting later but should point out that the climate drift in a 1-tier approach is not small compared with the signal one is trying to predict and this is likely to reduce the skill achievable.

The first coupled model forecast system was assembled in 1996 and real-time forecasts produced in 1997. The early forecasts of the 1997 El Nino were so interesting that the Council of ECMWF requested they be made publicly available on the web. This system was called System-1 (S1). For reasons that will become clear later, related to the handling of model error, one does not change these forecast systems frequently. In fact S1 was in use until March 2003 and was only turned off because it could not be easily ported to the new supercomputer. Preceding that, we were developing a new forecast model, called System-2 (S2). This has been running operationally since Jan 2002. We will first describe S1 and later S2. System 3 is in development for implementation in 2005.

Seasonal forecast System-1

The ocean analysis system

The ocean model used in S1 was HOPE at a resolution of 2 degrees but with the meridional resolution increased to 0.5 degrees in the equatorial region. The model covers the almost-global domain. The observed coverage of sea-ice is used in the ocean analysis though it is not well handled in S1 in the forecast. As part of the assimilation strategy, the model was forced with the wind stresses and heat and fresh water fluxes from the atmospheric analyses. These were from ERA15 until its end in 1993 and from the operational analysis-weather forecast system thereafter. Every ten days an ocean analysis was performed by assimilating all the data in a 10-day window and using the model as a first guess. The OI system was univariate. No correction was made to salinity or velocity. However, the temperature increments were applied smoothly over the 10 days following an assimilation to allow the model circulation field to adjust to the new density field. The details of the analysis system can be found in Alves et al 2004 and Balmaseda 2003.

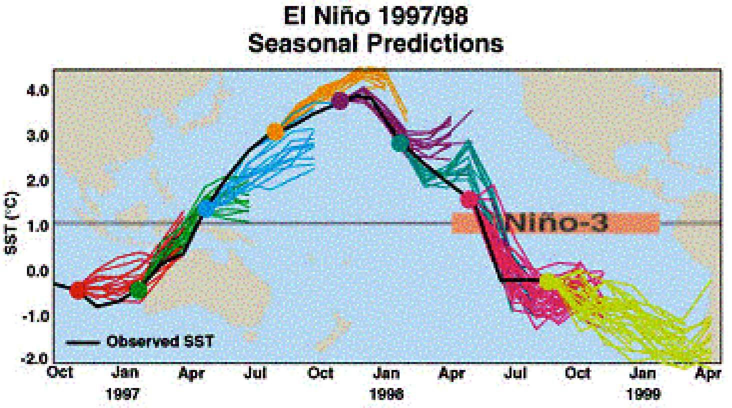
We do not describe the atmospheric analysis system. The atmospheric initial conditions are those produced either as part of ERA 15 or from the operational system, at a suitably truncated resolution.

The forecast system.

From the above ocean analyses, a set of forecasts was made. The coupled model is global in both media. The atmosphere is at a resolution of T63 (~2 degrees). Basically a forecast to 210 days was made every day so that over a month an ensemble of forecasts of between 28 and 31 members could be made. These would have a nominal date of the first of the month, but spanning the period the 16th of the previous month to the 15th of the current.

If the model had no biases, these would constitute the forecasts. Unfortunately, model error is significant and must be dealt with. The strategy adopted at ECMWF was to create a pdf (probability distribution function) for model fields based on past integrations of the model. For S1, the climate pdf was derived from a set of 11 integrations made each month for the 6 years 1991-96. Model forecasts of climate anomalies were then obtained by comparing the forecast pdf with the climate pdf.

S1 was rather successful in handling the 1997 El Nino as figure 1, produced by Clivar based on ECMWF data, shows. The onset of El Nino and its very rapid decline were well predicted as was its peak intensity. Forecasts from around April and May under-predicted the growth of Nino3, however (Vitart et al 2003). This is interesting since others have claimed that their forecasts were poor until after the westerly-winds/MJO of late February 1997. A detailed analysis of the 1997 El Nino in both S1 and S2 is given in Anderson et al 2003.



Source: ECMWF

Fig 1. Plot of forecasts of Nino3 for various start times throughout the large 97/98 El Nino. Different lines of the same colour indicate different ensemble members. The background indicates the location of Nino3. This plot was produced by CLIVAR based on data from ECMWF.

Seasonal forecast System-2

The operational implementation of S2 differs from S1 in a number of ways: the version of the atmospheric and ocean model, the horizontal resolution of the atmosphere and horizontal and vertical resolution of the ocean, the way the ensemble is generated and the climate pdf estimated, and the strategy for producing ocean analyses and generating forecast ensembles. (These latter four are linked).

An ensemble of ocean analyses

To represent the uncertainty in initial conditions of the ocean, an ensemble of ocean analyses was created. This was a 5 member ensemble of ocean analyses differing in that the wind fields used to force the ocean in the analysis system differed between the ensemble members by an amount that was commensurate with perceived accuracy in the winds. This should really be a function of the atmospheric observing system with the quality of the winds in the later years being better than in the early years but this level of sophistication was not included. Several differences in the analysis procedure were also adopted as described in Anderson et al 2003 and Balmaseda 2003. See http://www.ecmwf.int/products/forecasts/d/charts/seasonal/ocean/

Figure 2 shows a section along the equator from the analysis system. To the left is the Indian ocean, the middle the pacific and to the right, the Atlantic. Shown are anomalous temperatures in the upper 300m. Yellows and reds indicate warm anomalies, blues and greens, cold anomalies. Meridional sections are also available on the web, together with spatial maps of sea level anomalies. In the case shown, there is a substantial cold anomaly in the equatorial eastern Atlantic. The lower panel shows a typical data coverage in a monthly period (March 2002). The reds indicate the TAO/TRITON/PIRATA moorings (most reporting at least daily), the blacks indicate XBT data and blue the ARGO floats (reporting once every 10 days).

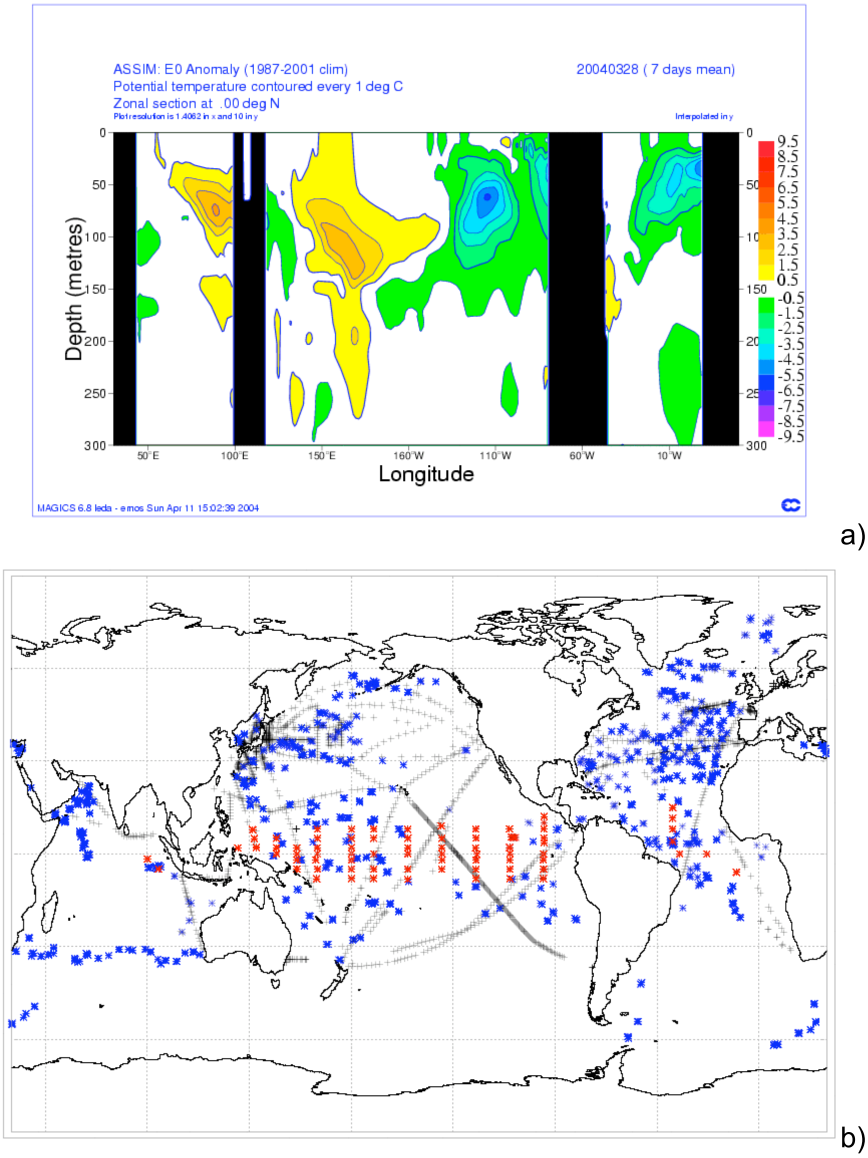


Fig 2 a) Vertical section along the equator of the temperature anomaly. The section on the right corresponds to the Atlantic. Contour interval=1K. From the ECMWF operational ocean analysis system. b) Data coverage for the month of June 2004. The data are those which enter the ECMWF ocean analysis system at a depth of 150m. By choosing this depth one gets a good indication of where there are vertical profile data. The grid of red stars in the Pacific, indicates TAO/TRITON moorings and those in the Atlantic are from PIRATA. The blue are ARGO. The black, dotted 'straight' lines indicate XBT tracks.

Recently a real-time ocean analysis has been developed. The standard analysis is typically 11 days behind real-time. (The analysis window is +-5 days, 6 days is allowed for data receipt, and a day for computation and updating the web, giving a delay of 12 days). For monthly forecasts (discussed later), this delay is unacceptable and a real-time ocean analysis is required. This is achieved by advancing from the standard analysis, forcing the ocean with the analysed surface fluxes and assimilating any data that are available: for example, the TAO/TRITON/PIRATA mooring data and some XBT data are usually available with a delay of less than a day. The SST field is usually available only with a delay of several days: the fields are based on a weekly window of data so imposing a minimum delay of 5 days but this can be as long as 11 days depending on how the weekly SST analysis fits with the 10-day ocean analysis.

An ensemble of climate forecasts

There were some drawbacks with S1. The fact that forecasts were spread over a month created some difficulties in interpreting the ensemble and calibrating the forecasts. Further, although the use of 28-31 different ocean initial conditions gave some spread to the ensemble, it did not represent the error in the ocean state. So the new system S2 aimed for a forecast start date of the 1st of the month. The ensemble is in burst mode rather than distributed as in S1, so all forecasts start on the same day. By having forecasts on the first of the month, rather than using forecasts up to the 15th, means that our forecasts can be released more than two weeks earlier than in S1.

The ocean model resolution in S2 was increased relative to S1 to 1 degree in the extra tropics and to 1/3 degree in the tropical strip. The vertical resolution was increased from 20 to 29 levels. Another major influence on the quality of the forecasts was the use of a newer cycle of the atmospheric model: S2 used IFS-23r4 whereas S1 used IFS-15r8. The ECMWF web site lists the many changes between atmospheric model cycles, but one important set of changes is that described by Gregory et al. 2000. A further change was in the calibration (climate) integrations. In S2 this consists of a 5-member ensemble spanning the years 1987-2001, rather than the 11-member ensemble for 91-96 as used in S1. A 40-member ensemble is generated twice per year (May and Nov) to allow a more in-depth analysis of mid-latitude signals.

Some results

Figure 3 shows the skill of the two systems as measured by anomaly correlation. While there are differences in detail the overall quality is very similar. Despite the extensive work in developing a new system, the results are remarkably stubborn to improvement. This figure also shows that the skill in the tropical Pacific is much higher than in the Atlantic and Indian oceans and that skill falls off rapidly with latitude.

The rms error of forecasts for the Nino3 region is shown in fig 4. The skill of the system beats persistence at all lead times. This is true for all start months although you cannot see this from the figure. The correlation of predicted SST is also higher than that from persistence. So, in that sense coupled model forecasts are good. Fig 4 also shows the growth of the spread in the ensemble (dashed curve). This grows less fast than the error. One can interpret this result in two ways. The negative approach says that the spread is smaller than the error and therefore the forecast system is poorly calibrated: the model forecasts are too confident when in fact the observed SST frequently lies outside of the range spanned by the forecast ensemble.

An alternative, more optimistic, interpretation is to take the model estimate of spread as a measure of potential predictability by interpreting one ensemble member as truth and measuring the differences of other members from that. This then gives the potential limit of predictability in the absence of model error. Our system is far from that limit. So by working harder and reducing model error we should (hope to) be able to improve the forecasts. Of course the current model might underestimate the limits to predictability since the model does not do a good job of reproducing intraseasonal variability (Madden Julian Oscillation) which, it is thought, might play a role in limiting predictability of ENSO. However, even if the latter optimistic interpretation of the limit of predictability were correct, the reality is that we are not there. We have to work with the practical reality that for now our model is not well calibrated.

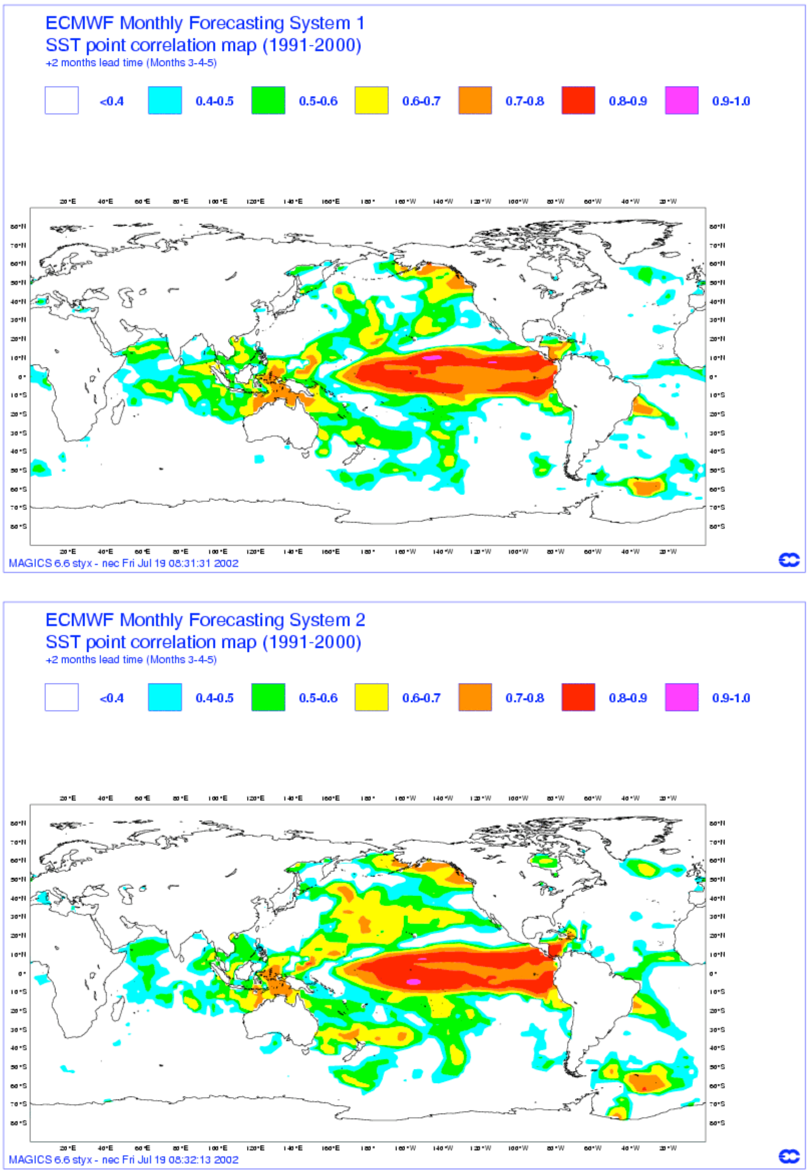


Fig 3 Plot of anomaly correlation of 6-month forecasts from S1 (top) and S2 (bottom). Red colours, mainly in the equatorial Pacific, indicate high correlation (high skill). Skill in the Atlantic is considerably lower at this time range (the latter half of a 6-month forecast).

One way of improving the forecast reliability is to sample model error in the pdf and one way to do that is to develop a multi-model approach. This has already been done in the context of DEMETER in a non-real-time mode. At ECMWF we are in the process of developing an operational multi-model forecast system. This currently consists of forecasts from the Met Office as well as ECMWF. These two models have the same calibration period (1987-2001) and similar wind perturbations. Despite this their ensemble spread is larger than that in the ECMWF model as they draw less strongly to the data in the ocean analysis and their coupled model is more active- perhaps too active whereas the ECMWF coupled model is not active enough. In future the real-time multi-model forecast system will include Meteo France forecasts and potentially others also.

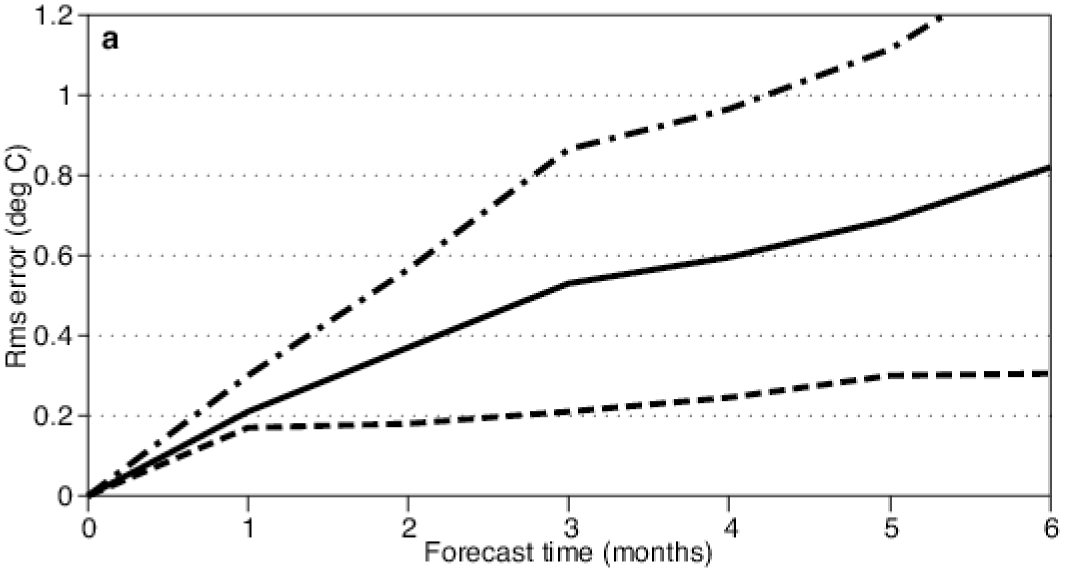
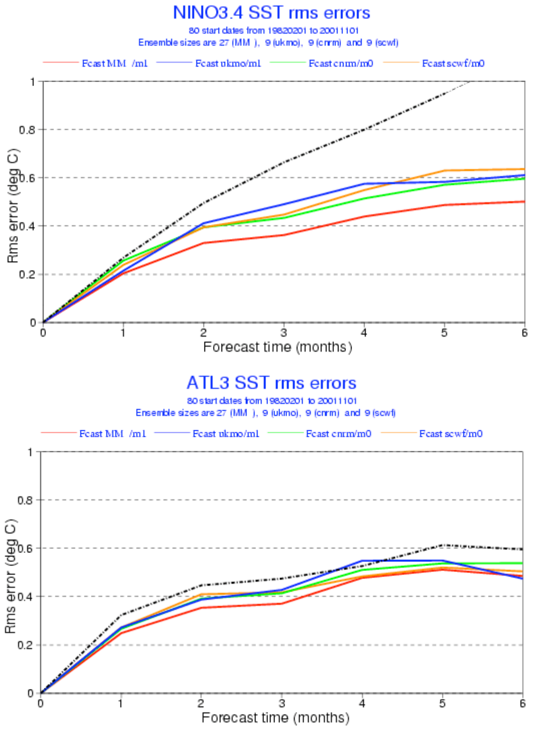


Fig 4 The growth of error in the forecasts of Nino3 (solid) together with the ensemble spread (dashed). The fact that the latter is less than the former indicates that the model is too confident. The two curves should be close in a well-balanced system. The dot-dashed curve indicates the skill of persistence and shows that the model easily beats persistence at all leadtimes.

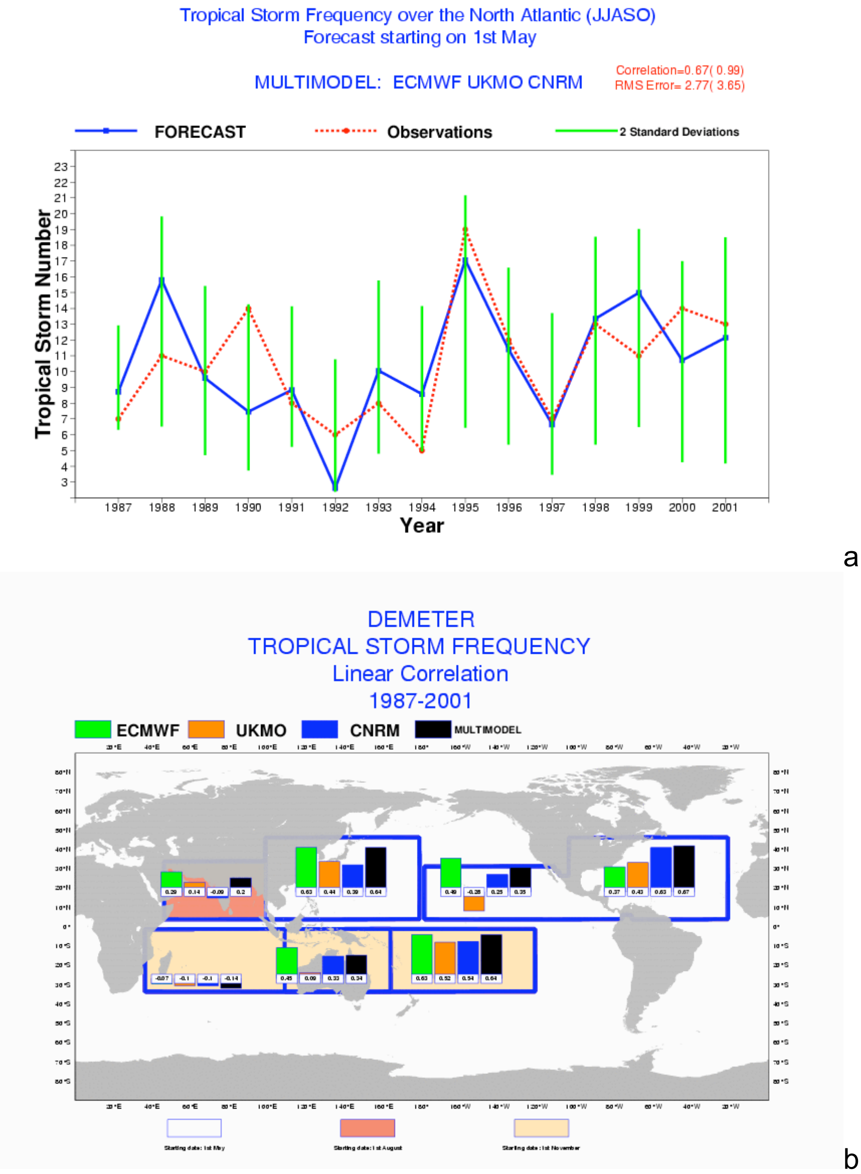


a)

b)

Fig 5 Plot of the rms error averaged over 20 years of forecasts from 3 models (ECMWF, MET Office and Meteo France) as a function of lead time. The red indicates the multi-model and the black dashed line indicates persistence. a) Nino3.4 in the central east Pacific where all forecasts significantly beat persistence. b)ATL3 in the central-east Atlantic where the skill of the forecasts relative to persistence is modest. In both cases, however, the multi-model seems the best.

In order to get some feel for the potential improvement in forecast skill as a result of the multi-model approach, we plot in fig 5 the rms error for the Nino3.4 region for the three models that will participate in real-time multi-model predictions at ECMWF. The models are actually from DEMETER and as such are slightly earlier versions than will be used in real-time operational applications but they should give a pretty good assessment of what to expect. The error growth is shown for two regions, one in the Pacific and one in the Atlantic. Both are equatorial. Consistent with fig 3, the skill in the Atlantic lower than in the Pacific: actually the error growth is similar but the size of the interannual signal is smaller in the Atlantic, so the error is more serious. This can also be seen in the anomaly correlation (not shown) which drops more rapidly in the Atlantic than the Pacific.



a)

b)

Fig 6 a) Plot of the interannual frequency of hurricanes observed in the Atlantic (dotted). Also shown is the number predicted by the ECMWF, Met Office and Meteo France multi-model combination. (Same combination as in previous figure.) b) Regional assessment of the model skill in predicting tropical cyclones.

In both S1 and S2 we make predictions of the number of tropical storms expected in a tropical storm season. In S1 there was quite good skill for hurricane prediction in the Atlantic. This skill decreased in S2 in the Atlantic though not in other regions. However we were able to recover skill through the multimodel forecasts. Fig 6 shows the skill based on the three models that will be part of the real-time multi-model forecast system. Figure 6 shows the forecast skill for various tropical cyclone regions. No one model is universally the best but the multi-model is better than taking just one model in most regions.

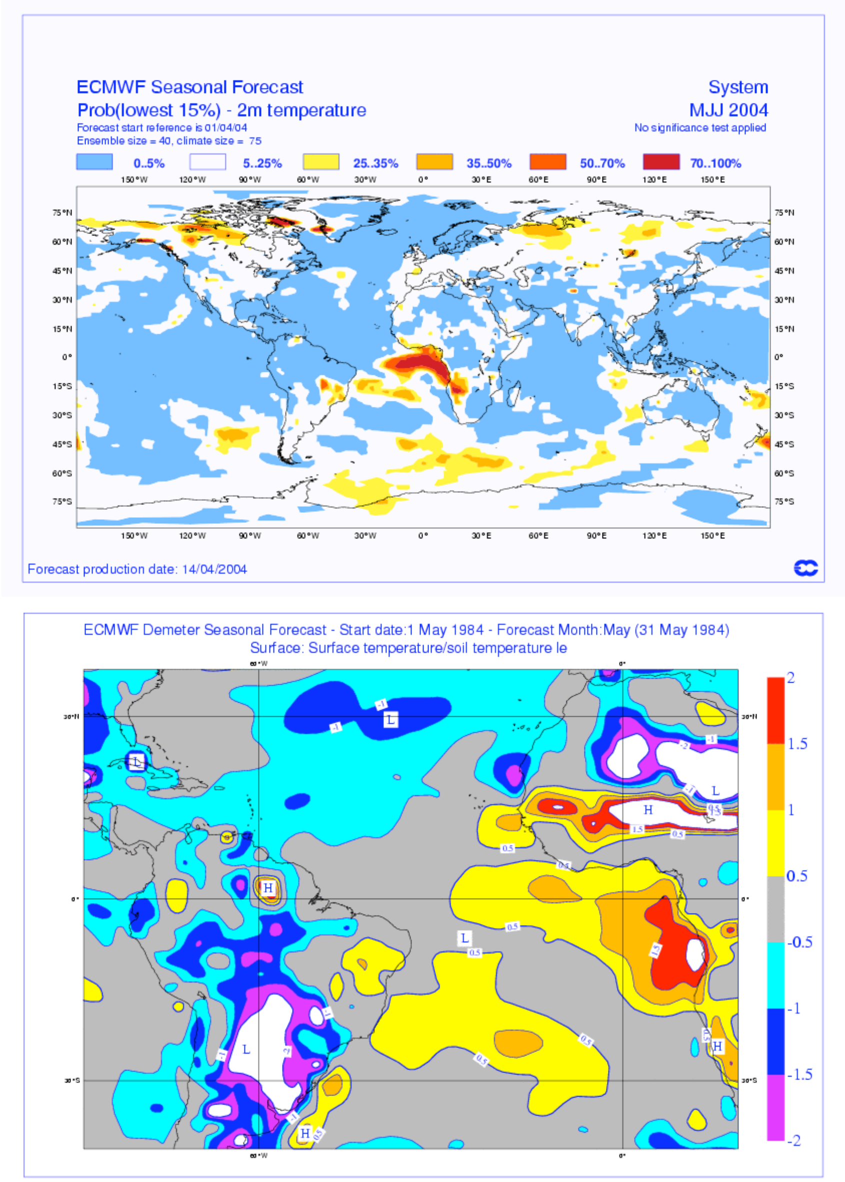


Fig 7 a) Plot of the probability of the predicted SST being in the lowest 15% of the climate distribution. Reds mean high probability. b) Observed surface temperature anomalies in 1984 (relative to the 1958-2001 mean). The high values along the African coast and eastern equatorial region are associated with a reduction in upwelling.

In S1 we made various products available on the web, such as the displacement of the ensemble mean, and the probability of forecasts being above or below normal. These products are also available in S2 but several more products are included, such as terciles or more extreme indices such as the probability of being in the top or bottom 15% of the distribution. As an example, we show in fig 7a the forecast for T2m being in the lowest 15% of the climate distribution. The figure is interesting since it indicates little signal anywhere except in the tropical east Atlantic where the signal is very strong.

Some specific examples.

The tropical Atlantic in Spring Summer of 1984.

The spring-summer of 1984 was quite unusual in the tropical Atlantic. SSTs were several degrees warmer than normal especially along the coast of Africa where upwelling usually takes places. In 1984 this upwelling was suppressed, much as it is suppressed during El Nino conditions in the Pacific. The ITCZ was displaced southward, but, according to Philander (1986), the convection over Amazonia was not displaced eastwards as happens in the Pacific during El Nino. The anomalies in the Atlantic were the largest in the previous 30 years and in the subsequent 20 years. Fig 7b shows the anomalous SST (sea surface temperature and soil temperature) for May 1984. This figure should be contrasted with panel a) which shows the predicted probability that SST will be below average in the summer of 2004. The patterns are amazingly similar, linked through the upwelling zones. But whereas 1984 was anomalously warm (weak upwelling), 2004 is predicted to be cold, presumably associated with anomalously strong upwelling.

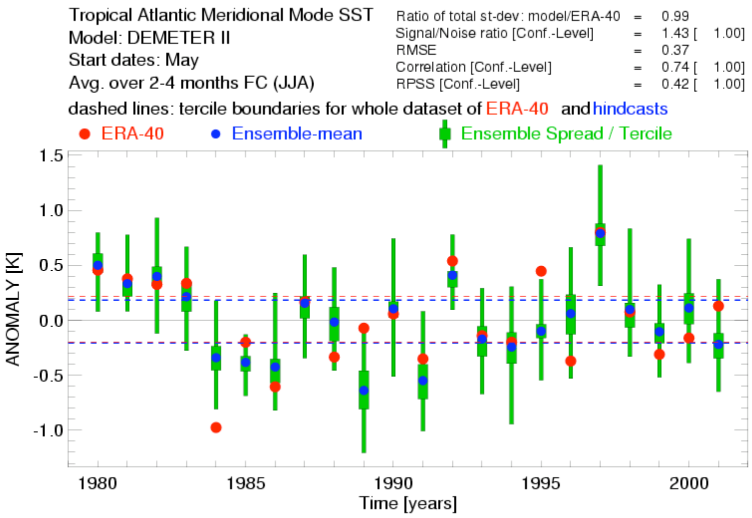


Fig 8 Red dots indicate the amplitude of the Atlantic meridional mode, defined as the difference in SST between box 5-25N, 55-15W and box 20S-Eq, 30W-10E. In 1984 this was at its most negative. The blue dots indicate the multi-model mean and the vertical bars a measure of the spread. The forecasts for 1984 were not especially good, though there is some overall skill in general as measured by the anomaly correlation coefficient of 0.74. From DEMETER website www.ecmwf.int.

Figure 8 shows the Atlantic meridional mode index for the period 1980 to 2001. The year 1984 clearly stands out as anomalous. How well was this predicted? Also shown on this figure are the multi-model results for predictions for June, July, August. The start date of these forecasts was 1st May. The green dots indicate the ensemble mean value and the whiskers give a measure of the ensemble width. The observations lie outside of the forecast range for 1984. On average, there is some skill over the years but in the particular case of 1984, it is limited. (See also the paper by Palmer, this issue, who discusses the prediction of 'extreme' events). The forecasts shown in fig 8 are not exactly from the operational system but the coupled models used by UKMO, Meteo France and ECMWF in DEMETER are very similar to those used for real-time seasonal forecasts. The multi-model predictions of ATL3 2-4 months ahead also appear to be skillful: the correlation with observed ATL3 index is 0.72. The predictions of rainfall over west Africa for 1984 were not good, however, and the overall skill in this region is low (correlation 0.28). Because the 1984 event was such a big event in the tropical Atlantic we intend to look more closely at this period. It has been suggested that it was linked to the large El Nino event in the Pacific in the preceding year (Delecluse et al 1994). However, the large El Nino of 1997/8 was not followed by a big Atlantic response the following year.

The floods of 2000

October, November, December 2000 and January 2001 saw very wet weather over western Europe. In the UK in October there was extensive flooding. Blackburn and Hoskins (private communication) have argued that this wet weather was linked to the Scandinavian pattern (not the North Atlantic Oscillation) and that preceding events in the tropical Atlantic may have been responsible. Were these wet conditions predicted months in advance? Given that this was the wettest Autumn on record one might have hoped for some signal in the forecast. In fact there was none: the forecast for SON from August showed normal conditions or rather no detectable signal in the ensemble mean. It was not only the ECMWF model which failed.

Subsequent simulations using observed SSTs and soil moisture failed to simulate the wet conditions. It is a debatable issue how meaningful it is to force the ocean with observed SSTs. The PROVOST integrations indicate that this may be acceptable in the tropics but at mid latitudes it might not be a good strategy (Palmer et al 2000). An increase in model resolution even as high as T255 did not improve the simulations, though there was sensitivity to convection in the west Pacific, possibly related to MJO activity. For further details, see Massacand 2003. It is therefore unknown if the floods were predictable. What one can say is that they were not predicted. Whether improvements in model physics, ocean data assimilation and analysis procedures would increase the skill is unknown.

The heat wave of 2003

As a final example we will consider the very warm and dry conditions of summer 2003 over western Europe. Schar et al 2004 have indicated how unusual this summer was. Fig 9 shows the observed anomalous 2m temperature for June, July, August. Fig 10a shows the probability of the two meter temperature for JJA being in the upper tercile from forecasts started in 1 May 2004. These show warm conditions over the Mediterranean and some enhanced probability of warm conditions over Europe but nothing major over land. Forecasts from April and June show even less signal over continental Europe.

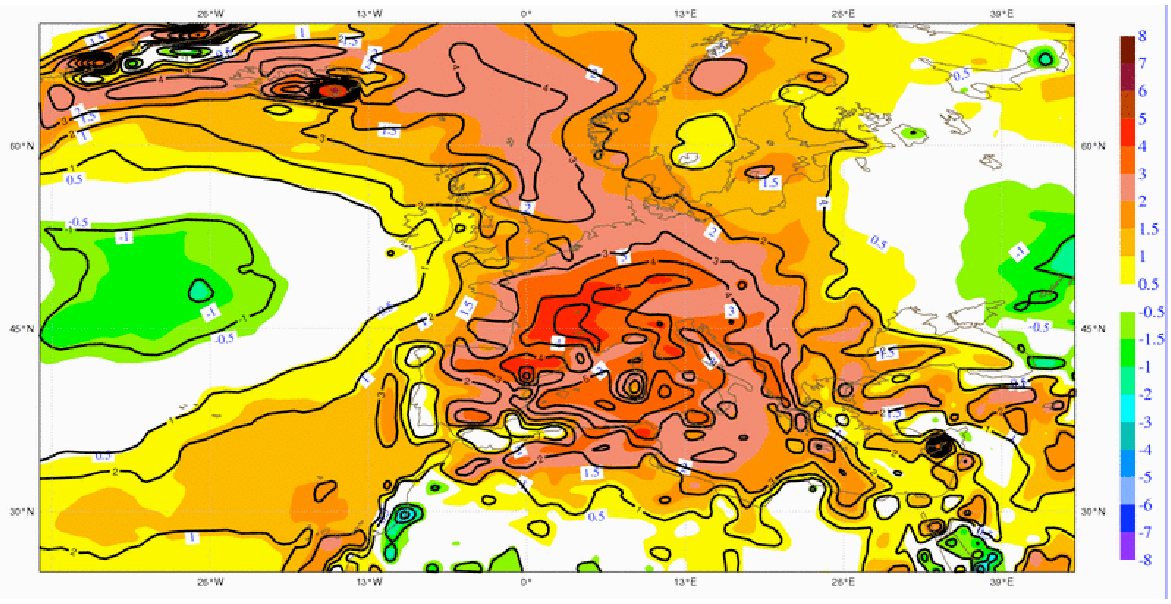


Fig 9 Observed 2m temperature anomaly for June, July and August 2003 relative to ERA-40 climatology

A question that arises once again is whether the failure was because of deficiencies in the forecast system or because the event was not predictable. Simulations using the observed SSTs were not able to reproduce this event over Europe. There were large SST anomalies in the north Atlantic in the summer of 2003 but the impression was more that they resulted from the anomalous flow rather than that they caused it. The very warm conditions over land in the UK and especially France can only really occur if the land is very dry. Analysis of soil moisture in the region 40N to 50N and from 0 to 15E show that there was a moisture deficit in July and August but that this deficit was evident from as early as March. Sensitivity studies were carried out changing the soil moisture content in the European sector. It was not possible to argue that the soil moisture anomalies created the unusual flow conditions that gave rise to the drought but it does appear that they were able to influence it. The summer of 1976 which was also very dry showed a long lasting soil moisture deficit.

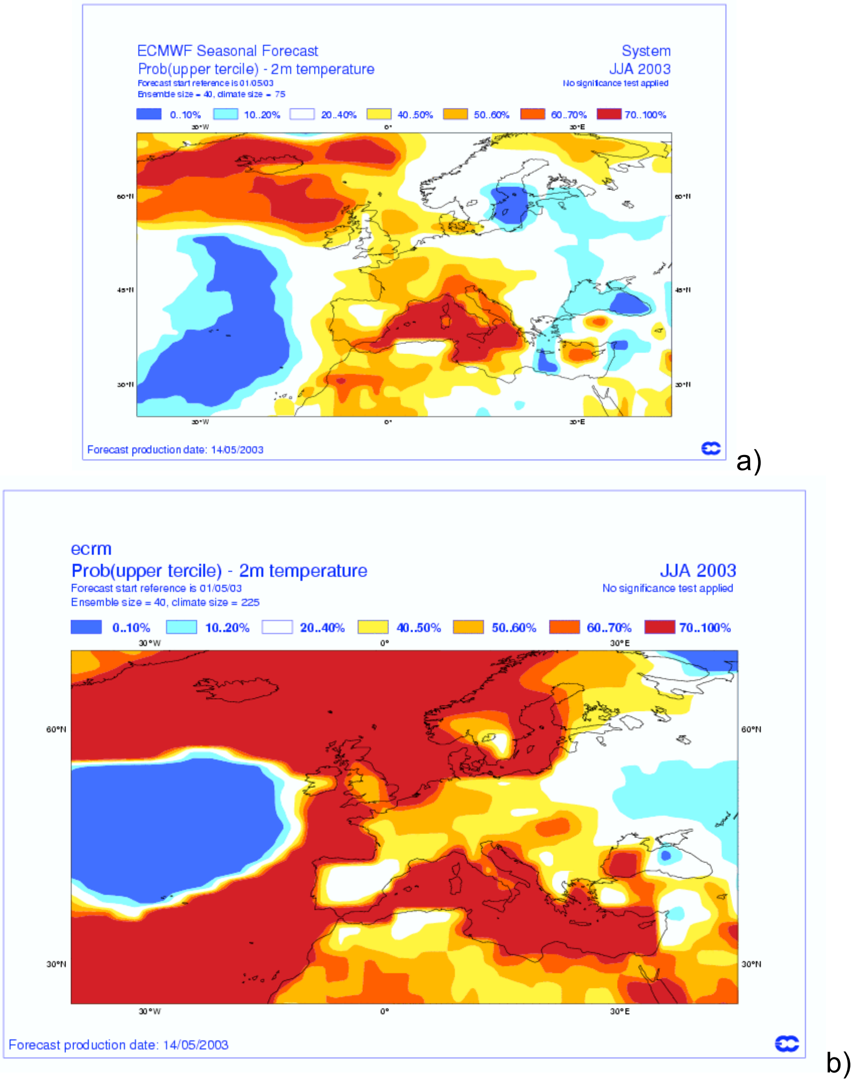


Fig 10 a) Plot of the probability of the T2M being in the upper tercile for JJA for forecasts begun 1 May 2004. b) As for a) but from simulations using observed SSTs

To what extent the poor seasonal predictions for the European hot summer are due to model errors or are related with the 'true' low predictability level of this event is difficult to establish. Results from an ensemble of simulations with atmospheric model forced by observed SST conditions (see fig 10) indicate that even with prescribed oceanic conditions the event was difficult to predict.

Since in the near future ECMWF seasonal predictions will be a multi-model ensemble-based system it is interesting to look at the performance of the other models. The probability pattern for the upper tercile of 2 m temperature from the UKMO ensemble of forecasts started in May 2003 forecasting the period June-July-August showed a warm signal over France, broadly comparable with the one in fig 10a while the warm anomalies over the Mediterranean are somehow under-estimated. UKMO predictions initiated in June did not show the warm signal. Similar inconsistency between predictions initiated in May and those initiated in June was also found in the Meteo-France forecasts (Andre et al. 2004).

Considering that the spring and summer of 2003 were rather dry, it is possible that the lack of soil moisture contributed to enhance the local heating. A study (Ferranti and Viterbo 2004) has been carried out to establish the soil water conditions and to evaluate the extent of the surface feedback and its contribution to the predictability. A brief description of the results obtained from this study is given below.

The typical seasonal and inter-annual fluctuations of soil water averaged over Central Europe were estimated by using the ERA-40 data. The operational soil water analysis for the period from March to September 2003 was extremely dry in comparison with ERA-40 record. August 2003 was drier than any of the months in ERA-40. Despite the dearth of soil water observations, evidence that the ERA-40 annual cycle of soil moisture is too small was found. In fact the soil water analysis increments show a systematic wetting in summer. This reduces the annual cycle and makes the soil overly moist in summer.

Since large uncertainties in the analysed soil moisture values can have an impact on the seasonal forecast particularly on the predictions initiated in spring, numerical experimentation has been used to document the model sensitivity to the soil moisture initial conditions. Several 9-member ensembles of 4-month atmospheric integrations, forced with observed sea surface temperature (SST), were performed. Each ensemble had initial soil moisture between the surface and a depth of one metre set to prescribed uniform values in a large European area. The prescribed soil moisture values ranged from very dry values, effectively shutting-off model evaporation (soil moisture index, SMI=0), to very wet values (SMI=100).

By examining the ensemble mean 2m temperature differences between simulations with soil wetness initial conditions prescribed to a value of SMI=25 and with those set to a value of SMI=75, one finds that the impact of drier soil initial conditions is mainly local and highly significant even after 2 months. The response remains significant in the temperature at 850 hPa and, although over a smaller area, in the geopotential height at 500 hpa.

Due to lack of soil water measurements, it has not been possible to compare the various values of soil wetness used as initial conditions with those that were actually present in June 2003. Therefore has been difficult to quantify the real contribution of the surface conditions to the high temperature anomalies observed. Nevertheless, extensive experimentation has shown that the atmospheric response to large soil moisture initial perturbations extends up to month 2 and it is non-linear: the response is larger for drier regimes. Extending the perturbations to the soil below the root zone (to a depth of 2.89 m) increases the atmospheric response and its memory up to 3 months if the anomalies are large.

In conclusion it can be said that the anomalous hot European Summer of 2003 is difficult to predict beyond one month. In fact at this time the instrumental forcing that sustained the large-scale anti-cyclonic circulation for longer than a season is not well understood. However the dry soil conditions has contributed in amplifying the local temperature anomalies. The large uncertainties in the soil moisture analysis and the atmospheric response to soil water conditions documented in this study suggest: i) the need to improve soil moisture assimilation; ii) the use of perturbations in the initial conditions of soil water commensurate with soil moisture uncertainties in the generation of the seasonal forecast ensembles.

Monthly forecasting

A recent activity at ECMWF is to make forecasts out to one month using the coupled model. The ocean component is the same as for the seasonal system but the atmospheric cycle and resolution are different. The resolution is higher (T159 compared to T95). Whereas the atmospheric model cycle is frozen during the lifetime of a seasonal forecast system, in the monthly system it is the same as that used in the medium range. Forecasts are made currently every fortnight but soon they will be made weekly and perhaps even bi-weekly. An extensive evaluation of the monthly forecast system is available online in Vitart 2003. Here we include just one example, showing the skill of predicting that the T2m is in the upper tercile. The region is all land points north of 30N. The extent to which the curve is above the diagonal gives a measure of usefulness of the forecast. This can be quantified using the cost-loss diagram which gives a sense of the potential value of the forecasts. For details see Richardson 2000.

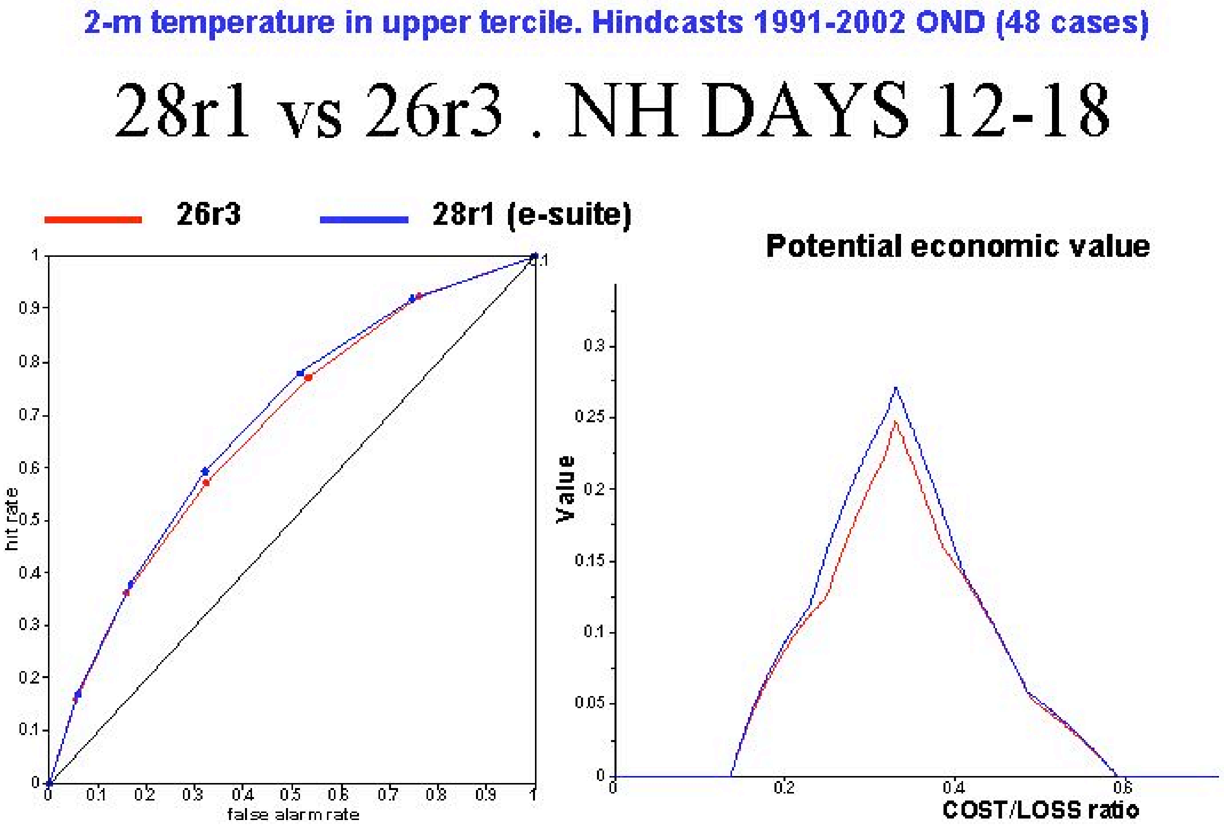


Fig 11. Plot of the hit-rate versus false-alarm-rate for forecasts range days 12-18. The more the curve lies above the diagonal the better. Also shown is a Cost Loss diagram giving the potential value of the monthly forecasts. For cost-loss values too high or too low, the forecasts have no value but for a range in the middle, they are useful.

Further analysis of the relative skill of the forecasts over Europe and over North America indicates that the latter are generally more skillful. The heat wave over Europe referred to in the previous section is discussed in Vitart 2004. In this case some ensemble members had quite strong warming more than three weeks ahead, indicating some probability of high temperatures on the medium to monthly time-range.

Summary, conclusion and future directions.

ECMWF has run a seasonal forecast system for several years now. This is based on global coupled atmosphere ocean models which are fully interactive. They even include a wave model though this is not yet fully integrated into the coupling process. The models have considerable skill in the Pacific related to ENSO but less in the Atlantic. The teleconnections to countries bordering the Atlantic is also reduced at middle latitudes. The tropical Atlantic is a region where there are difficulties in representing the ocean well (Vidard et al 2004).

ECMWF also runs a monthly forecast system based on coupled atmosphere ocean models, similar to those used for seasonal forecasting, but differing in the atmospheric resolution and version.

Work is ongoing to evaluate the ocean observing array, not just for the Atlantic but other regions as well. In time we expect to extract more information from the observations than is currently done. This is likely to depend on the assimilation method as well as improving the model.

Model error has been shown to be a major limitatrion to improved forecasts. This can be handled to some degree by using multi-models and work is well in hand to produce forecasts from the three fully coupled GCMs (ECMWF, Meteo France and UKMO), all run at ECMWF. In time more models are likely to participate. This has been shown to generally improve skill and to overcome the tendency for individual models to be too confident in their predictions.

Strategies for combining the models in an optimum way have yet to be developed.

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Climate Prediction at CPC

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Review of seasonal forecast procedures

In conjunction with white paper # 7 (Van den Dool et al 2004) we here review prediction methods and tools used in Canada and the US for their seasonal forecasts with emphasis on the question: which of these tools have anything to do with the Atlantic explicitly and /or the Atlantic as a cause of climate variability?. The methods used, in no particular order, are a) Canonical Correlation Analysis (CCA) (Barnston 1994; Shabbar and Barnston 1996; Johansson et al 1998), b) Optimal Climate Normals (OCN) (Huang et al 1996; Zhang et al 1996), c) 2 tier or 1 tier Coupled Model (Kanamitsu et al 2002; Saha et al 2003 for US; Derome et al 2001 for the Canadian models). These are the main tools always run and used in some fashion for US and Canadian seasonal forecasts. In the US there are a handful of other tools of opportunity (ENSO composites), or warm season tools based on soil moisture (Van den Dool 2003a). Tier2 coupled models from other centers are also increasingly available.

Of the primary tools, CCA takes global gridded SST during the most recent four non-overlapping seasons into account as predictor. So the Atlantic is included, or at least not excluded. But the general assumption is that most CCA skill over NA is from the Pacific. The need to analyze this further for real time forecasts is not always apparent. The CCA 'modes' reflecting the Pacific influence may also have some projections in the Atlantic, spurious or otherwise. To address this problem we present in section 4 some CCA modes where the Atlantic is the only predictor. The model version described in Kanamitsu et al(2002) had atmosphere-ocean interaction only in the tropical Pacific. The new coupled model in the US (CFS; Saha et al 2003) has a global ocean and will be implemented in 2004 - some early results (discussed in section 7) indicate low (moderate) prediction skill in North (tropical) Atlantic SST but at least moderate predictability for both mid latitudes and tropics.

One of the main sources of skill in Canadian and US seasonal forecasts is (or can be) harvested by a very simple tool called OCN, Optimal Climate Normals (Huang et al 1996; Zhang et al 1996). This is basically persistence of the anomaly of the last K years for the same named season. This sort of tool works because the climate is not stationary and changes on a time scale in excess of K years. We found K=10 to be optimal for US-Temperature. The trends being that important for forecasts for next season out to 1-2 years, the question is: "what is the physical origin of these predictable trends"?. Many have pointed to the NAO, and its trends in the last 50 years. This certainly appears to be contributing along Eastern NA, especially in winter. It is also clear that the OCN defined trends are related to similar trends in global SST, not only in the Atlantic, but also in the Pacific (Van den Dool 2003b). Some trends turn around (like the AMO) so if OCN was based on just AMO its 'skill' would be negative at a certain phase of the 'cycle' (no periodicity implied). However, the 5-year running mean skill of OCN for temperature has never been negative since 1960, so, indeed, there are apparently several components to trends over land. That a 10 year average is optimal is a succinct statement about the power spectrum of all low frequencies relevant to NA.

A-posteriori verification for the period JFM1995-FMA2002 gives the following skill of CPC seasonal temperature forecasts:

	SS1	SS2	Coverage OFF
	22.7	9.4	41.4% (Lead 0.5 thru 12.5 months
CCA	25.1	6.4	25.5 “
OCN	22.2	8.3	37.4 “
CMF	7.6	2.5	32.7 (Lead 0.5 thru 3.5 months)

The measure used is Heidke skill score on a scale from -50 to 100. SS1 is for the areas where we make a probability forecast that differs from the climatological probabilities (1/3rd, 1/3rd, 1/3rd) for the three classes used, the so-called nonCL forecasts which cover typically 41% of the maps for the US. SS2 is for the entire map (SS2=SS1*coverage). See Van den Dool et al(1999) for details of definitions etc. In the areas a-priori identified as skillful, the real time forecasts have indeed some skill, higher than nation averaged. The official (OFF) forecast has more skill than the tools, and also higher coverage. Among the tools OCN appears to contribute the most over 1995-2002, emphasizing the role of trends in making seasonal predictions.
Since 1998 CPC/NOAA is also engaged in seasonal prediction of the total number of hurricanes, see discussion in section 6 of white paper # 7, see Van den Dool et al (2004).

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Long Range Forecasting activities at the Met Office

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The Met Office has been active in long range forecasting for many years, with a particular interest in the Atlantic sector: the longest series of seasonal rainfall forecasts that we still issue issued are those for the Sahel (since 1986) and north east Brazil (since 1987). Originally statistical methods (principally linear regression and discriminant analysis) were used to make the long-range forecasts, by relating precursor SST anomaly patterns to seasonal regional climate variations. From the outset these forecasts incorporated probability information about several forecast categories. The continued evolution of dynamical methods, based on general circulation models, led to the introduction of ensemble forecast systems and a wider range of LRF products. This article provides an overview of recent and current LRF activities, emphasising the seasonal aspects. Forecast products and further information can be found at http://www.metoffice.com/research/seasonal and http://www.metoffice.com/monoutlook .

GCM ensemble forecast systems and products

The Met Office global seasonal forecasting system (known as GloSea) is based on a coupled GCM that is a variation of the Hadley Centre HadCM3 climate model. The GloSea CGCM has basically the same atmospheric component (HadAM3) as HadCM3, but the ocean component was enhanced to have higher horizontal (1/3 degree meridional grid near the equator) and vertical (40 levels) resolution, and a surface tiling scheme was included among other modifications. With the aim of an operational multi-model, the GloSea system infrastructure was designed in parallel with ECMWF system2, and the CGCM is run on the ECMWF computing facility. Ocean initial conditions in the GloSea system are produced at the Met Office and transferred as required to ECMWF. A 5-ensemble of ocean analyses is generated by using sampled perturbations to the surface wind stress. (Recently this component has been modified by reducing the perturbations and tightening constraints to sub-surface temperature observations, in order to reduce the analysis ensemble spread which was judged to be too large and which influenced the ensemble spread in the first few months of the forecasts.)

A 40-member forecast ensemble is run in the middle of each month, with a start date of the first day of the month, and a range of six months. Precipitation and surface temperature data from the ensemble are calibrated by calculating anomalies relative to the model forecast climatology for the same start time-of-year and forecast range, based on a 15-year 15-member hindcast set. Two- and three- category 3-month-average global gridded forecast probability products are derived from the calibrated ensemble for the Met Office forecast website. The hindcast set is also used to provide skill information about each of the products. With regard to the tropical Pacific, forecast plumes (trajectories for each of the ensemble members) are produced for the standard Nino3, Nino3.4, Nino4 regions. Multi-model products are still under development and not yet openly available, but the intention is to introduce these in the near future.

Using the GloSea system, 9-member hindcasts over a 43 year period were produced quarterly as part of the EC DEMETER project, along with other European partners. Extensive information about the performance of the DEMETER models, individually and in multi-model form, is available on http://www.ecmwf.int/research/demeter . An overview can be found in Palmer et al. (2004).

Comparison of 2-tier and coupled ocean-atmosphere systems

Prior to implementation of the coupled GCM system in 2003, a 2-tier system with essentially the same atmospheric model (HadAM3) with statistically predicted SST was the main dynamical LRF model. As extensive hindcasts with the 2-tier system were also produced in DEMETER, we have been able to compare the performance of the coupled and uncoupled systems in detail (Graham et al., 2004). The coupled system has the advantage of ocean-atmosphere interactions, but the disadvantage of larger drifts and biases, particularly in ocean regions. Overall the forecast performance of the coupled system is better, largely as a result of improved representation of ENSO events and their teleconnections.

Notable improvements in the tropical Atlantic and Indian ocean sectors are associated with lagged ENSO effects. In the equatorial Atlantic coupled model SST forecast skill is highest in NDJ and FMA, when correlation with observations are greater than 0.4 over most of the area with patches greater than 0.6 . However, in MJJ correlations are near zero in the equatorial Atlantic. In the north tropical Atlantic, predictability is best in NDJ and MJJ. In the extratropical North Atlantic CGCM performance is best in the North-East sector, where in NDJ we find correlations greater than 0.6 in the central north Atlantic, in a region historically linked with European climate variability in empirical studies. Relative to the 2-tier system, the CGCM has substantially improved reliability for spring season 2m temperatures over Europe. Case studies suggest that this improvement occurs because the CGCM can evolve SST anomalies realistically in some situations, such as 1989 when the NAO was strongly positive (Graham et al. 2004), but further investigation is needed before drawing firm conclusions.

For specific tropical Atlantic region rainy seasons, the CGCM has significant skill for the NE Brazil and Guinea areas at both 1-month and 2-month leads, with predictions for the latter region showing substantial benefits over the 2-tier system. However, scores for the Sahel region at 1-month and 2-month leads appear close to the no-skill levels with both systems. Somewhat better skill for the Sahel appears available at 3-month lead with the GloSea model. For these regions, for which specific statistically-based forecasts have been issued since the 1980s, dynamical forecast information is combined with the statistical predictions to improve the forecast quality. (See the forecast website for details.)

The global-mean annual-mean temperature forecast

Led by Chris Folland, in recent years the Met Office Climate Analysis group has issued a statistical forecast in December of global mean temperature for the year ahead, using predictors such as trends and foreseen atmospheric composition and ENSO state. Trials of dynamical year-ahead forecasts were made in 2003 with the GloSea ensemble system. Over a test period of 15 years the performance of the dynamical model was closely comparable to that of the statistical approach, and in December 2003 a real-time year-ahead forecast was produced.

The European summer forecast

Following evidence for a connection between Jan-Feb north Atlantic SST anomalies and European summer seasonal climate, gridded tercile probability forecasts of July-Aug temperatures in Europe have been issued since 1999, generated using simple statistical methods (see the forecast website: notably, the statistical forecast for summer 2003 strongly favoured the upper tercile). However, the mechanism for this connection is not yet well understood, and merits further investigation using dynamical systems.

The ENACT project: ocean data and analyses

The EC ENACT project (http://www.lodyc/jussieu.fr/ENACT/) is now well underway, with the aim of producing global ocean analyses from various ocean models and data assimilation systems, in the context of improving seasonal forecasts through improvements in ocean initial conditions. The ocean analyses have two main streams: 1987 to 2001 (when satellite altimetry data are available), and 1962 to 2001. An important preliminary outcome of this project is that several relevant datasets have been prepared with regard to ocean in situ data, altimeter-based sea level data, and surface flux data adapted from ERA40. The Met Office has been responsible for preparing the in situ dataset, covering the period 1962 to 2001. Temperature and salinity observations from several sources (including WOD01) have been collected, uniformly quality controlled, and written in a standard NetCDF format. It is expected that this dataset will be made generally available for research purposes.

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A Statistical/Dynamical Treatment of Tropical Atlantic SSTs

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Previous work by the authors (Penland and Matrosova 1998) has shown that skillful statistical forecasts can be made of north tropical Atlantic (NTA) and Caribbean (CAR) sea surface temperatures. Predictors consist of SSTs in the global tropical strip. The authors also showed that this forecast skill was due to the remote influence of the Pacific since the skill disappeared when tropical Atlantic SSTs alone were used as predictors. In this article, we review the prediction method and its skill of forecasting tropical Atlantic SSTs using a data set longer than that used in our previous study.

One interesting aspect of Penland and Matrosova (1998) was an indication by the empirical-dynamical model that the controversial tropical Atlantic dipole might actually have some physical basis, but that the northern branch is disrupted by the influences of the tropical Pacific. We show here that this idea is correct but incomplete. Using a novel method for filtering out the ENSO signal from tropical SSTs, we find a global tropical trend pattern similar to that found by Livezey and Smith (1999). The evolution of this pattern, which has large loadings in the south tropical Atlantic (STA), is extremely smooth, allowing the data to be easily detrended. When this is done, the detrended, de-ENSOed NTA and STA sea surface temperature anomalies are significantly anticorrelated in all seasons

Tropical Atlantic SST Forecasts

Using the methods discussed in Penland and Matrosova (1998; PM98 hereafter), skillful statistical forecasts of north tropical Atlantic (NTA) and Caribbean (CAR) sea surface temperatures anomalies (SSTAs) are performed (Fig. 1). Briefly, the prediction method consists of Linear Inverse Modeling (LIM), which is an extension of Principal Oscillation Pattern analysis (Von Storch et al. 1988; Penland 1989). A prediction at lead time *t* is made by applying a statistically-estimated Green function **G**(*t*) to an observed initial condition consisting of SSTA in the circumglobal tropical belt. Although the parameters of the prediction model are estimated statistically, the dynamical assumption of stable linearity inherent in the method requires a fixed-point attractor in phase space. That is, we assume that SSTA can in large part be represented as a stable linear process maintained by stochastic forcing:

$$d\mathbf{x}/dt = \mathbf{B}\mathbf{x} + \xi \qquad (1)$$

where x_i is the sea surface temperature anomaly at location *i*, and ξ is the contribution to the dynamics from the stochastic forcing at location *i*. In this scenario, the linear operator **B** in the dynamical equation is non-normal, allowing transient growth of SST variance (e.g., Farrell 1988). The technique, therefore, cannot be considered a purely statistical prediction method (Penland 1989; Penland and Sardeshmukh 1995). Forecasts of NTA and STA SST anomalies are available on the World Wide Web at the following site: http://www.cdc.noaa.gov/forecasts/Globalsst.html.

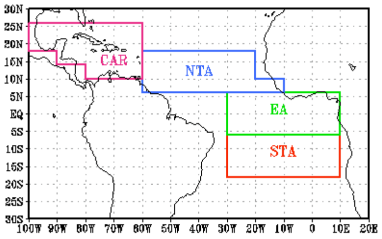


Fig. 1: Location of SSTA indices.

Only CAR and NTA indices are predicted since PM98 found that LIM forecasts of SSTA in the south tropical Atlantic (STA) and equatorial Atlantic (EA) were no more skillful than those made using a univariate AR1 process.

We have recently updated our prediction method to take advantage of additions made to the data set since we began issuing forecasts. We employ SSTA from the Comprehensive Ocean-Atmosphere Data Set (Woodruff et al. 2001) and NCEP Real-Time Surface Marine data. Data were consolidated onto a 4^{o}¥10^{o} grid and subjected to a three-month running mean. The 1950-2000 climatology was then removed from the SST data and the anomalies were projected onto 20 Empirical Orthogonal Functions (EOFs) containing about two-thirds of the variance. Assuming that the SST anomalies obey dynamics described by Eq. (1), the matrix **B**, its normal modes, and the singular vectors of the propagator **G**(□) = *exp*(**B**□) were estimated using Linear Inverse Modeling (LIM).

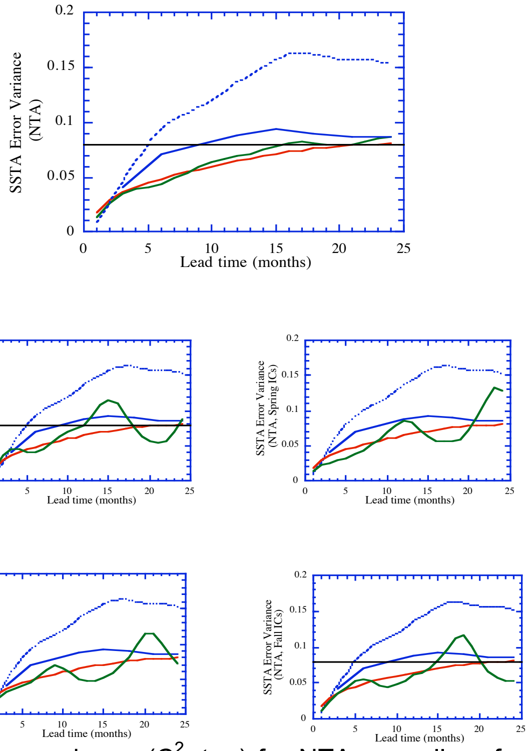


Fig. 2: Stationary forecast error variance (C^2, top) for NTA as well as forecast variance stratified by season of initial conditions (lower graphs). Blue dotted line: Persistence forecast error. Blue solid line: AR1 forecast error. Red solid line: theoretically expected forecast error. Green line: Observed LIM forecast error.

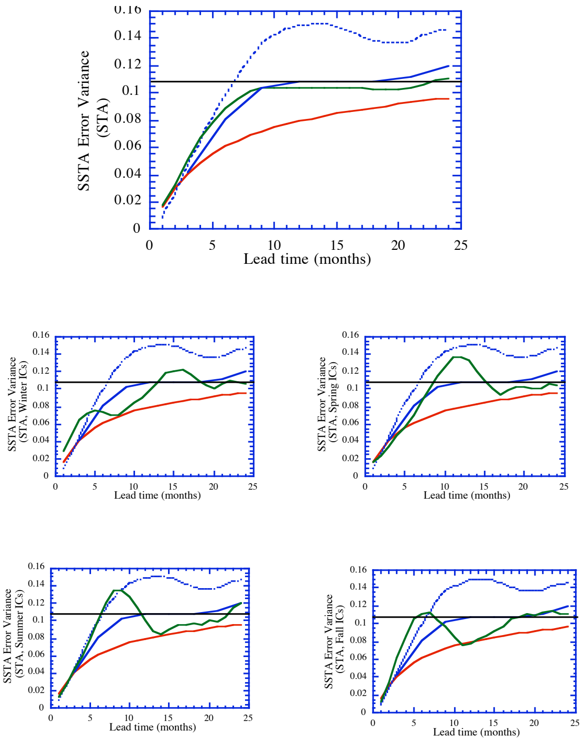


Fig. 3: As in Fig. 2, but for STA

We used a jackknifing procedure to investigate LIM's predictability of tropical Atlantic SSTA. The five-year chunk of data between 1970 and 1975 was withheld for verification purposes and the remaining data between 1950 and 2000 were used to train LIM and estimate the model parameters.

This procedure was repeated for a total of six verification chunks between 1970 and 2000, allowing estimation of average forecast error variance. The error variance was estimated for SSTA indices corresponding to each of the geographical indices shown in Fig. 1. Figs. 2 and 3 show the stationary error variance in (C^2) as a function of lead time, as well as the error variance stratified by the season of the initial conditions for NTA and STA SSTA. The systematic dependence of the error variance on the annual cycle is clear. What is *not* clear is whether or not this dependence is due to the assumption of deterministic stationarity, or rather to the nonstationary nature of a rapidly varying unpredictable component. Penland and Sardeshmukh (1995) and Penland (1996) have shown convincing evidence that the annual cycle in ENSO predictability is due to the periodic nature of stochastic forcing, but a similar conclusion is not so compelling in the Atlantic.

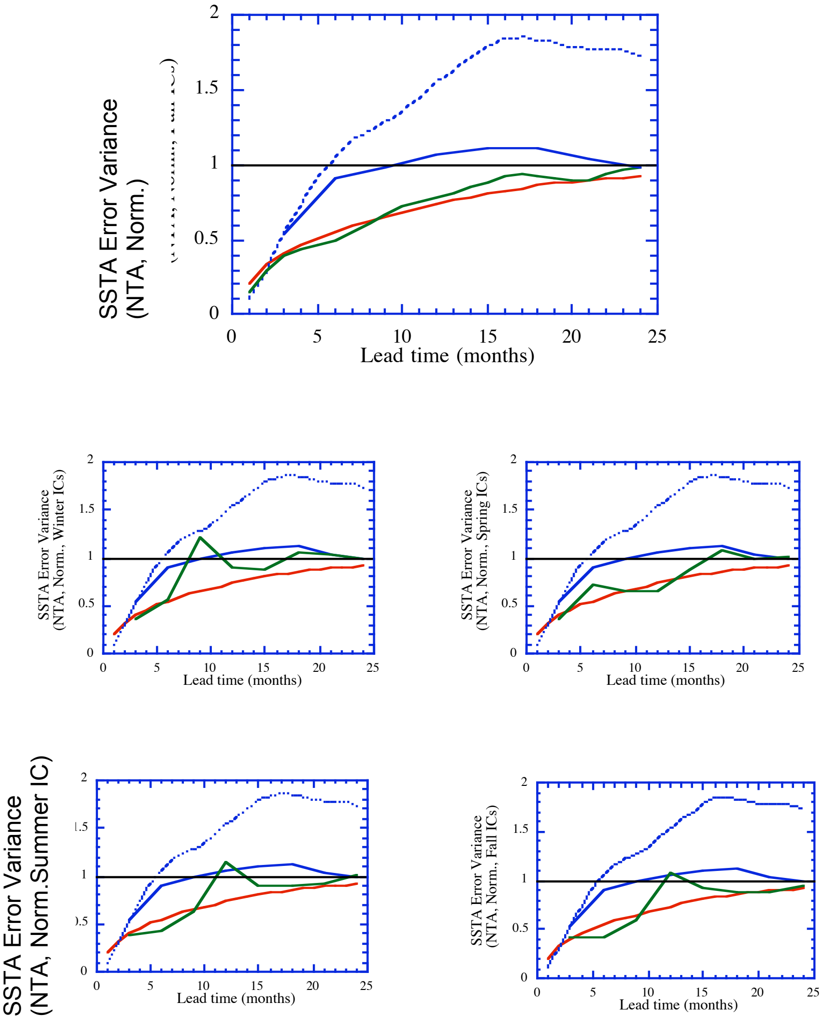


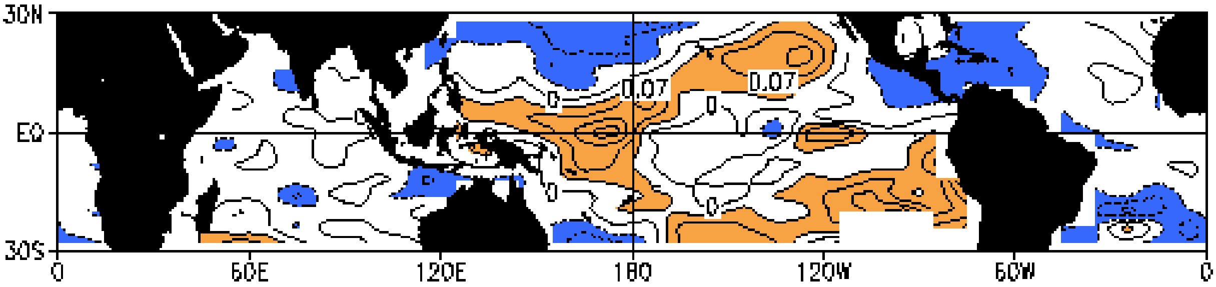
Fig. 4. As in Fig. 2, but normalized to the verification season.

For example, in Fig. 4 we see the same errors as in Fig. 2, but normalized to the variance of the verification season. While the normalized predictability does appear to depend on the annual cycle, this dependence is not systematic, leading to doubt as to its origin. Further study is needed to clarify this point. In any case, it is clear that the annually averaged NTA forecasts are skillful, while the STA forecasts are not.

Getting Rid of El Niño

Penland and Sardeshmukh (1995) found that the development of a mature El Niño pattern was due to the transient growth of SST variance. That is, when the SSTA field projects strongly onto an optimal initial structure (Fig. 5a), the nonorthogonal eigenvectors of **B** evolve at different rates and interfere in such a way that the spatial variance of the anomaly field temporarily increases to a maximum (Fig. 5b; see also Farrell 1988).

a)



b)

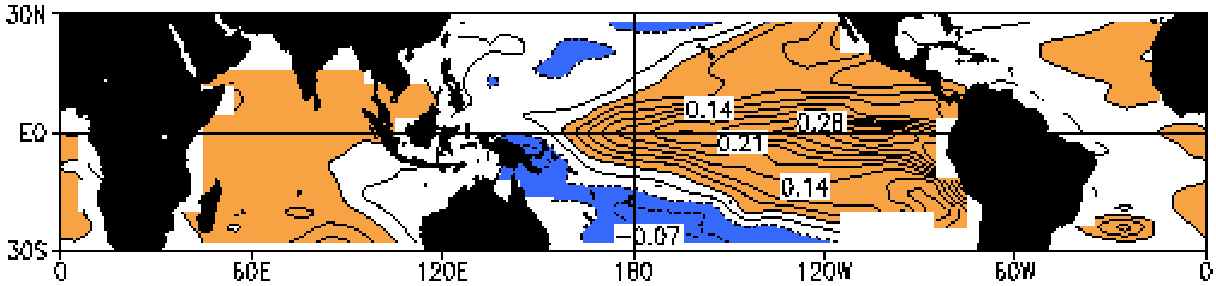


Fig. 5: a) Optimal initial pattern for growth. When the tropical SST anomaly field has a strong positive projection onto this pattern, a mature El Niño (Fig. 4b) is predicted to appear seven to nine months later. A strong negative projection implies evolution into La Niña. The field in Fig. 4a has been normalized to unity; the field variance in Fig. 4b is a factor of three to five large

The leading right and left singular vectors of the propagator at lead times τ between seven and nine months were found to be essentially indistinguishable. These singular vectors are, in fact, the optimal structure and ENSO mature pattern shown in Fig. 5. Now, it may appear that projecting onto one or the other of these patterns might be a good way to isolate the ENSO signal Unfortunately, each pattern in Fig. 5 is orthogonal to the rest of the SST anomaly field so this type of projection cannot by itself describe an evolving field.

The quandary is resolved by noting that linear combinations of three empirically derived, complex normal mode pairs dominate both patterns; the real part of each of these mode pairs is extremely similar to Fig. 5b, and the corresponding adjoints project strongly onto Fig. 5a (Fig 6). These normal mode pairs, in fact, account for most of the development of a mature El Niño or La Niña pattern and have (decay times, periods) of (16 mo, 233 mo), (15 mo, 56 mo) and (7 mo, 25 mo). Thus, the linearly predictable ENSO signal can be removed from SST anomaly data by projecting the anomaly map at any time onto the adjoints of the relevant normal modes, and then subtracting out the normal mode patterns weighted by that date's projection.

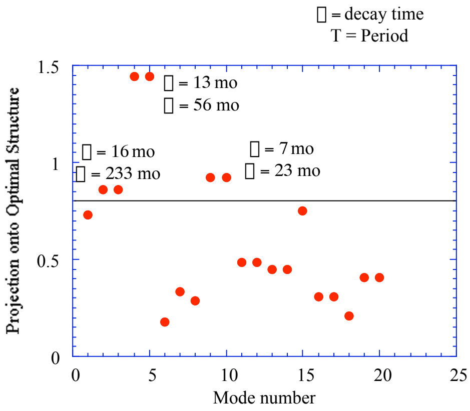


Fig. 6: Magnitude of the projection of empirically derived modal adjoints onto the optimal structure shown in Fig. 4a. Modes are numbered in order of decreasing decay time. Horizontal line is at 0.8.

We applied this procedure to the tropical SST data prepared as described above, thus separating the data into a set, which we call the linear ENSO signal, and another set, which we here call the background-pass filtered set. Spectra of the filtered and unfiltered SST data were evaluated at various locations throughout the tropics. Fig. 7 shows the time series of SST anomaly in the Niño 3.4 region (6^oN – 6^oS, 170^oW – 120^oW) before and after applying the background-pass filter.

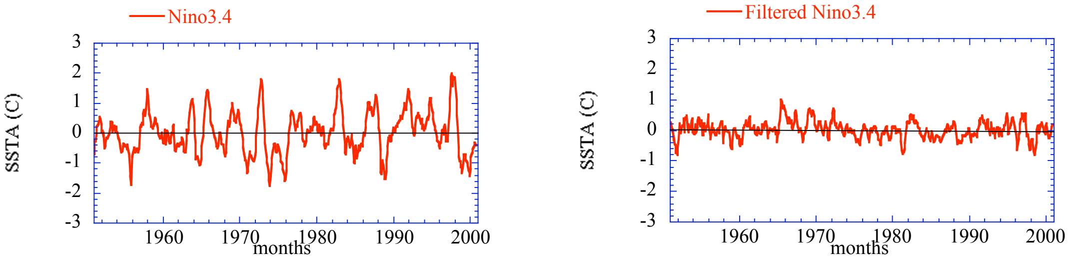


Fig.7: Time series of SST anomaly in the Niño 3.4 region before (left) and after (right) applying the background-pass filter.

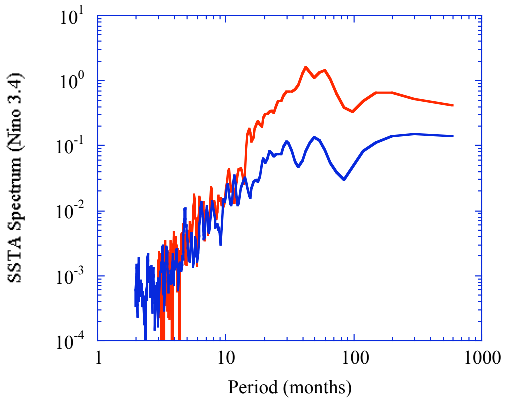


Fig. 8: FFT Spectrum of Niño 3.4 SST anomalies before (red) and after (blue) background-pass filtering.

It is not visually obvious in Fig. 7, but the filtered Niño 3.4 SST anomalies are dominated by low frequencies (Fig. 8). The efficiency of the filter in removing the broadband ENSO signal is displayed in Fig. 9.

An advantage of this filter is that its application involves spatial patterns rather than long timeseries. Therefore, because the linear dynamics provides a unique correspondence between the spatial patterns and the frequencies associated with them, the filter can be applied at any temporal resolution. Further, it appears that the filter does not need to be recalculated for every data set; using the modes and adjoints evaluated from the COADS as described above when filtering weekly SST data since 1980 (Reynolds et al. 2002) was also successful (not shown).

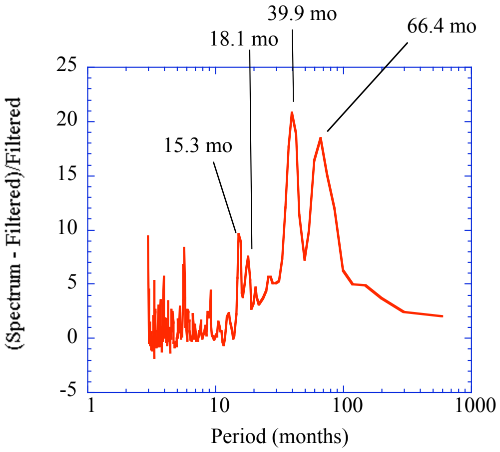


Fig. 9: Difference of spectra shown in Fig. 10, normalized to the background-pass filtered spectrum.

Implications for the tropical Atlantic

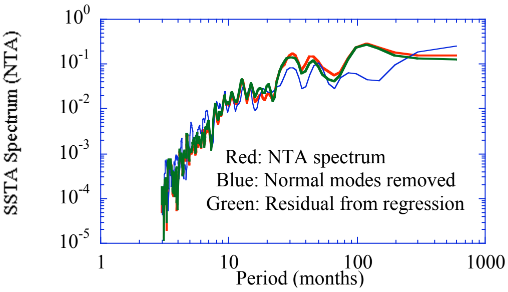


Fig. 10: As in Fig. 8, but for the NTA region. Also shown (green) is the FFT spectrum of the residual time series left when SST anomalies in NTA have been regressed onto those in the Niño 3.4 region and subtracted from the original NTA time series.

To illustrate the advantage this method has over the regression-residual method of isolating the ENSO signal, we considered NTA SST anomalies. These anomalies have been shown by Enfield and Mayer (1997) and by Penland and Matrosova (1998) to be significantly correlated with SST anomalies in the east-central tropical Pacific at a lag of six months.

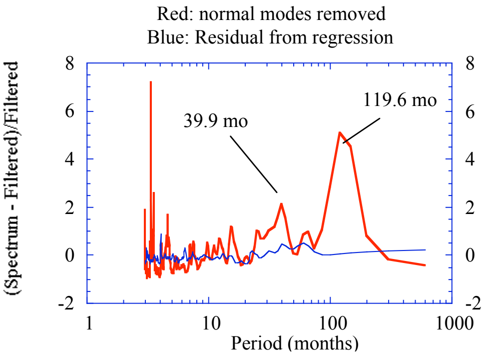


Fig. 11: As in Fig. 9, but for the NTA region. Blue line compares spectrum of regression-residual time series with that of original NTA SST anomalies.

In Figs. 10 and 11 we see that the residual formed by regressing NTA SST anomalies onto Niño 3.4 and then subtracting that signal from NTA SSTs has a spectrum practically indistinguishable from that of the original anomalies. In contrast, the modal filtering has indeed reduced spectral peaks associated with El Niño, although it is clear that the linear ENSO signal at interdecadal frequencies is stronger in NTA than the usual interannual frequencies associated with it. The spectra shown in Fig. 10 do suggest that some of the variance at frequencies usually associated with El Niño is not contained in the linear ENSO signal, although the significance of those peaks is debatable.

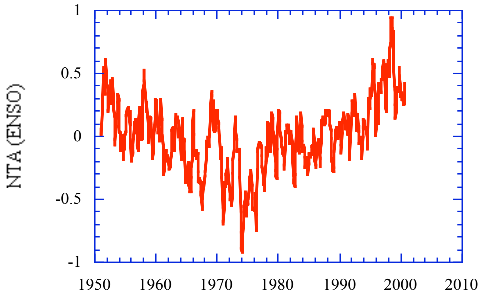


Fig. 12: Time series of NTA SST anomalies associated with the linear ENSO signal

In fact, it is interesting to compare the time series of NTA SSTA with and without the linear ENSO signal (Figs. 12 and 13). Fig. 12 shows a strong consistency with Figs. 10 and 11, with a striking change of character having occurred in the mid 1970's. This change is reminiscent of assertions (e.g., Graham 1994) that the climate suddenly shifted sometime around 1976.

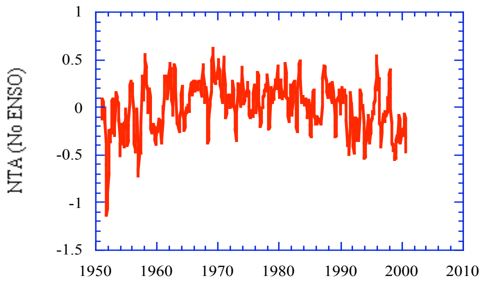


Fig. 13: Time series of background-pass filtered NTA SST anomalies.

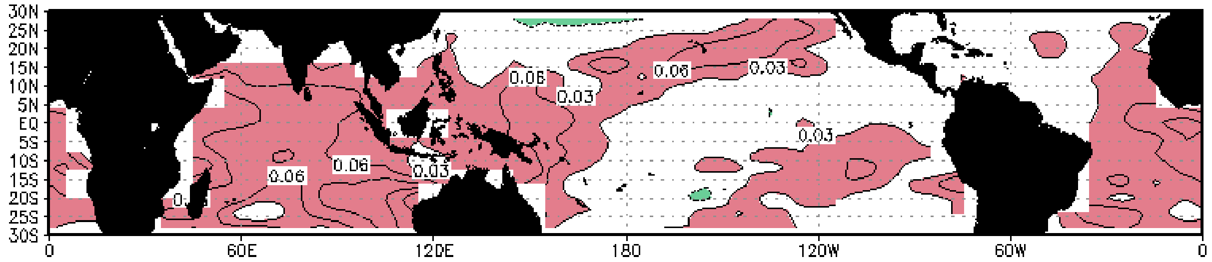


Fig. 14: First EOF of background-filtered SST anomaly. This pattern corresponds to an EOF eigenvalue of 13.3($^{o}C^{2}$), compared with the eigenvalue corresponding to the first EOF of the unfiltered SST anomaly, 29.8($^{o}C^{2}$).

The curvature of these time series is interesting. In fact, particularly in the first part of the period, the background-pass NTA anomalies are affected by a global-scale trend pattern (i.e. EOF 1 after the modal filtering) whose variance is about half that of the ENSO pattern (i.e., EOF 1 *before* any modal filtering – not shown) in the entire tropical strip. This trend pattern is shown in Fig. 14, and its corresponding time series is shown in Fig. 15.

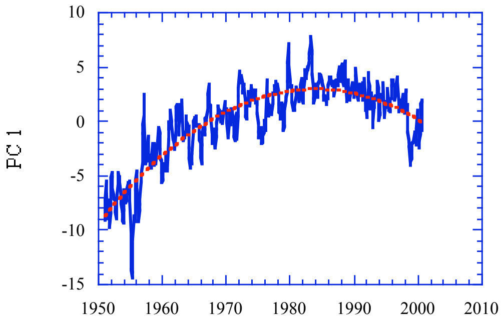


Fig. 15: Time series coefficient (solid blue line) of the pattern shown in Fig. 14. Dotted red line: quadratic fit to time series.

The trend pattern shown and its time series coefficient have several interesting properties. First, a quadratic fit to the time series shown in Fig. 15 explains more than 76% of the variance. Second, the pattern has large loadings in STA, and the entire pattern resembles the tropical loadings of the global trend pattern found by Livezey and Smith (1999). Thus, it is possible to consider the SSTA in the tropical Atlantic from which *both* the trend and the linearly predictable ENSO signal has been removed. When this is done (Fig. 16), the filtered NTA and STA time series are significantly anticorrelated in every season, with an average correlation of –0.48. This result supports the hypothesis suggested by Penland and Matrosova (1998) that a physical mechanism for a tropical Atlantic dipole does exist in nature, but that this dipole is rarely seen because El Niño disrupts the northern branch. A modification is in order, however; the large-scale plays at least as strong a role in disrupting this signal as does ENSO.

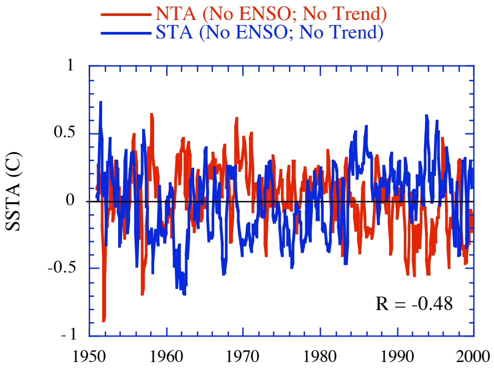


Fig. 16.

Conclusions and future plans

Results concerning predictability basically reaffirm the results of PM98. Using this linear method of forecasting SST, the most predictable regions of the tropical Atlantic are the NTA and CAR regions. Most of this predictability comes from remote tropical Pacific influences.

Our new filter does offer some intriguing perspectives. The “climate shift” observed in some studies (e.g., Graham 1994) in the north tropical Atlantic is confined to the linearly predictable ENSO signal, indicating a tropical Pacific origin.

PM98 found using tropical Atlantic SST predictors alone that an optimal initial structure for transient growth evolved into a tropical Atlantic dipole. When the entire tropical belt was used, this phenomenon disappeared. PM98 concluded that the physical mechanisms for a topical Atlantic dipole probably existed, but a disrupting influence of the tropical Pacific on SSTs in the NTA region prevented a consistent dipole signal from being observed. This current study corroborates that conclusion to some extent, but provides a major modification. The global trend signal in the tropics also has a disruptive effect. When both the ENSO and global trend signals are removed, the filtered NTA SST anomaly is significantly anticorrelated with the filtered STA SSTA time series in every season.

Acknowledgements

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Water Management and Climate Forecast: Regionalized Model at FUNCEME

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The Northeast of Brazil is characterized by a semi-arid climate, water scarcity, and a highly variable precipitation regimen. Periodical droughts have modeled the behavior of the inhabitants of the inland area (sertãos). Since the begging of colonization, the sertanejos and techniques of the regions has been looking for models to forecast the quality of rainy season as a tool to mitigate the effects of droughts. FUNCEME (Fundação Cearense de Meteorologia e Recursos Hídricos) was created, in 1972, with objective of understanding the climate and weather of the region as well as of developing techniques of artificial rain. After 1982, FUNCEME has introducing in its objectives also the understanding of hydrological regimen of the state as well as the environmental subject. The climate forecast has been included since the 1980 decade as an operational task of the Institution. In order to improve the forecast, FUNCEME and IRI (International Research Institute for Climate Prediction) developed a dynamical climate downscaling prediction system over Northeast Brazil, having the NCEP regional spectral model (RSM) and ECHAM atmospheric general circulation model (AGCM) as its core. Sea surface temperature forecasts are produced first, and then used as lower boundary condition forcing for the RSM - ECHAM4.5 AGCM nested system. A number of simulations were performed to obtain the best combination of horizontal resolution and domain size for the RSM. Then, an ensemble of ten runs of the RSM - ECHAM4.5 AGCM nested system was carried out for the period of 1971-2000, using observed SSTs as boundary forcing. Skill estimates obtained from this sort of hindcasting are considered as upper limit of forecast skills. A number of statistical tools were used to correct for systematic and conditional biases in the post-processing of model forecasts. Results of seasonal climate forecasts for February-May 2002 are presented.

Introduction

As water resources management occurs in a context of human values and physical realities, each society develops its own systems and goals. The perceptions of natural resources by societies reflect biophysical realities, cultural values, historical experiences, as well as political realities (Perry and Vanderklein, 1996). The Northeast of Brazil (NEB) has a climate characterized by a precipitation regimen involving a concentrated rainy season, usually from three to four months, and a high annual variability. These conditions come together with an intense evaporation rate and with low permeability soil. . That combination results in intermittent rivers that have a season of no flows that can last from six to nine months or even the whole year when severe droughts occurs.

This adverse climate and hydrologic conditions retarded significantly the occupation of Northeastern Semi-Arid. Periodical droughts usually resulted in reducing the livestock and migration of the inhabitants of the region. In 1887 the years of severe droughts have resulted in a largest worse disaster that ever occurred in Brazil: it was estimated that have died approximately 500.000 persons and the livestock was reduced to 1/6.

That drought resulted in a National commotion. It is attributed to the Brazilian Emperor, D. Pedro II, the statement: “I will sell the last stone of my crown before a Nordestino to die of hunger.” At that time, the Emperor sends a technical mission to NEB to look for solutions for the droughts. Some suggestions were made as: to build large reservoirs and drill wells in order to make water supply more dependable; to build roads to take supplies to the flagellates when a drought comes and others suggestions. That public policy was implemented, slowly since than.

Nordestinos has been looking for climate and weather prevision hardly since the very beginning of the occupation of sertãos. In that context a lot of research has been done regarding Forecast in Brazil, and political support is present most of the time. FUNCEME, (FUNDAÇÂO CEARENSE DE METEOROLOGIA E RECURSOS HÌDRICOS) was created in that context: to make artificial rainfall and to study the meteorology of the state.

Nowadays, the Ceara State has a significant number of large reservoirs, used to supply the cities, industries and irrigation, and is looking for an efficient way to manage its water resources. Nevertheless, besides the development of industries and la big urban population, there are still a large number of sertanejos leaving for rain fed agriculture. For those people, the need for climate forecast still remains as in the beginning of last century.

In this context, FUNCEME, in collaboration with other National and International Institutions, has been developing and improving forecast models. The need of a better spatial resolution for forecast makes FUNCEME to sign a cooperation agreement with IRI to improve and apply the regionalized. This paper presents the context of forecast in NEB as well some results of application of downscaling techniques in Ceara State.

The Climatic and Hydrological Aspects

The annual rainfall in Ceará state ranges from 1400 mm on the coast and mountains to close from 500mm in the inland (Sertão Central). More than 90% of annual precipitations are concentrated in six months (Dec-Jun) and more than 75% happen in four months (Feb-May). The evaporation in some place reaches more than 2500mm. These conditions associated to a crystalline soil results in a net of intermittent rivers. The water budget is positive only during three to four months in a normal year. This wet period is used by sertanejo to cultivate subsistence crops (bean and corn).

Most of the rivers of North of Brazilian Northeast stay dry six to nine months per year, or even more than a year when severe droughts occur. For example, describing the 1903 drought at Rio Grande do Norte, Guerra (1980:131), stated: “Rivers, as the Mossoró, started flowing, and since 24 months that doesn’t flow water over its bed. If we consider the next six months of summer, it will reach, December, so we will have the frightening fact of river with 360 km –more or less in the same extension of Tames, stay empty thirty consecutives months.”.... “We are in July, nevertheless, there are several farms without water, and there are many sertanejos that goes for water to drink as far as three, six and even twelve kilometers.”.

Besides of that, the over-year variations of rivers discharges in Ceará state are among the highest of the word. The coefficient of variation of annual inflows ranges from 0,6 to 1,8; while in temperate regions, perennial rivers, these values are, usually, close to 0,3-0,4. This high variability implies in need of large reservoirs to give some reliability in water supply.

Cultural Aspects

The climatic and hydrologic uncertainties and adversities have modulated the sertanejo culture. Guerra (1980) described very well the feelings of the sertanejos who lives from rain fed agriculture:

> *“The sertanejo is always frightened and afflicted with the possibility of drought. In October, begins the anxiety and bad feeling. Will it rain? Will drought come? Could we execute such a service? Will it be good investing money in such a project? Increment commercial transaction?”*

The certainty that a drought is always a real menace created among sertanejos a culture of storing water during the wet season to use it cautiously during dry season. All farms in Northeast of Brazil, to be sustainable, have to have an açude or be located close to an artificially perennial river. This feeling of sertanejos is also well described by Guerra (1980): "In sertão, more is worthy to leave for the family a good açude than a rich and beautiful palace." The need of reservoirs in Northeast as an efficient policy to mitigate the droughts is almost unanimity among scientists and technicians of the region. Some of them even defend the need of building reservoirs as large as possible in order to control all the water in such a way that nor any drop of water flows to the ocean (Guerra, 1981:142).

These cultural aspects are main motivation for the use of climate and weather forecast: the first one is related to public police to mitigate droughts; the second one is related to the management of water stored in reservoirs.

The Forecast Practice at Ceara State

Over the last 20 years, Ceará State Foundation for Meteorology and Water Resources (FUNCEME), in partnership with National Institute for Space Research (INPE) and other Brazilian and foreign meteorology entities, has worked on a conceptual model of climate forecast that is supported by several regional and global climatic models. In addition, information about oceanic and atmospheric patterns that have a significant influence on the rainy season quality over Ceará and Northeast Brazil are analyzed too.

Every year, FUNCEME holds a workshop in Fortaleza, which is attended by its technical staff and experts from national and international institutes or universities, to make the analysis of such oceanic and atmospheric variables that are significant for the identification of rainy period, and make forecasts based on the application of several numeric models. At the end of the workshop, the panel of researchers and experts issue a climate forecast for the main rainy period in both the State of Ceará and the northern portion of Brazil Northeast (February-May).

Forecast is read out publicly on the last day of the workshop at a session attended by the major users (EMATERCE, Civil Defense, COGERH, SEAGRI, agricultural businesspersons, and other stakeholders). Forecasts are usually covered and published by the local media(press and TV). It should also be highlighted that, prior to the public disclosure of forecasts, a team of professionals led by the President of FUNCEME, submits the workshop conclusions to the Governor of the State of Ceará.

Once the first forecast for a particular year is issued, FUNCEME team continues to monitor the oceanic and atmospheric patterns. Eventual changes in forecasts is published in technical releases and informed immediately to the end-users. This remains available in the web site of FUNCEME (www.funceme.br).

It should be pointed out that climate forecast issued in December is considered as an initial approach, as it is based on oceanic and atmospheric conditions observed in November. Previous experiences have shown a high forecast reliability when observations made in January-February are used.

This anticipated climate and weather forecast combined with the daily monitoring of sea and atmosphere conditions has helped the State of Ceará over all those years to plan actions for agriculture (e.g. *Hora de Plantar* (Time to Plant Program), water resources (reservoir management), civil defense (alerts against extreme rainy events in Fortaleza Metropolitan Region), civil construction (best periods for concrete application), etc. General society has also benefited of such forecasts through a range of measures taken by the civil defense, Secretariat of Agriculture, Secretariat of Water Resources, Civil Construction, and other sectors that use meteorological information to carry on their activities.

The Downscaling Model

The downscaling model consists in a Regional Model nested in a Global Model (AGCM). The AGCM used is the European Community - HAMburg (ECHAM) AGCM version 4.5, developed at the Max Plank Institute fur Meteorolgie (MPI) in Germany. The model was configured at triangular 42 (T42) spectral truncation, giving a spatial resolution of about 2.8 degrees latitude-longitude, with 19 vertical layers (Roeckner et al. 1996). ECHAM4.5 AGCM is one of the forecast AGCMs at the International Research Institute for Climate Prediction (IRI). It is capable to produce the large-scale climate variability well over Northeast South America.

The regional model used is the Regional Spectral Model (RSM) version 97, developed at the National Centers for Environmental Prediction (NCEP) (Juang and Kanamitsu 1994). NCEP RSM is one of the regional models involved in the IRI/ARCs Regional Model Intercomparison over Brazil, and the overall performance of RSM is good among all the regional models. Case study with RSM on downscaling of ECHAM AGCM seasonal prediction over NEB also produced encouraging results (Nobre et al. 2001).

NCEP RSM97 is used to downscale ECHAM4.5 AGCM simulations. The one-way nesting of the NCEP RSM97 into the ECHAM4.5 AGCM is done in a way that is different from conventional methods, which use global model results along the lateral boundary zone only. The perturbation nesting method used here allows the global model outputs to be used over the entire regional domain, not just in the lateral boundary zone. The dependent variables in the regional domain are defined as a summation of perturbation and base. The base is a time dependent prediction from the AGCM. All others that cannot be predicted by the AGCM but can be resolved and predicted by the RSM in the regional domain are defined as perturbations. The ECHAM AGCM provides the base field every 6 hours in this study. Nesting is done in such a way that the perturbation is nonzero inside the domain but zero outside the domain.

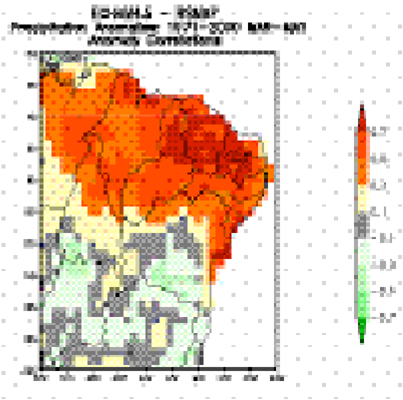


Figure 1. Temporal correlations between observed and RSM simulated precipitation anomalies for February-March-April 1971-2000.

The choice of regional model domain and resolution is very important when setting up the downscaling experiment. A number of test simulations were performed to determine the optimum horizontal resolution and the size of the computational domain. The resolution varied between 30 km and 100 km, and the later boundaries were placed at west as far as100° W, at east as far as 10° E, at north as far as 20° N, and at south as far as 30° S. We found that the RSM with horizontal resolution of 60 km and the domain defined in Fig. 1 (109×72 grid) generated the best results among the test simulations. Thus, this configuration is chosen for our downscaling study. Note that Nordeste is far from the lateral boundaries. This prevents possible noise generated at the lateral boundaries from excessively contaminating the solution over Nordeste. The dominant forcing driving the Nordeste precipitation variability is local to the tropical Atlantic, with the remote influence of the tropical Pacific playing a secondary role. The test showed that the Atlantic ITCZ is very critical for the precipitation in Nordeste. The entire tropical Atlantic Ocean has to be included in the domain. The displacement of ITCZ occurs when only a portion of tropical Atlantic Ocean is included in the domain. With the resolution of 60 km, the main features of the bottom topography in Nordeste are resolved by

With observed SSTs as boundary forcing, an ensemble of ten runs of NCEP RSM _ ECHAM4.5 AGCM nested system was done for the period of 1971-2000. The skill estimates obtained from this sort of hindcasting are considered as upper limit of forecast skills. The ability of nested RSM in simulating precipitation interannual variability is illustrated in Fig. 1. Anomaly correlations between observed and simulated MAM precipitation exceed 0.7 over some of Nordeste. The correlation drops rapidly beyond the latitude 9^{o} S. This result confirmed that the SST anomaly forcing is the primary factor responsible for the interannual variability of precipitation in Nordeste since the only external forcing for the nested RSM simulation is observed SSTs.

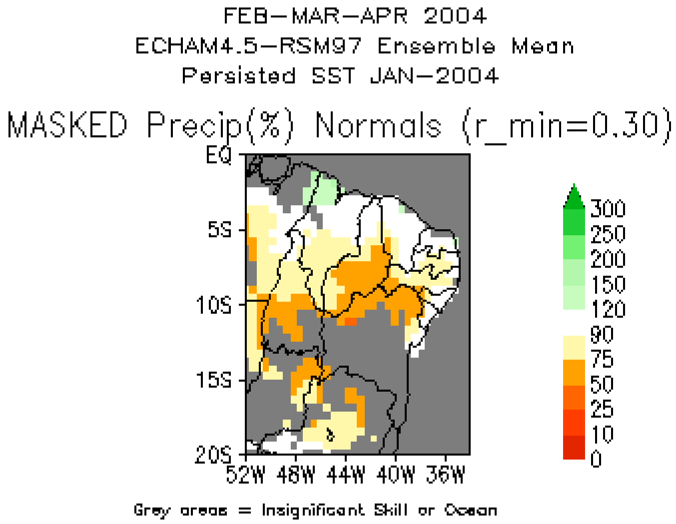


Figure 2 - Forecast of precipitation in percentage of the climatology for February to April 2004 with SST persisted from January 2004

FUNCEME has issued one-month lead seasonal climate forecasts for the period of January _ June (rainy season), and will update the forecasts monthly until the rainy season is over. The forecasts are based on this climate dynamical downscaling prediction system, some AGCM, statistical models, conceptual models. The downscaling system becomes operational at December 2001.

To run the forecast with downscaling system we assume two scenarios for global SST forecasts, one is persisted of anomaly, and other is predicted SST, they are updated monthly, are used as lower boundary forcing for the NCEP RSM _ ECHAM4.5 AGCM nested model system. The AGCM are running at IRI and RSM at FUNCEME. For each scenario we use an ensemble of 10 runs.

Figures 2, 3 and 4 are shown three of the products of forecast generated by the model for the period of February to April of 2004, carried through in February of 2004. Figure 2 shows the forecast of the percentage of the climatology of the precipitation. The areas in grey show where the model did not have ability in carrying through the forecast, considering that the correlation coefficient was minor than 0,3 in climatological simulation or ocean. Areas in green colors show forecast above climatogical mean and in yellow to red below climatological mean.
For figure 3 we start by examining how well the model-simulated year-to-year variability, covering the years 1971 forward for some given season, agrees with the observed variability in those years.. The climatological base period is designated as 1971-2000. The seasonal precipitation anomalies, which are the deviation from average 1971-2000 seasonal conditions, are categorized as "Above Normal", "Near Normal", or "Below Normal" for each point on the grid model. At each point, the wettest 1/3 of the years from 1971-2000 define the "Above Normal" category for precipitation at that point for a particular season, the driest 1/3 of the years

from 1971-2000 define the "Below Normal" category, and the values during the other 10 years in the 1971-2000 period define the "Near Normal" category. These categorical determinations are made for both the observed climate variability and the historical model-simulated climate variability, using the ensemble mean of the model simulations.

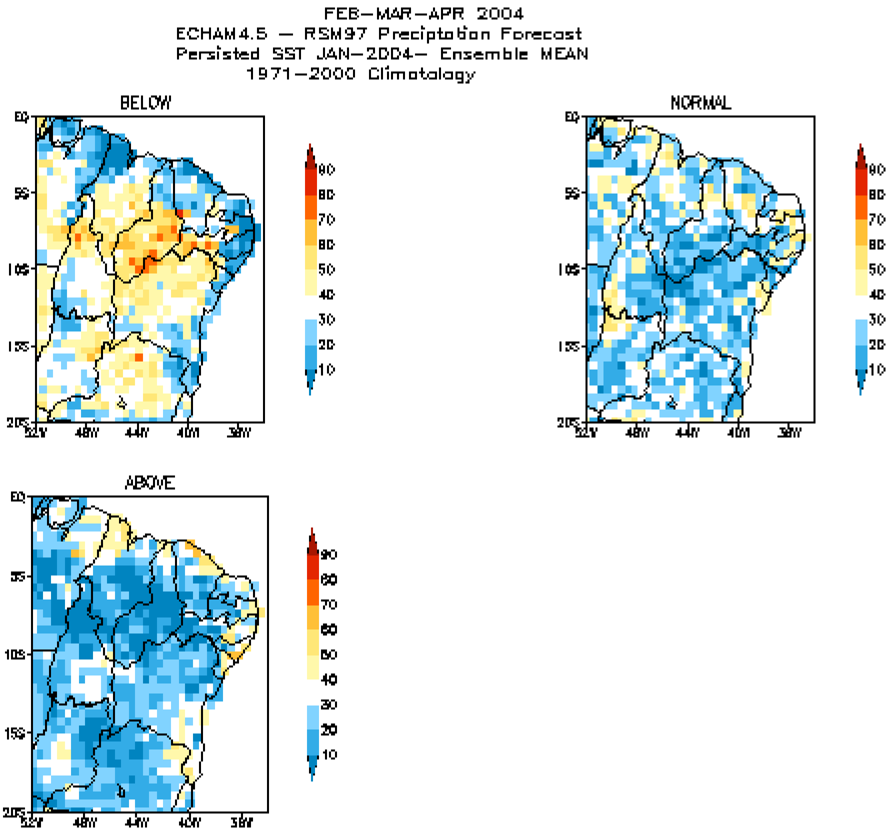
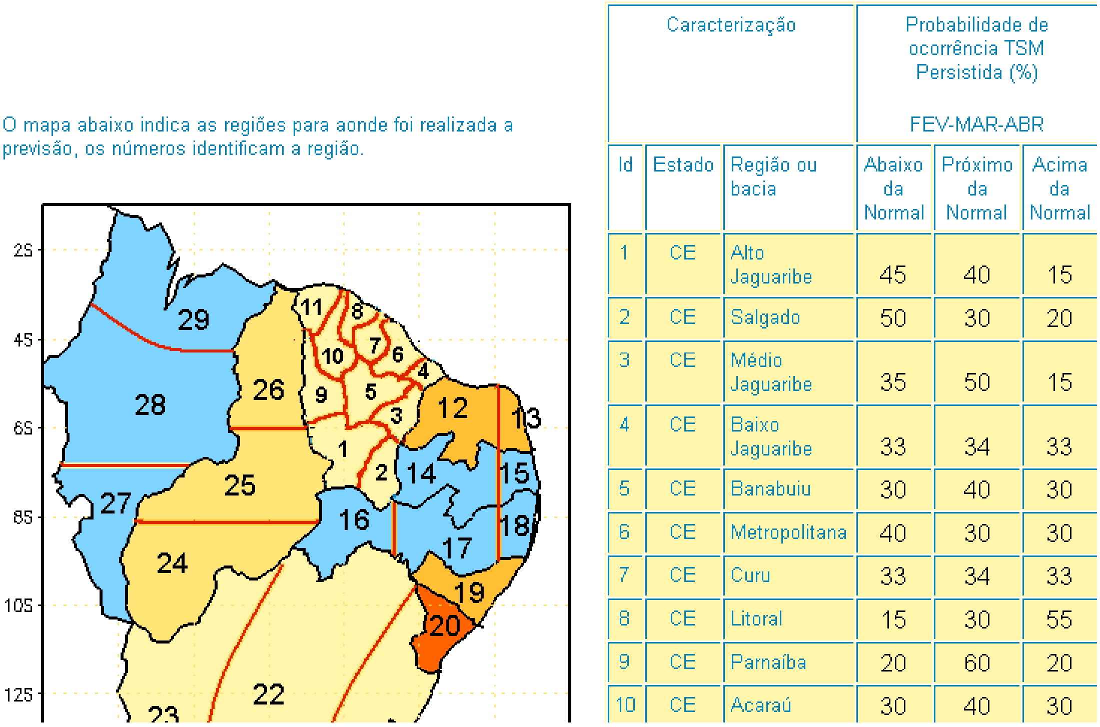


Figure 3: Categorical percentage probabilistic seasonal forecast precipitation for February to April 2004 using persisted SST anomaly from January 2004.

Next we consider how often the model correctly simulated the conditions for each category, during the historical simulation. For example, when the model ensemble mean says it will be "Above Normal" precipitation, how often was the observed precipitation "Above Normal"? At a particular grid box, it may be that for 60% of the years when the model indicated "Above Normal" precipitation, the location was observed to receive "Above Normal" precipitation. This means that 40% of the years when the model indicated "Above Normal" precipitation, it was not observed to be "Above Normal" precipitation. It may be that 30% of those years the observed precipitation was "Near Normal", and in 10% of the years the precipitation was actually "Below Normal". From this information, one can tell that there is very low probability that there would be "Below Normal" rainfall at this location if the model were to show "Above Normal" conditions.

Finally at figure 3, the forecast maps show the probabilities of each of the three categories ("Above Normal", "Near Normal", "Below Normal"), based on the category indicated by the ensemble mean forecast, and the model's past performance with respect to the observations when predicting that category

Figure 4 we did the same methodology of figure three, but we use rainfall anomaly over regions instead of grid point. The regions area are bigger than grid point. Over Ceara the regions are the main watersheds of the state.



O mapa abaixo indica as regiões para aonde foi realizada a previsão, os números identificam a região.

Caracterização			Probabilidade de ocorrência TSM Persistida (%) FEV-MAR-ABR		
Id	Estado	Região ou bacia	Abaixo da Normal	Próximo da Normal	Acima da Normal
1	CE	Alto Jaguaribe	45	40	15
2	CE	Salgado	50	30	20
3	CE	Médio Jaguaribe	35	50	15
4	CE	Baixo Jaguaribe	33	34	33
5	CE	Banabuiu	30	40	30
6	CE	Metropolitana	40	30	30
7	CE	Curu	33	34	33
8	CE	Litoral	15	30	55
9	CE	Parnaíba	20	60	20
10	CE	Acaraú	30	40	30

Figure 4: Categorical percentage probabilistic seasonal forecast precipitation for February to April 2004 using persisted SST anomaly from January 2004.

Concluding Remarks

The water scarcity at Ceará State has modeled the construction of water management system of the state. Climate forecast has been an important and very useful tool for the water users and managers in Ceara State. The society has demanded of Governments and scientist for good models to improve the water management practices as well as a tool to mitigate the droughts in the region. The need for more precise models, in a finer grid, motivates FUNCEME to incorporate the regionalized model in its forecast practice. The users have monthly in the www.funceme.br and use the information in their decision making process.

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Development of a Decadal Climate Prediction System

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A decadal climate prediction system based on the Hadley Centre coupled global climate model, HadCM3, has been developed.
In order to initialise the ocean component a new dataset of monthly mean optimally interpolated ocean temperature and salinity anomalies has been created. The main innovation in creating this dataset is the use of local covariances computed from HadCM3 to propagate information from data-rich to data-sparse regions.
Climate drift during forecasts is avoided by assimilating observed anomalies added to the model climate, rather than observed values.
The skill of the system has been assessed in a set of 60 hindcasts initialised from 1979 to 1993. Compared with state-of-the-art seasonal forecasting models, the decadal prediction system performs satisfactorily on seasonal timescales. As expected, the hindcast skill of annual mean near surface air temperature over Western Europe initially decreases with increasing forecast lead time due to the non-linear growth of errors arising from imperfections in the model formulation and uncertainties in the initial conditions. However, there is a return of skill at long lead times resulting from the ability to predict the warming trend due to increasing concentrations of greenhouse gases.

Introduction

The ability to predict climate variability on annual to decadal timescales would be important both to pre-empt criticism of greenhouse gas emissions policy in the event of a run of cold years, and to enable vulnerable sectors of industry and commerce to take account of climate change in future planning. A system for predicting climate variability on these timescales should account for both internal natural variability of the climate system and external radiative forcing, due to changes in the solar flux, volcanic aerosol and greenhouse gases. Due to the rapid growth of initial perturbations, internal natural variability of the atmosphere is unlikely to be predictable beyond a couple of weeks. However, important modes of variability involving feedback from the ocean to the atmosphere, including El Niño and changes in the thermohaline circulation, offer the possibility of predicting some aspects of internal natural climate variability on annual and longer timescales. Development of a decadal climate prediction system at the Hadley Centre has therefore focused mainly on initialisation of the ocean component of the coupled global model, HadCM3. Here we summarise the development of a new three-dimensional optimally-interpolated dataset of monthly mean ocean temperature and salinity anomalies for initialising ocean models, and present some initial hindcast results relevant to Western Europe.

Ocean Analysis

In order to make ocean analyses from spatially incomplete distributions of observations it is necessary to infer values remote from observation sites using spatial covariance statistics. Our main innovation is to use spatially varying covariances computed directly from the coupled model, HadCM3. Other studies (*e.g.* Carton *et al.*, 2000, Ishii *et al.*, 2003) typically employ parameterized covariances based on observed correlation length scales, which must be defined over large areas in order to obtain statistically robust results from sparse ocean observations. Model covariances potentially capture important local modes of variability and water mass generation more accurately than using observed correlations defined over large areas.

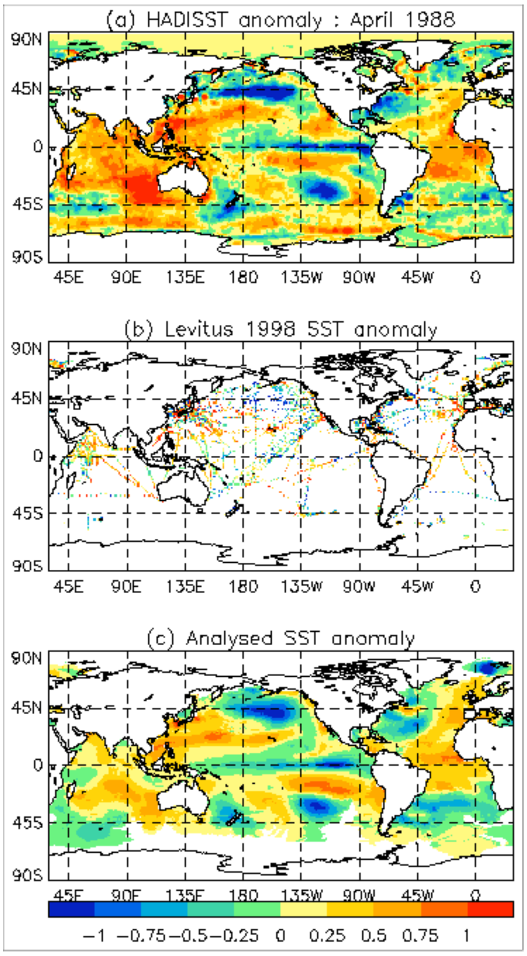

Figure 1: Reconstruction (c) of SST by optimal interpolation of surface profile data from the World Ocean Database (Levitus *et al.*,1998) dataset (b). HadISST (a) (Rayner *et al.*, 2003) is an analysis of all SST observations, including satellite data, and may be regarded as close to the truth.

However, this potential advantage will be eroded by model errors. We therefore restrict the use of model covariances to local regions in which they are sufficiently accurate that model error would not be expected to have a detrimental impact on the resulting analysis. Since observations of salinity are particularly sparse, we employ multivariate optimal interpolation of temperature and salinity observations to generate temperature and salinity analyses. This takes advantage of any correlation between temperature and salinity anomalies to generate salinity analyses from temperature observations, resulting in much better salinity analyses than would be obtained from optimal interpolation of salinity observations alone. Full details of our methodology for generating ocean analyses, together with considerable evidence justifying the use of model covariances, are given by Smith *et al.*, 2004.

Example ocean analyses are presented in Figures 1 and 2. As a test of the analysis procedure, Figure 2 demonstrates that analysed sea surface temperature (SST) anomalies (c) created by optimal interpolation of profile data (b) are in reasonably good agreement with analyses which include satellite data (a). Figure 3 demonstrates that the analyses are able to capture important oceanic dynamical signals, such as the eastward propagation of subsurface temperature anomalies in the equatorial Pacific which contribute to the generation of El Niños and La Niñas.

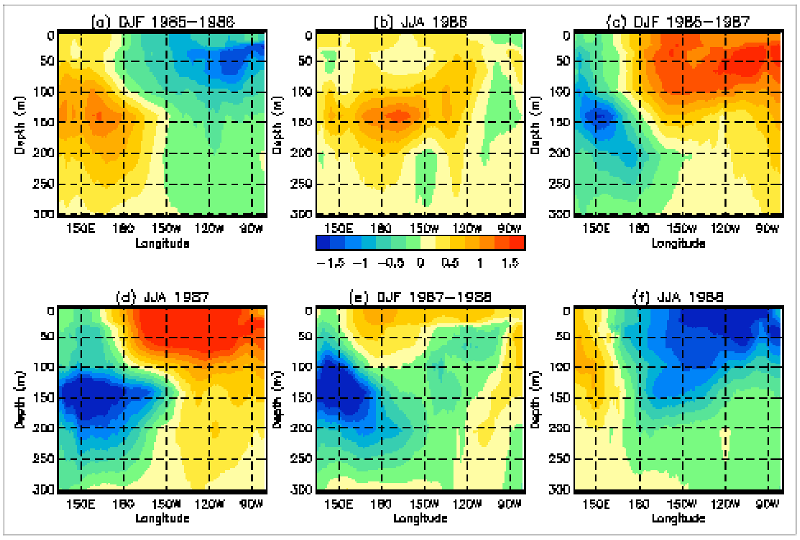

Figure 2: Time series of analysed temperature anomalies on a longitude-depth cross section of the equatorial Pacific. The eastward propagation of subsurface anomalies leading to the El Niño of 1986-87 and the following La Niña can clearly be seen.

Model initialisation

Before making forecasts, the ocean component of HadCM3 is initialised by relaxing (with a 6 hour timescale) the temperature and salinity fields to the ocean analyses described above. In addition, the atmosphere component of HadCM3 is initialised by relaxing (with a 3 hour timescale) the horizontal winds, potential temperature and surface pressure to the ECMWF 15 year reanalysis of atmospheric observations (www.ecmwf.int/research/era/ERA-15).

Models are not able to simulate the observed climate perfectly. This is liable to introduce a bias in the forecasts as the model drifts away from the observed state towards its preferred climate. In seasonal prediction it is standard practice to pre-calculate this bias over a large number of test cases and remove it from forecasts as an *a posteriori* empirical correction. We believe this strategy to be unfeasible for decadal prediction, since it is not possible to run the large number of test cases required to specify the time, space (and possibly flow) dependent bias accurately relative to the magnitude of the predictable signal being sought. We therefore adopt an alternative approach in which the model is initialised with observed anomalies added to the model climate, rather than with observed values.

Assessment of hindcast skill

In order to assess the skill of the Hadley Centre decadal prediction system (DePreSys), a set of 60 hindcasts has been performed. Initial conditions were created as described above for the period 1979 to 1993, from which 10-year forecasts were initiated from the 1st March, June, September and December in each year. During the forecasts anthropogenic forcing from greenhouse gases and sulphate aerosols was increased in line with observations. Aerosol from major volcanic eruptions occurring prior to initialisation was assumed to reduce exponentially with a timescale of one year, and solar variability was accounted for by repeating the previous 11-year solar cycle. Ensemble forecasts of 4 members were generated in order to sample the range of predictions consistent with observational uncertainty. Each ensemble member was initialised from consecutive days immediately preceding the forecast period.

A system capable of predicting climate variability on inter-annual to decadal timescales would also be expected to perform reasonably well on seasonal timescales. This was verified by comparing forecasts of El Niño with state-of-the-art seasonal prediction systems from the European DEMETER project (Palmer *et al*., 2004). Table 1 shows that DePreSys performs satisfactorily, subject to the caveat that a totally clean comparison is not possible, since the DePreSys forecasts started on 1st March (cf 1st February for the DEMETER forecasts), and the forecast years are not the same (even for the different DEMETER models).

	Months 2-4	Months 4-6
DEMETER	0.65-0.95 (0.80-0.96)	0.42-0.79 (0.50-0.88)
DePreSys	0.90 (0.94)	0.69 (0.79)

Table 1: Anomaly correlation of Niño3 (Niño4) SST for the Decadal Prediction System (DePreSys) developed in this study (March forecasts, 1979-1993) compared with seasonal forecasting models from the European DEMETER project (www.ecmwf.int/research/demeter).

Figure 3 shows the hindcast skill of annual mean near surface air temperature over Western Europe (15W-25E,35-60N) as a function of forecast lead time. The skill obtained by persisting the annual mean anomaly preceding the forecast start date is also shown for reference. The eight member ensemble is constructed by averaging the four ensemble members from the appropriate start date with the four ensemble members started in the previous season. The eight member ensemble is significantly more skilful than a single member, especially at longer lead times, and the dynamical forecasts are significantly better than persistence. As expected, the hindcast skill initially decreases with lead time due to the non-linear growth of errors arising from imperfections in the model formulation and imperfect knowledge of the initial conditions. However, there is an increase of skill at longer lead times. If the average trend in global temperature as a function of lead time is removed from the hindcasts the skill does not increase at longer lead times (see the orange dashed line in Figure 3), suggesting that the increase of skill reflects the ability of the hindcasts to predict the general warming caused by rising greenhouse gas concentrations in the atmosphere.

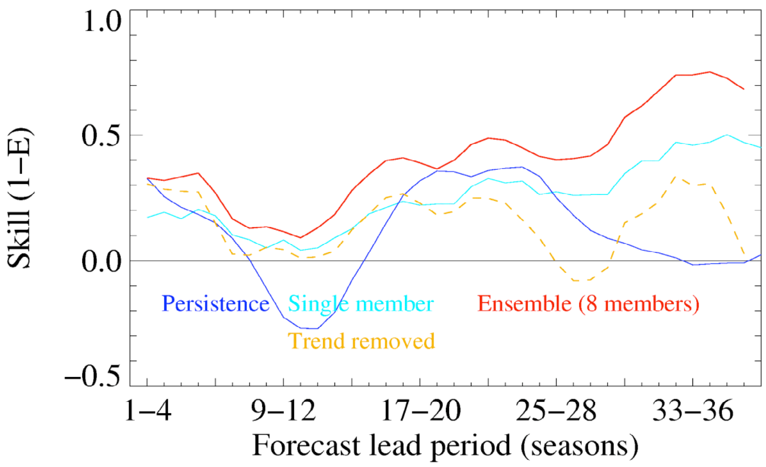

Figure 3: Hindcast skill of annual mean near surface air temperature over Western Europe (15W-25E,35-60N) as a function of forecast lead time. See text for further details. Skill is measured as 1-E, where E is the normalised error variance of anomalies computed relative to a 1979-1993 climatology.

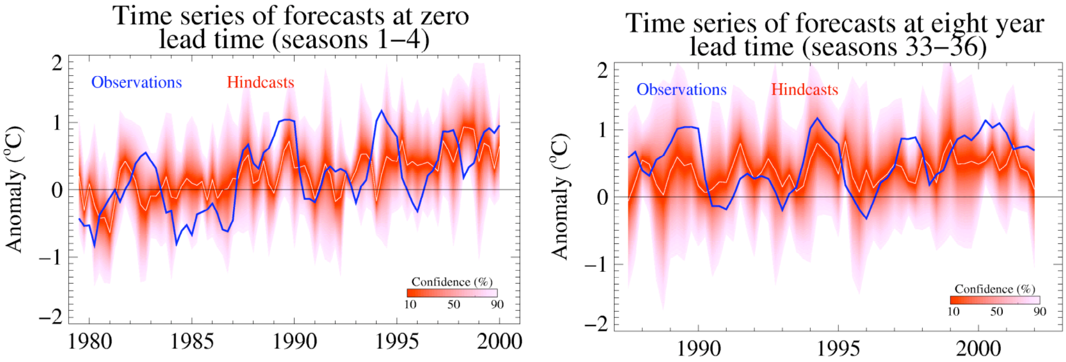

Figure 4: Retrospective ensemble forecasts of annual mean surface temperature over Western Europe (15W-25E,35-60N) at zero and eight year lead times from DePreSys (labelled 'Hindcasts'). Forecasts consist of eight ensemble members constructed by combining four integrations started from initial conditions immediately preceding the verification period with another four integrations started one season earlier. The white curve shows the DePreSys ensemble mean hindcast and the 90% confidence intervals, diagnosed from the standard deviation of values simulated by individual ensemble members, are also shown. Note that the forecasts at zero lead time have been extended from the original 1979-93 period to include the period 1994-99.

Figure 4 shows the time series of forecasts of annual mean near surface air temperature over Western Europe at zero and eight year lead times. Although the inter-annual variability is not well predicted, the forecasts do capture the general trend at zero lead time and the warming after eight years. Furthermore, the observations generally lie within the forecast uncertainty limits diagnosed from the standard deviation of the ensemble members, illustrating the potential value of probabilistic, rather than deterministic, forecasts.

Future work

The DePreSys hindcasts will be extended to the present day to enable more robust estimates of the likely skill of annual to decadal forecasts to be made. Analysis of the results will be expanded to include probabilistic measures of skill relevant to potential users in addition to traditional measures of skill such as error variance and anomaly correlation typically used in climate research and numerical weather prediction. Furthermore, other elements of climate such as precipitation, atmospheric circulation and extreme events will also be examined. The sources of forecast skill (for example the relative contributions of anthropogenic and naturally forced variability) will also be investigated in order to build confidence in the scientific credibility of the results.

We plan to generalise the design of our ensembles to include modelling uncertainties as well as initial condition uncertainties. This will be achieved by producing perturbed physics ensemble predictions by varying uncertain model parameters (Murphy *et al.* 2004).

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6. White Papers

The Physical Basis for Predicting Atlantic Sector Seasonal-to-Interannual Climate Varaibility

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This paper reviews the observational and theoretical basis for the predictability of seasonal-to-interannual (S/I) climate variability in the Atlantic Sector. The emphasis is on the large-scale picture rather than on regional details. The paper is divided into two main parts: a discussion of the predictability of the North Atlantic Oscillation (NAO) – the dominant pattern of variability in the North Atlantic and a review of the tropical Atlantic prediction problem. The remote effects of El Niño are also mentioned as an important factor in Atlantic climate variability. Only a brief discussion is provided on the subject of South Atlantic climate predictability.

It is argued that, because of its chaotic dynamical nature, the NAO and its related rainfall and temperature variability, while highly significant over Europe and North America, are largely unpredictable. This also affects the predictive skill over the tropical Atlantic. That said, there appears to be an insufficiently understood, and possibly predictable marginal signal in the NAO behavior that may be useful to certain end users. It is manifested in the deviation of the NAO temporal behavior from first-order autoregressive behavior.

Tropical Atlantic variability results from the sensitivity of the marine ITCZ to remote forcing from the equatorial Pacific and from the local interaction with the underlying ocean. Both mechanisms are potentially predictable – that is, given the underlying SST and the strength of El Niño, one could determine with a high degree of skill the anomalies in ITCZ position and intensity. Due to the strong coupling between ocean and atmosphere, however, and perhaps also the lack of sufficient understanding of local air-sea interaction, it is not easy to achieve the level of skill indicated by hindcast experiments. Overcoming this obstacle is a major challenge to improved S/I prediction in the Atlantic Sector.

1. Introduction

Prediction of climate variability is a search for determinism in the evolution of climate in time and space. Such determinism can come from the influence of known external forcings that are not influenced by climate itself (e.g., solar irradiance, volcanoes, and human activities such as changes in land use and the emissions of pollutants and greenhouse gases), or from the internal dynamics of the atmosphere and its interactions with the ocean and the land. Notably, however, deterministic atmospheric dynamical processes are largely chaotic (Lorenz 1963), effectively contributing a stochastic element to short-term climate statistics derived from the time averaging of weather. The resulting "natural climate variability" is inherently unpredictable (Leith 1973; Madden 1976) implying that prospects for short-term climate prediction lie in the existence of "modes" of variability that have either a quasi-periodic evolution or a large persistence. Such behavior is most likely to come from the interaction of the atmosphere with the "slower" components of the climate system, the oceans, the cryosphere, and the land. This is why climate prediction is centered on the sensitivity of the atmospheric circulation to persistent surface anomalies.

Because the study of climate is strongly empirical, the normal evolution of the science of climate prediction has been based on a search for observational-statistical evidence for these two paradigms of determinism, followed by an attempt to understand the theoretical basis for their existence and, in recent years, to replicate them in climate models. Establishing a theoretical foundation for the observational evidence is particularly important, because it enables interpretation and correct application of results based on the relatively short observational records and offsets the uncertainties resulting from the small signal-to-noise ratios often inherent in climate variability.

In this appraisal of the physical basis for climate prediction in the Atlantic Basin, we focus on relatively short-term, namely seasonal to interannual (hereafter S/I), climate variability. More precisely, we address the ability to predict the year-to-year variation in seasonal averages (or higher statistics of seasonal weather) several months to several seasons in advance, on the basis of the second paradigm for deterministic behavior mentioned above. The discussion of the effect of external forcing (solar, and anthropogenic gases and aerosols) is outside the scope of this review, although some discussion is presented regarding the effects of volcanic forcing.

The paper is divided as follows: In Section 2 we describe the leading patterns affecting climate variability in the Atlantic Basin: El Niño, the North Atlantic Oscillation (NAO), and the sea surface temperature (SST) patterns associated with tropical Atlantic variability (TAV). We assess their impact on two primary surface climate variables: temperature and rainfall. In this, we ask the following question: Had we known the evolution of these patterns in advance, how much of the variance of surface temperature and rainfall could we explain, by season, in the Atlantic Sector? In Section 3 we discuss the dynamics and predictability of the NAO and its interaction with the ocean, land, and stratosphere – all three being considered as sources of predictability for this midlatitude phenomenon. In Section 4 we discuss the theory behind TAV and its predictability, particularly in conjunction with the large influence exerted on this region by El Niño. Section 6 offers a summary and closing remarks.

2. The patterns of climate variability in the Atlantic Sector

The notion that climate variability is associated with large-scale patterns linking fluctuations in remote areas of the world is old. Scholars studying the NAO recall the work of the Danish missionary, Hans Egede Saabye, who in 1745 wrote about the severity of winter climate in Greenland displaying a negative correlation with that in Scandinavia. The seminal work of Walker in the early 20th Century (Walker 1924; Walker and Bliss 1932) laid out a systematic approach to recognizing and defining such patterns (teleconnections) for the characterization and projection of climate impacts, with the implicit idea that such patterns can be deployed towards prediction (although, notably, Walker rejected the notion of periodicities in climate). Walker's work and subsequent other research culminated in the well-known study of teleconnections by Wallace and Gutzler (1981) which added a modern, objective approach to the descriptive work of the early investigators. From this and more recent work, it is now recognized that there are three major patterns associated with climate variability in and around the Atlantic Basin: (i) The NAO, which affects the climate of the North Atlantic from its subtropical regions to the polar latitudes (Hurrell *et al.* 2002); (ii) El Niño, which influences the global atmospheric circulation in the tropics and extratropics including the Atlantic Sector (Trenberth *et al.* 1998), and (iii) the SST variability in the tropical Atlantic region, which affects the atmospheric circulation of that region, particularly the seasonal migration of the intertropical convergence zone (ITCZ) and hence rainfall over South America and West Africa (Ruiz-Barradas *et al.* 2000). The latter phenomenon is normally discussed in terms of two different time-varying patterns, an equatorially centered SST anomaly and an off equatorial variability that affects the meridional temperature gradient in the tropical Atlantic region, each acting during a different time of the year (Sutton *et al.* 2000). It should be mentioned that, in the midlatitudes in particular, the spatial and temporal spectrum of climate variability cannot be captured by a single teleconnection pattern. Thus the NAO, while dominating the variability in the North Atlantic on time scales longer than 10-days or so, is not the only pattern emerging in a subjective analysis of the covariance field (Wallace and Gutzler 1981; Barnston and Livezey 1987). Part of this diversity can be explained by the meandering of the spatial location and changes in shape of the NAO itself, but other patterns may be genuinely independent phenomena (Kushnir and Wallace 1989).

The relevance of these patterns to climate prediction is that, if their impact is large and they can demonstrably maintain their overall shape, they can be used to simplify the objectives of the forecaster: determine the future phase and amplitude of the pattern and you have come close to predicting the climate variables with societal importance.

To demonstrate the influence of these patterns, we use their historical amplitudes and phases as indices for reconstructing historical surface air temperature and precipitation, by means of multiple, linear regression. The correlation between the reconstructed variables and the observed ones provides an upper limit for the potential for prediction embodied in these patterns. We begin with the two more dominant patterns – El Niño and the NAO. This approach entails an implicit assumption that the evolution of TAV depends, to a large extent, on these remote forcing factors (Czaja *et al.* 2002).

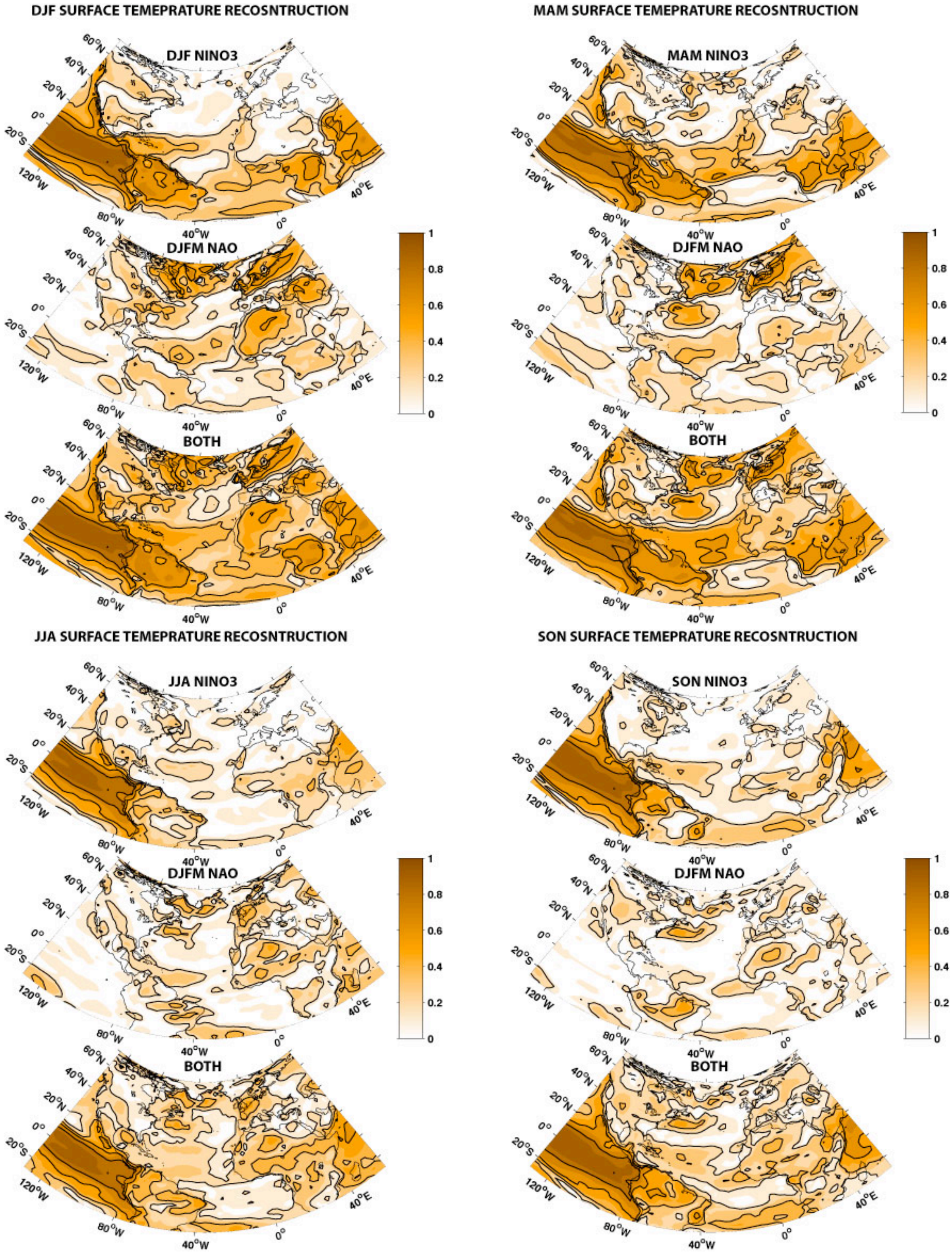

Figure 2.1: Correlation between observed and reconstructed seasonal surface temperatures. Reconstruction is based on a multiple regression with the winter NAO index and the same-season NINO3 index.

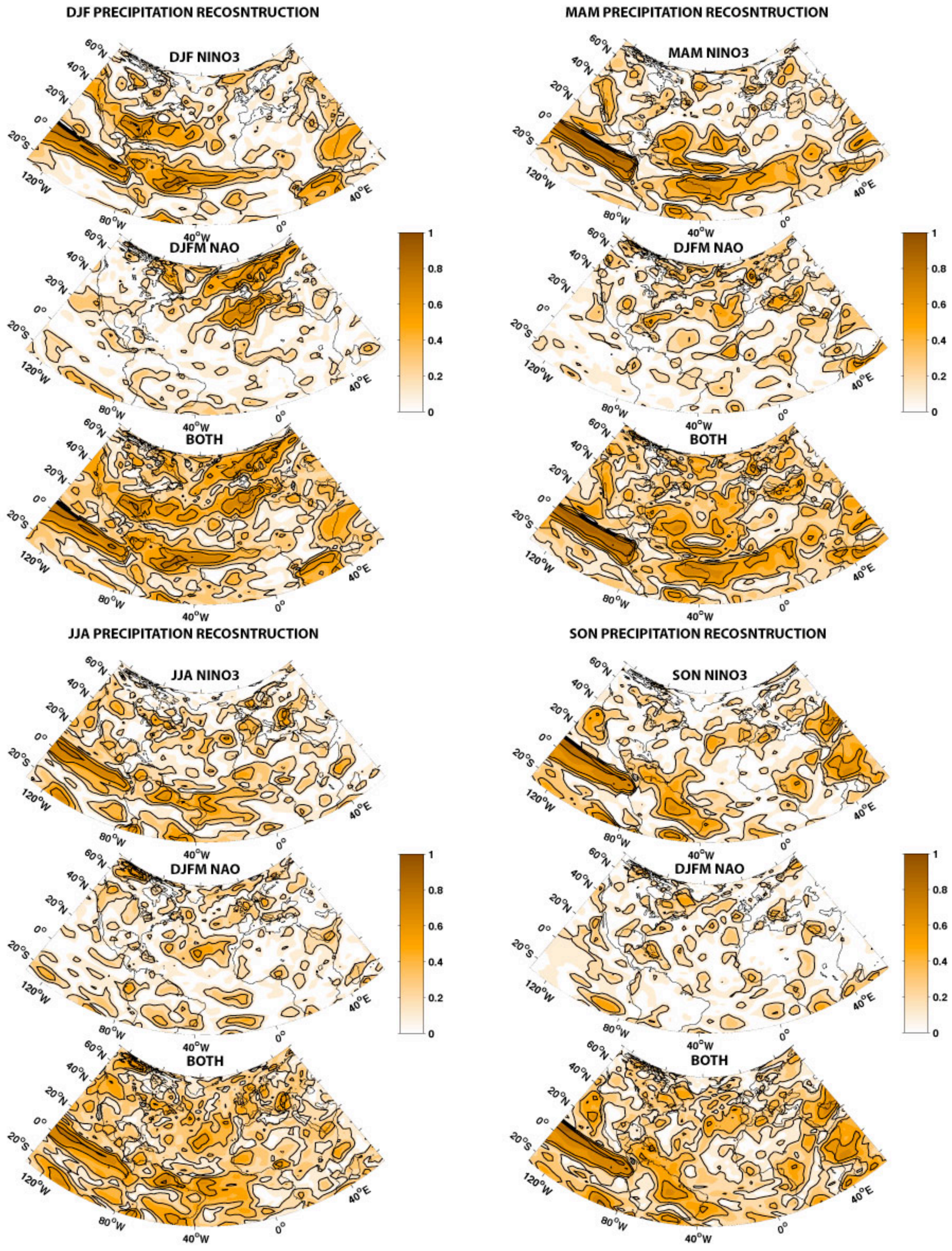

Figure 2.2: Correlation between observed and reconstructed seasonal precipitation. Reconstruction is based on a multiple regression with the winter NAO index and the same-season NINO3 index. Rainfall data are from NASA/GPCP 1980-2003. Contour interval is 0.2 (see text for further explanation).

The potential for predicting air temperature given perfect knowledge of the Niño3 index (SST in the region 90°W-150°W and 5°S-5°N, based on the Kaplan et al (1998) SST reconstruction) and the NAO index (based on the station index of Hurrell (1995)) is depicted in Figure 2.1. Here the monthly-averaged, 2-m above ground air temperature from the NCEP/NCAR reanalysis is used as a proxy for surface temperature. The temperature data are seasonally averaged, regressed on the observed indices between 1950 and 2003 (using multiple regression) and then reconstructed separately and jointly. The correlations shown are between the actual seasonal temperature anomaly and the reconstructed one, at every grid point. The reconstruction was done keeping the NAO index at its same-year boreal winter (December-March) value and the NINO3 index at its same-season value. Figure 2.2 shows a similar analysis but for rainfall. The data are taken from NASA/GPCP project, 1980-2003. It is important to note that the combination of indices and seasons used in this example is somewhat arbitrary and is not meant to be a comprehensive objective choice. By picking the wintertime NAO we account for the relatively large coherence displayed by this pattern during the boreal winter and the persistent imprint it leaves on surface fields, mainly the SST (Visbeck *et al.* 2002). In using the simultaneous NINO3 we recognize the long persistence and intrinsic predictability of that index. The overall impression from this analysis is that both indices are equally important over the Atlantic Sector but their regions of influence differ. Some of the main, and mostly unsurprising, features in these figures are the dominance of the El Niño influence over the tropics and subtropics and that of the NAO in the middle and high latitudes, on both sides of the Atlantic. El Niño is very important for tropical prediction. The NAO is also associated with boreal wintertime temperature anomalies over North Africa and the Middle East. El Niño is associated with significant rainfall anomalies over North America and the Atlantic and with weaker anomalies over Europe, mainly along the Mediterranean. In regions where large fractions of the variance are explained, the NAO and El Niño together account for between 20 and 40% of the variance in temperature and in precipitation in this linear analysis, with values reaching over 50% in the tropical rainfall. Temperature data are from NCEP/NCAR reanalysis, 1950-2003. Contour interval is 0.2 (see text for further explanation).

3.1 The physical nature of the NAO

On the large scales[1], seasonal and interannual predictability over the North Atlantic basin necessarily depends on our ability to forecast the dominant structures of climatic variability. Foremost among these is the North Atlantic Oscillation (NAO). The NAO is an equivalent barotropic seesaw in atmospheric pressure or geopotential height between middle latitudes and the sub-Arctic. In its positive phase it represents a poleward shift of the North Atlantic jet and its associated storm track (Fig. 3.1). While the NAO is typically considered a middle-to-high latitude pattern, it has a significant association with variability in the zonal winds well into the tropics. El Niño also influences the Atlantic basin (Fig. 3.1 bottom) with enhanced upper-level westerlies in low latitudes and bands of easterly and westerly anomalies nearly in meridional quadrature with the NAO pattern. Thus the direct influence of El Niño on the NAO is slight. The El Niño pattern over the Atlantic is approximately a superposition of a forced stationary Rossby wavetrain (Hoskins and Karoly 1981; Wallace and Gutzler 1981) and a more recently recognized zonally symmetric response to tropical warming (Seager *et al.* 2003).

Time series of the NAO are nearly indistinguishable from red noise, with a decorrelation time, during winter – the season of its greatest persistence – of less than ten days. Longer timescale behavior in the NAO can then be considered nothing more than the result of sampling time averages of a red-noise process – which offers little hope for extended range prediction – or it may be associated with behavior of the NAO that does not conform to the red-noise model. Here we focus on the possible mechanisms and potential utility for prediction of such deviations from red-noise behavior. We also review the evidence that such deviations do, indeed, exist. First, however, we place this in context by describing the basic atmospheric dynamics of the NAO.

The NAO is an intrinsic atmospheric structure. Its spatial scale is determined by the fact that it is a quasi-stationary structure – thus its Rossby-wave frequency must be approximately zero. That it shows little or no tilt with height insures that it does not lose its energy to vertical propagation. This does not, however, explain its persistence – typical tropospheric dissipation times are considerably shorter than 10 days (Klinker and Sardeshmukh 1992). There is plentiful evidence that this persistence is provided by reinforcing interactions with transient baroclinic

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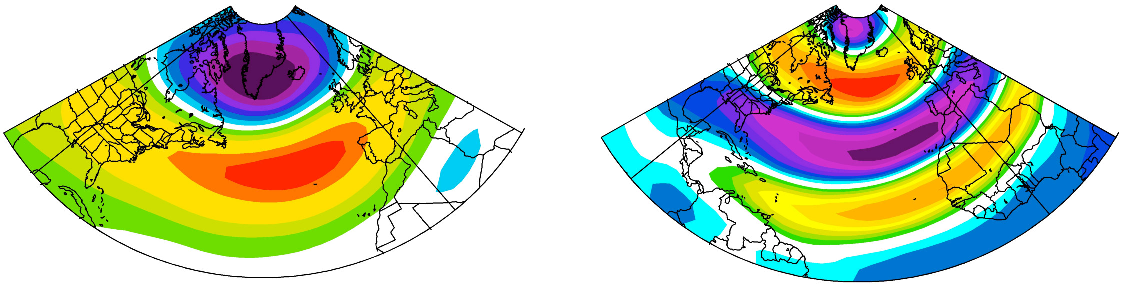
[1] Here we do not discuss the predictability of small-scale regional features, such as coastal anomalies, that may be due to localized regional features.

eddies in the storm track. In fact, an alternative description of the NAO is that it is a self-maintaining poleward or equatorward shift in the location of the eddy-driven extratropical jet and its associated stormtrack across the North Atlantic (Lee and Kim 2003). The closely related Arctic Oscillation, or Northern Annular Mode is just such a meridional shift of circumpolar extent.



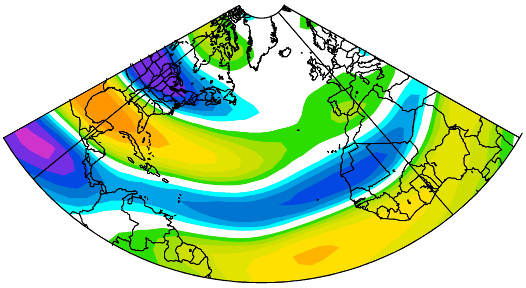


Figure 3.1 The NAO: DJF 500 hPa geopotential heights regressed on the CPC NAO indexed (contour interval =10 m) – top left, and correlated with 300 hPa zonal winds (contour interval = 0.1) – top right. The bottom panel shows the 300 hPA winds correlated with the Niño3 index. Calculated using on-line tools at the Climate Diagnostics center website (http://www.cdc.noaa.gov/Correlation/).

What is the source of the NAO? The simple, if unsatisfying, answer is that the NAO is excited by the chaotic dynamics of the atmosphere. It can arise from stochastically varying interactions with transient eddies. Such eddies systematically reinforce the NAO only in the average sense – most transient-eddy forcing of the NAO cannot be parameterized as a feedback. It can arise from variations in the climatological stationary waves (DeWeaver and Nigam 2000). It can evolve from remotely forced large-scale disturbances that “break” over the North Atlantic (Franzke *et al.* 2004). Given its many possible sources, none of which arise from processes that are predictable over longer times than those of conventional medium-range weather forecasting, and given its typical decay time on the order of ten days, it would appear that the prospects for seasonal and longer forecasting of the NAO are slight. Indeed, there is little physical basis for hoping to predict more than a small portion of the variability in the NAO more than a few weeks in advance. What potential does exist, however, derives from interactions of the troposphere with its more slowly evolving boundaries: the sea-surface, soil moisture, snow cover, and the stratosphere. These boundary forcings are all thought to be weak in their influence, however, in comparison with the robust intrinsic variability of the NAO. Thus, it should not be expected that any boundary influence would fix the NAO in one sign or another during an entire season. Rather, the best that can be hoped for is a small but persistent bias in the sign of the NAO. Even after averaging over a month or a season, most of the variability in the NAO is likely to be attributed to the stochastic variations that remain after performing a time average of a red-noise process - so-called “climate noise” (Feldstein 2000a, 2000b). In particular, it is misleading to denote climatic fluctuations associated with monthly or seasonal anomalies in the NAO as “potentially predictable.”

3.2 Intraseasonal persistence of the NAO

Before turning to mechanisms that can drive persistent anomalies, it is worth considering the evidence that such mechanisms are in operation. We begin by considering the month-to-month persistence of the NAO. Figure 3.2 shows the seasonal cycle of 1-month lag autocorrelation of the monthly mean NAO. These monthly means are projections on a rotated empirical orthogonal function of 500 hPa geopotential heights from the NCEP/NCAR reanalysis, obtained from the Climate Prediction Center (http://www.cpc.ncep.noaa.gov/data/teledoc/nao.html).

Is this what we expect from red noise? In some respects it is not. The relatively large values of persistence from January to February and from February to March imply either that the decorrelation time of the NAO is longer than ten days, or that the simple red-noise model is incomplete. It is readily shown that the correlation of successive averages of time interval *T* of a red-noise process with decorrelation time τ is given by,

$$Cor\left(\bar{x}(t),\bar{x}(t+\tau)\right)=\frac{\tau}{T}\frac{e^{-2T/\tau}}{\left[1-\frac{\tau}{T}\left(1-e^{-T/\tau}\right)\right]}. \qquad (1)$$

For a 10-day decorrelation time and consecutive 30-day means, we calculate a lag correlation of 0.22. Thus the wintertime values in Figure 3.2 are larger than expected from the daily red noise model, though it should be kept in mind that these "large" values suggest no more than 10% of the variability of the NAO in one month can be explained by its value in the previous month. The observed negative lag-correlations in spring are also inconsistent with the red-noise model. This springtime loss of persistence is a general feature of the Northern Hemisphere large-scale flow, first noted by (van den Dool and Livezey 1984).

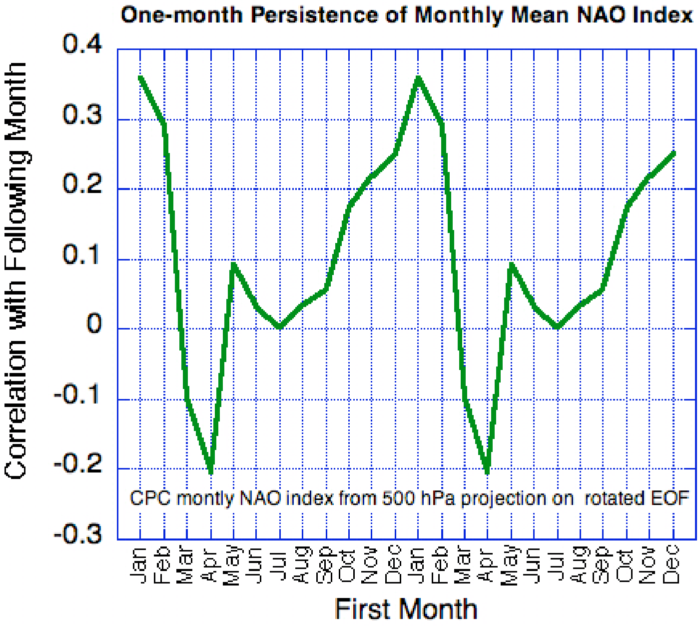


Figure 3.2: Month-to-month autocorrelations of the monthly mean CPC NAO index.

Daily data may also be examined to see if these are consistent with the red-noise hypothesis. Lag correlations for daily values of the NAO index, from the same source as before, are shown in Figure 3.3. In all seasons the correlations decay to values below 1/e in fewer than 10 days. In the winter, and to some extent in the fall, however, there is a "shoulder" in the lag correlations, a deviation from exponential decay such that correlations greater than expected from the red-noise model persist for lags a month or longer.

Thus, it appears something more than red noise is going on, offering hope for predictability on long timescales. A note of caution, however, is that longer records of the NAO based on station barometric records (e.g., Jones (1997)) suggest a weaker mid-winter maximum in persistence, though it is unclear if this results from the differing nature of the surface-based and 500 hPa-based indices, if it suggests that the 50 year CPC record is insufficiently long, or if it indicates a true trend towards increasing persistence in the NAO.

What are possible sources for the shoulder? The long thermal memory of the upper ocean is a prime candidate. Barsugli and Battisti (1998) provide a simple linear model useful for quantifying the role of the upper ocean in enhancing the persistence of atmospheric variability. Their model has two equations, one representing the evolution of atmospheric temperature, T_a, or an index of a mode of atmospheric variability, and the second representing the evolution of the ocean mixed-layer temperature, T_o, or the amplitude of a pattern of mixed-layer temperature that interacts with the atmospheric mode. The atmosphere is forced by noise, $N(t)$, associated with the chaotic variability of synoptic systems. There is dissipation in both fluids, and each influences the other. All dissipation and interactions are assumed linear. The resulting equations are:

$$\frac{dT_a}{dt} = -aT_a + bT_o + N(t),$$
$$\gamma\frac{dT_o}{dt} = cT_a - dT_o. \qquad (2)$$

With a non-dimensional unit of time equal to about five days, Barsugli and Battisti estimate that appropriate values for the dissipation and interaction parameters are,

d it decays approximately on the atmospheric dissipation time, $\tau_a = 1/a$. The second represents the quasi-steady atmospheric response to an anomaly in T_0, $\begin{pmatrix} T_a \\ T_o \end{pmatrix} \propto \begin{pmatrix} b/a \\ 1 \end{pmatrix}$, and it decays approximately on the ocean dissipation time, $\tau_o = \gamma/d$. Atmospheric forcing of the ocean, the c parameter, causes the first eigenvector, and thus the response to impulsive atmospheric forcing, to include a small response in the ocean, mixing the two eigenvectors.

Two examples of the response to atmospheric impulsive forcing are shown in Figure 3.4. The atmospheric curves also represent the expected lagged autocorrelations for the atmospheric index. Here the atmospheric damping parameter, *a*, has been reduced from Barsugli and Battisti's value to 0.6. This gives an initial exponential decay of the atmospheric index on a timescale of less than 10 days, consistent with wintertime observations of the NAO. In the case where there is no ocean feedback on the atmosphere, b=0, the exponential decay continues. When the ocean feedback is increased to the largest value at which the system remains stable, b=1.1, there is a "shoulder" in the atmospheric response, and significant persistence to the end of the month and beyond.

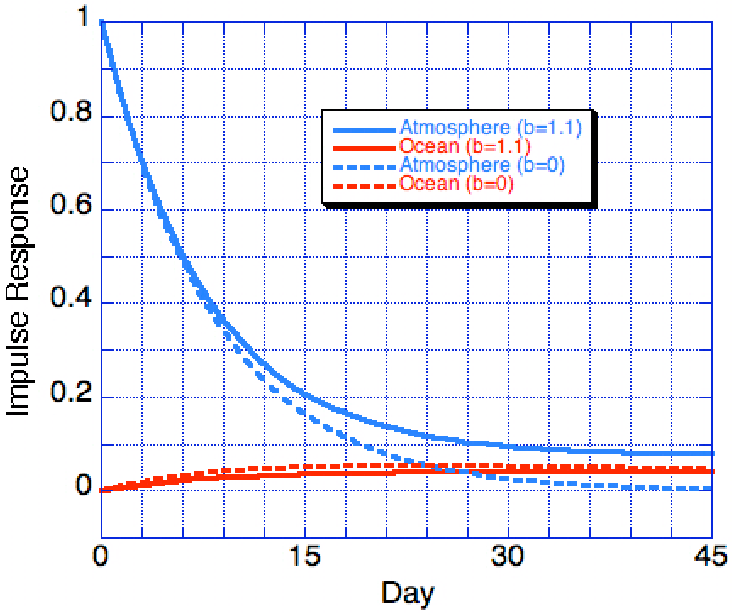


Figure 3.4: Impulse response of the Barsugli and Battisti model in the atmosphere and the ocean for two different values of the coupling parameter, *b*.

The shoulder, in the case with strong ocean feedback, gives rise to a significant increase in the one-month lag correlations of the atmospheric index, from 0.18 when b = 0, to 0.31, when b = 1.1. This greater value for the persistence is close to what is observed for the NAO in the winter. Thus it appears that the thermal memory of the ocean mixed layer could be responsible for the persistence of the NAO beyond the timescales of atmospheric dissipation. If so, this is "good news" for seasonal to interannual predictability, since it implies that there is a significant two-way interaction between the atmosphere and the ocean. Such an interaction could contribute to interseasonal or interannual predictability, if ocean temperature anomalies are, as suggested by observational and modeling studies, affected by re-emergence. That is, mixed layer temperature anomalies created during one cold season, then preserved beneath the shallow seasonal thermocline in the summertime "re-emerge" during the following cold season (Alexander and Deser 1995; Alexander *et al.* 1999).

Unfortunately, there are reasons to suspect that the ocean is not responsible for the NAO shoulder. To obtain a value of the persistence close to what is observed, the parameters must take on values that are probably unrealistic, because they are barely stable, and because they are quite different from the original values chosen by Barsugli and Battisti, based on the integration of a coupled model. Moreover, Bretherton and Battisti (2000) found that these original parameter settings yielded excellent agreement with the results of experiments in which the observed historical evolution of SSTs is used to drive large ensembles of atmospheric models. Secondly, the observed month-to-month variability in NAO persistence is hard to explain in terms of local interactions with the upper ocean, since the basic physics of the toy model should operate throughout the winter. Such month-to-month changes are more readily understood if the shoulder comes from the stratosphere (e.g. Baldwin (2003a), since there are distinct seasonal "windows" for robust stratosphere-troposphere interactions – those months when the stratospheric winds are westerly, but when the flow is sufficiently disturbed to permit strong variability.

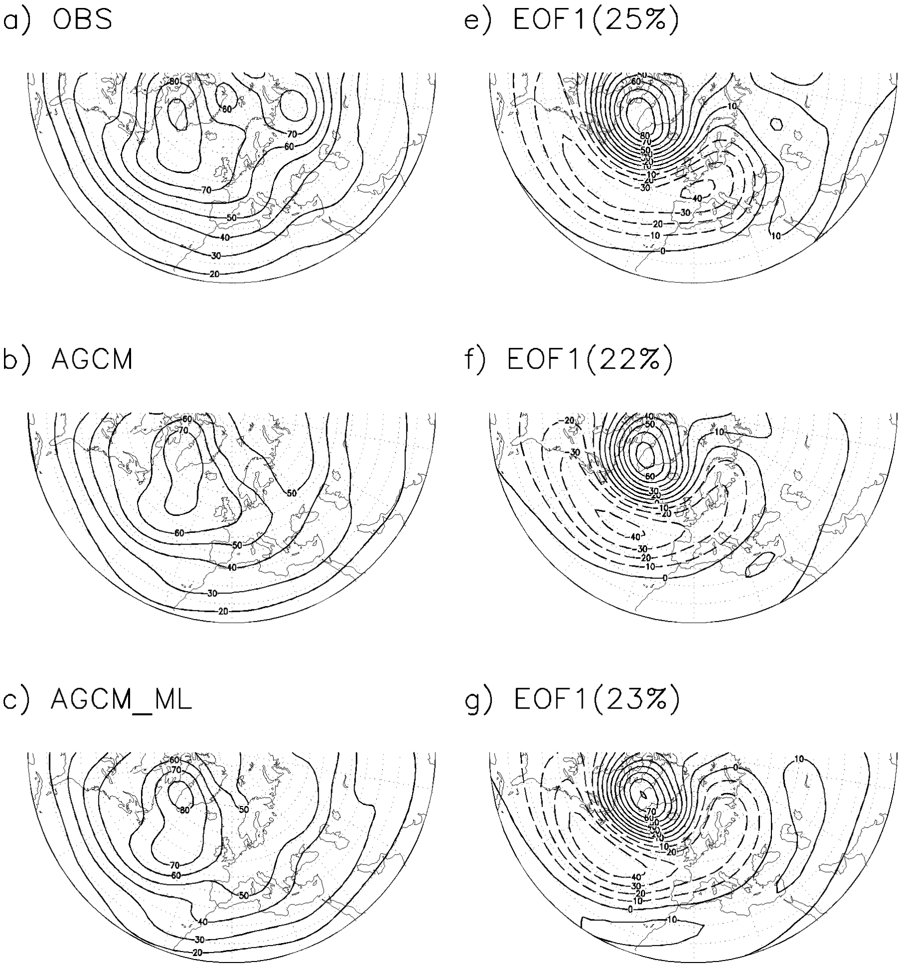


Figure 3.5: The standard deviation (left) and leading EOF of late winter (February-March-April) monthly mean, Atlantic sector 500 hPa heights in observations (a and e), in an atmospheric model with climatological SST (b and f) and the same atmospheric model coupled to a 50-meter slab ocean mixed layer (c and g). From Peng et al. (2004).

An atmospheric model, one that realistically reproduces the observed structure and variability of the NAO, does not show any increased persistence in the NAO when it is coupled to an ocean mixed layer. Figure 3.5 shows the leading EOF of 500 hPa heights in the Atlantic sector of a version of the U.S. National Center for Environmental Prediction medium range forecast model (Peng *et al.* 2004). The model's NAO pattern is very similar in the coupled (AGCM-ML) and uncoupled (AGCM) versions of this model, though the variability of monthly means is slightly stronger in the coupled model. The model greatly underestimates the month-to-persistence in the NAO, however (Figure 3.6), and there is only a small difference in the persistence of the NAO between the coupled and uncoupled models, even though the coupled model does produces a significantly greater variance in the NAO in mid winter. It should be noted that while this model has excellent vertical resolution in the troposphere, it does not have a well-resolved stratosphere. Unlike the GCM, the heuristic model of Barsugli and Battisti predicts that increased coupling will significantly enhance the persistence while only slightly increasing the variance. Bladé (1997), on the other hand, found that coupling with a mixed-layer model did, as expected, enhance the month-to-month persistence of the leading EOF of 500 hPa heights in her model. It is perhaps relevant, however, that her experiment was conducted in a perpetual January setting, while the Peng *et al.* model includes the seasonal cycle. It is possible that subtle month-to-month shifts in the preferred patterns of variability create a mismatch between the SST anomalies created in one month and the leading atmospheric pattern in the next.

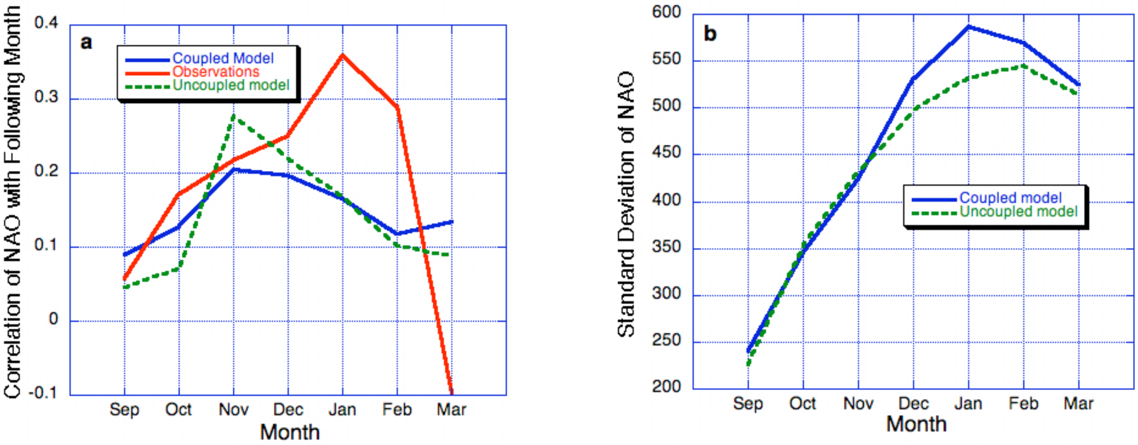


Figure 3.6: (a) Month-to-month persistence of the NAO in observations and in models coupled and uncoupled to an ocean mixed layer. (b) Standard deviation of the monthly mean NAO index in the coupled and uncoupled models.

3.3 Interannual persistence and predictability of the NAO

What are the possible sources of interseasonal to interannual predictability of the NAO?

- The underlying North Atlantic Ocean.
- Persistent or predictable elements of the stratospheric circulation.
- Persistent or predictable elements of the land surface – especially snow cover.
- Persistent or predictable behavior elsewhere in the climate system influencing the North Atlantic basin remotely.

Here we exclude the influence of climatic trends, such as anthropogenic global warming, that can contribute to the apparent predictability of interannual variability. From the list above, the first has received the most attention. Observationally, on the interseasonal timescale, the most convincing findings are those of Czaja and Frankignoul (2002). They used a lagged singular value decomposition (SVD) analysis between sea-surface temperatures (SST) and 500 hPa geopotential heights over the Atlantic to determine the patterns of heights and SST with the strongest association at a given lag. They find that an early winter (November-December-January) pattern in geopotential, which strongly resembles the negative NAO, is preceded in summer and fall by an SST pattern with two distinct components, an extratropical pattern with warm water in the midlatitude east Atlantic, spreading westward at higher and lower latitudes and enclosing a cold SST anomaly off the east coast of the United States – denoted the "North Atlantic Horseshoe" (NAH) – and a region of elevated SST near the equator extending westward from the Gulf of Guinea. The SST pattern simultaneous with the negative NAO, denoted the “tripole”, features alternating zonal bands of SST anomalies stretching nearly across the Atlantic – a warm anomaly stretching westward from the African coast between the Equator and 20 °N, a cold anomaly extending eastward from the North American coast between 25 and 45 °N, and again a warm anomaly north of 45 °N (the tripole and horseshoe patterns are shown in Figure 3.7). There is copious observational and modeling evidence that the tripole is primarily a result of atmospheric forcing of the SST field associated with the NAO, although models indicate that the “tripole” can also force the NAO (Seager *et al.* 2000; sutton *et al.* 2000; Peng *et al.* 2002; Lin and Derome 2003).

How might these SST patterns influence the NAO? It is implausible that the NAO “remembers” the SST from the preceding season. Rather, Czaja and Frankignoul suggest that the horseshoe pattern is contained within the tripole – inspection of Figure 3.7 indicates they have a significant spatial correlation – and that the NAO is a manifestation of the atmospheric response to the horseshoe, with the tripole then appearing as a result of the back influence of the NAO on the ocean. When this hypothesis was tested in model experiments (Peng *et al.,* 2004), however, it was found that the horseshoe was ineffective in forcing the NAO, at least in their one model. Conversely, Peng *et al.* found that the equatorial Atlantic SST anomaly does generate the NAO pattern in late winter. Moreover, they suggest that the evolution observed by Czaja and Frankignoul, of the horseshoe into the tripole, results from the evolution of the response to equatorial Atlantic SST anomalies. The atmospheric wavetrain response to such anomalies in the fall tends to produce the horseshoe, whereas in late winter, once transient eddy feedbacks become active, the equatorial SST anomalies generate the NAO, which, in turn, produces the tripole (Figure 3.8).

It remains unclear what these results imply for inter-seasonal prediction. Peng *et al*. forced their atmospheric model with an equatorial SST anomaly that persisted throughout the entire winter – clearly an exceptional evolution of the SST field. It could be hoped that the “tripole” generated through this atmospheric bridge from the equatorial Atlantic earlier in the winter could persist and then provide forcing of the NAO later in the winter – this would lead to predictability without requiring the equatorial anomaly to persist throughout the winter. While this is a possibility, Peng *et al.* found that the “tripole” SST anomalies produced in response to the equatorially forced NAO are on the order of only 0.5 °C. Given a typical model NAO response to the tripole of 20 m in 500 hPa geopotential height per degree “tripole” SST anomaly, this suggests that, at most, 10 m, 500 hPa heights, of interannual variability in the NAO, is predictable through this pathway, compared with observed interannual variations of more than 80 m is the northern lobe of the NAO (Figure 3.5).

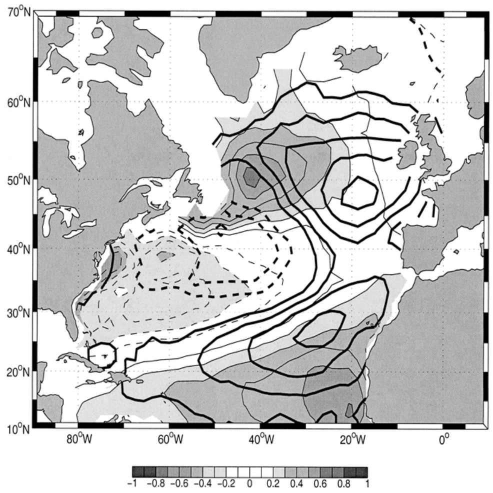


Figure 3.7: The tripole (shading) and horseshoe (contours at 0.1 K intervals) SST patterns, from Czaja and Frankignoul (2002).

“Interannual” prediction of the NAO, for current purposes, is defined as predictions made in one cold season for the following one, with an intervening summer. Focusing again on interactions with the underlying ocean, the physical basis for interannual predictability depends on the reappearance of SST anomalies generated during one winter at the beginning of the following one. This happens because the SST anomalies generated late in the winter are, during the summer, preserved in isolation from the surface beneath the seasonal thermocline. These SST anomalies then “reemerge” when atmospherically driven cooling and mixing destroys the seasonal thermocline at the beginning of the subsequent cold season (Alexander *et al.* 1999; Kushnir *et al.* 2002b). Once they reemerge, the SST anomalies exert some influence on the overlying atmosphere. This is the probable physical basis of “interannual” – really “late winter to early in the following winter” prediction schemes proposed by Rodwell (2002) and put into practice by the British Met Office (http://www.metoffice.gov.uk/research/seasonal/regional/nao/).

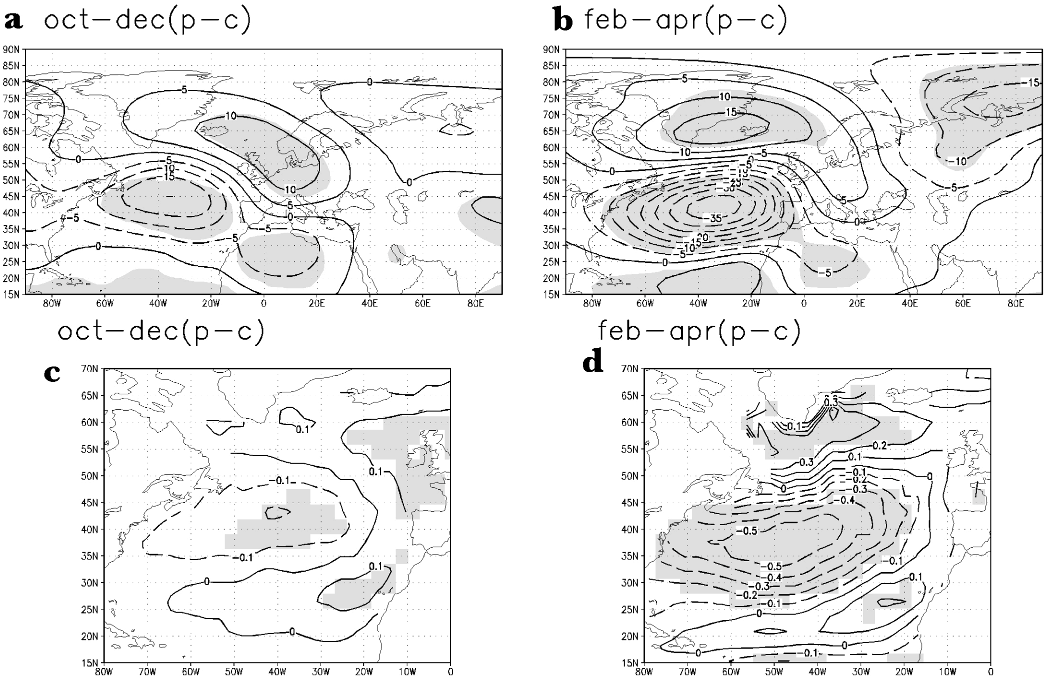


Figure 3.8: Early (left) and late (right) winter responses to a warm equatorial Atlantic SST anomaly in an atmospheric model coupled to an extratropical ocean mixed layer. The top panels show the 500-hPa geopotential response (contour interval of 5 m) and the lower panels show the SST response (contour interval of 0.1 K). From Peng *et al.* (2004).

If, as model results suggest, there is a positive feedback between the NAO and the “tripole”, then reemergence is expected to lead to interannual persistence of the NAO. How much interannual persistence should we expect? Once again, we use the heuristic model of Barsugli and Battisti to address this. We imagine that the ocean - represented by a single index denoting the strength of the “tripole” SST pattern – accumulates a value over the course of the first winter proportional to a weighted average of the NAO during that winter. This signal is then perfectly preserved over the summer and reemerges in the following winter, whereupon it decays exponentially on the mixed-layer timescale. As it decays, however, it induces an NAO response in the atmosphere. Under the assumption that atmospheric variability is primarily intrinsic (i.e. only a small portion is contributed at any time by the SST), then the correlation between the NAO averaged over a period, *T*, at the end of the first winter and the tripole index at the end of that period, is given by,

$$C\left(NAO_1,Tripole\right)=\left(1\square e^{\square\square T}\right)\Big/\sqrt{\square T},$$

where the mixed layer damping rate, *d*, is given by, $\square = d\big/\square$, and takes on a numerical value, according to Barsugli and Battisti, of 1/185 days^{-1}. The correlation between the tripole index at the beginning of the second winter and the average NAO is given by,

$$C\left(Tripole,NAO_2\right)=\frac{bc}{ad}\left(1\square e^{\square\square T}\right)\Big/\sqrt{\square T}.$$

The year-to-year correlation of the NAO is then,

$$C(NAO_1, NAO_2) = \frac{bc}{ad\square T}\left(1 \square e^{\square\square T}\right)^2.$$

For the standard values of parameters, and averaging the NAO over 3 months, this gives,

$$C(NAO_1, Tripole) = 0.55,$$
$$C(Tripole, NAO_2) = 0.23,$$
$$C(NAO_1, NAO_2) = 0.13.$$

How do these values compare with observations? Table 3.1 shows correlations of detrended three-month averages of the NAO between consecutive years.

Months	**NDJ_2**	**DJF_2**	**JFM_2**
NDJ_1	0.11	0.14	0.10
DJF_1	0.19	0.25	0.17
JFM_1	0.32	0.26	0.09

Table 3.1 – One-year lag autocorrelations of the NAO

Months	**NDJ**	**DJF**	**JFM**
M_1	0.29	0.26	0.38
N_2	0.35	0.10	0.03

Table 3.2 – Correlations of the NAO with the tripole index in the preceding November and following March.

The correlations between the subsequent years of NAO are greater than predicted by the simple model, while the correlation between the NAO and the tripole (Table 3.2) are smaller. Moreover, the tripole index is, unsurprisingly, not perfectly preserved from the end of one winter to the beginning of the next – the correlation of the tripole index between March of one year and November of the next is 0.70. These results may suggest only that SST patterns other than the Atlantic tripole provide year-to-year memory for the NAO. In this case, it implies that the standard Barsugli and Battisti parameters overestimate the strength of the local North Atlantic air-sea coupling. How then, was this model, with these parameters, successful in predicting the correlations between the observed and simulated NAO in general circulation model experiments (Bretherton and Battisti 2000)? A possible answer is that in the model experiments analyzed by Bretherton and Battisti, the observed time-varying SST fields were specified *globally*. Thus, it is possible that features of the SST field in regions other than the North Atlantic provide much of the year-to-year memory for the NAO. The assumption that a systematic relationship between the SST in the North Atlantic in one year and the NAO in the subsequent year is primarily a result of local air-sea interactions may be false.

Several pieces of evidence support a possibly important role for remote SST in providing the year-to-year memory in the NAO. Firstly, there is the negative evidence that a forecasting scheme (Rodwell and Folland 2002) predicated on such a local interaction, while appearing to perform credibly in hindcast mode has performed poorly, to date (see http://www.metoffice.gov.uk/research/seasonal/regional/nao/), in the skill of its actual forecasts, though, given the relatively modest skill expected from the hindcasts, this may indicate nothing more than "bad luck" over the five years of its application. Perhaps more convincing is the accumulating modeling evidence that tropical SST in the Atlantic (Robertson *et al.* 2000, Peng *et al.* 2004) and in the Indian Oceans (Hoerling *et al.* 2001; Hoerling *et al.* 2004) can have a significant influence on the NAO. Figure 3.9 (from Hoerling *et al.* 2001) shows the global SST pattern that simultaneously varies with the wintertime NAO, determined by a regression of the interannual variability in SST on the NAO over the last half of the 20th century. In the North Atlantic the tripole pattern is evident, presumably a result, primarily, of atmospheric forcing of the ocean. Elsewhere there are apparently significant anomalies in the equatorial Pacific and Indian Oceans, and in the Austral tropics in the Atlantic Ocean – the latter is the region considered by Robertson *et al.* (2000). The lower panel shows that an ensemble of atmospheric GCM runs forced by the observed time-varying SST field reproduces much of the observed association between the NAO and global SST. The relevance of these particular results to interannual prediction is, however, not entirely clear, since a severe (73-month) low-pass filter was applied to the data to obtain Fig. 3.9, and much of the "signal" it displays results from the trends over this period of warming climate and increasing NAO index (Hoerling *et al.*, 2004).

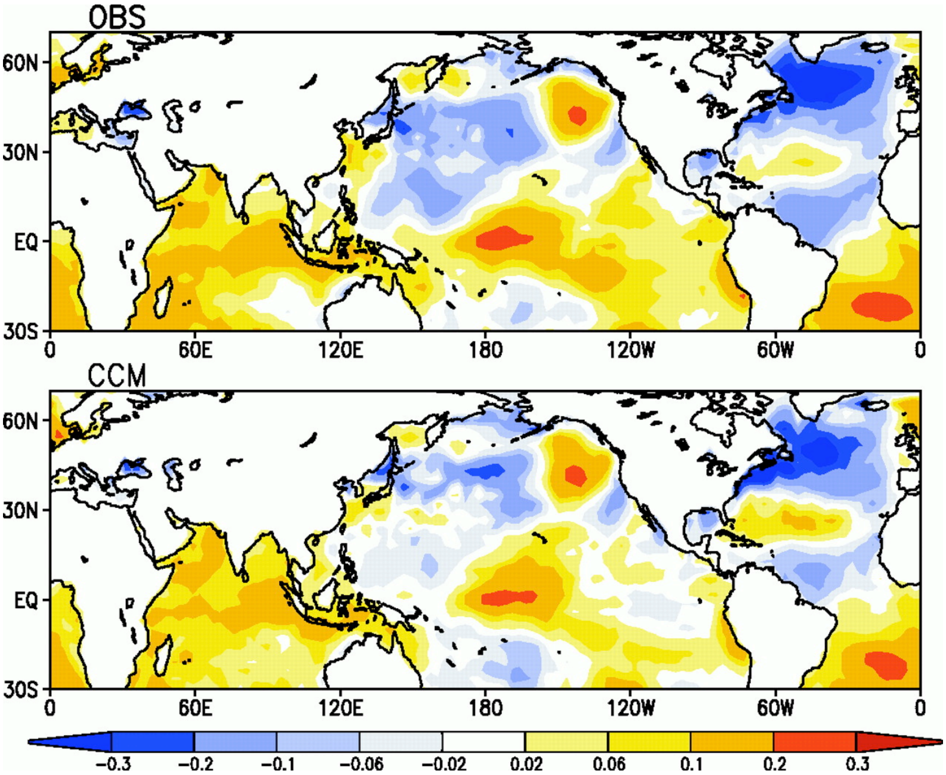


Figure 3.9: Linear regression of winter (December-January-February) SST (K) onto the low-pass filtered NAO index in observations (top) and a GCM (bottom). From Hoerling *et al.*, 2000.

Finally, a remote, presumably tropical, SST influence on the NAO could explain the otherwise perplexing finding by Eshel (2003) that certain patterns of surface barometric pressure anomalies over the North Pacific Ocean are useful predictors of the wintertime NAO at leads of up to 21 months. This result can be most readily understood physically if the atmosphere over the Pacific responds to some feature of SST that later in its systematic evolution forces the NAO. It should, however, be noted, that Eshel's scheme has not, to our knowledge, been tested in true forward forecast mode. Also, Eshel did not remove the trend from his data, so it possible that his results are contaminated by longterm trends in the NAO and in the global sea-level pressure field.

3.4 The role of the stratosphere

Evidence is accumulating that the strength of the boreal stratospheric polar vortex influences the tropospheric circulation on intraseasonal timescales, especially the Northern Annular Mode (NAM), which is well correlated with the NAO. Because the polar vortex exhibits dynamical memory over tens of days, such stratospheric influences can extend the persistence of the NAM or NAO (Baldwin *et al.* 2003b) during those months, mid to late winter, when there is strong dynamical coupling between the troposphere and stratosphere. Thus, the suggestion made earlier in this report, that the stratosphere is responsible for the "shoulder" in the lagged autocorrelation of the NAO. The dynamical mechanisms for this downward influence are not entirely understood (Kushner and Polvani 2004; Song and Robinson 2004), but presumably involve the downward closing secondary circulations induced by anomalous stratospheric wave driving (Haynes *et al.* 1991), altered planetary wave propagation (Chen and Robinson 1992; Limpasuvan and Hartmann 2000; Perlwitz and Harnik 2003), tropospheric transient eddy feedbacks (Song and Robinson), and possibly planetary-scale baroclinic waves (Tanaka and Tokinaga 2002).

The question is if, and if so, how, stratospheric influences are relevant to interseasonal forecasting. At first glace the prospect is gloomy, since the polar vortex is variable and coupled to the troposphere only during the winter, and the summertime reversal of stratospheric winds effectively "resets" the flow – memory within the stratosphere from one winter to the next is not expected. There are, however, phenomena through which the stratosphere may provide some interseasonal or interannual predictability. Foremost among these is the quasi-biennial oscillation (QBO) of the equatorial stratosphere. The QBO is unique among modes of atmospheric variability in that it is nearly periodic, and therefore predictable, without being driven by an astronomical periodicity – it is an internal nonlinear oscillation of the atmosphere, with an average period of about 28 months (Baldwin *et al.* 2001). The two pieces that comprise a possible QBO influence on the NAO are the influence of the polar vortex on the NAO, discussed above, and the influence of the QBO on the polar vortex. That the QBO does, indeed, influence the strength of the polar vortex was demonstrated by (Holton and Tan 1980). They found that the polar vortex is stronger when the equatorial stratospheric zonal winds are more westerly. They suggested a dynamical explanation for this correlation that was later confirmed in a numerical modeling study (O'Sullivan and Salby 1990). When the QBO winds are easterly, the critical line for quasi-stationary planetary Rossby waves shifts poleward. Through nonlinear critical-layer reflection this concentrates the planetary wave activity in high latitudes, leading to a weakening of the polar vortex. The opposite is true for the westerly phase of the QBO.

This provides a plausible physical link between the equatorial QBO and the NAO, but does observational evidence support such a connection? Figure 3.10 (from Baldwin *et al.* 2001) shows the difference in 1000 hPa geopotential heights between averages over QBO westerly and easterly winters. The composite shows the expected low heights over the Arctic and positive height anomalies in lower latitudes, with a significant projection on the NAO pattern. The contribution of the QBO to the interannual variability of the NAO is, however, modest. The correlation between the QBO (defined by 30 hPa equatorial zonal winds) and the December-January-February average of the NAO index over the period 1950-2000 (with the trend in the NAO removed) is 0.22 – the positive sign of the correlation being consistent with dynamical expectations and the composite of Figure 3.10.

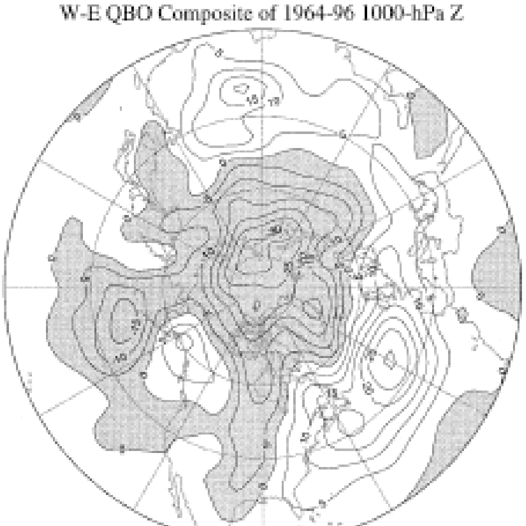


Figure 3.10: Difference in 1000 hPa geopotential height composites (5 m countours) between QBO westerly and easterly winters (December-January-February), from Baldwin *et al.* 2001.

Another phenomenon with significant predictive power for the NAO, albeit at rare intervals, is the occurrence of an explosive tropical volcanic eruption (Robock 2000), the best-studied case being that of Mt. Pinatubo in 1991. As for the QBO, volcanic eruptions affect the stratospheric polar vortex, and this influence is again transmitted downward dynamically to the NAO. The sulfate aerosol that forms in the stratosphere following an explosive eruption warms the low-latitude stratosphere by absorbing upwelling terrestrial infrared radiation and solar near infrared. Since there is less anomalous radiative heating of the polar winter stratosphere, the equator-to-pole temperature contrast is strengthened, thus strengthening the polar vortex. This leads to an enhancement of the NAO in the winters following an eruption. An interesting wrinkle on this (Stenchikov *et al.* 2004), at least in a general circulation model, is that the influence of the eruption combines nonlinearly with that of the QBO, so that the strengthening of the NAO in the winter following an eruption will be significantly greater if that winter is in the westerly phase of the QBO.

A final possible role for the stratosphere comes, surprisingly, in explaining the observed relationship between fall snow cover over Eurasia and the NAO in the following winter. It is observed (Cohen and Entekhabi 1999) that fall seasons with anomalously extensive snow cover in Eurasia are followed by winters with a positive NAO. While it might be expected that this was a manifestation of atmospheric persistence, or of an evolving influence from remote SST anomalies, in two recent papers (Gong *et al.* 2003; Gong *et al.* 2004) the case is made that Siberian snow-cover anomalies perturb the orographic generation of vertically propagating planetary waves, and thus influence the strength of the stratospheric polar vortex. As discussed earlier, however, influences from the stratosphere must act in the mid-to-late winter, not the fall. The thermal forcing associated with the snow cover anomalies does indeed persist through the winter in the Gong *et al.* general circulation model experiments, because they associated snow-cover anomalies with snow-depth anomalies, and the snow is added or removed over the course of the winter to maintain the anomalous snow depth. Thus, anomalous planetary-wave forcing associated with the resulting thermal anomaly acts over the course of the winter, when the dynamics permit both variations in the strength of the polar vortex and its subsequent downward influence. The question that must be addressed, in order to assess the practical relevance of the Gong *et al.* results, is whether, in nature, fall snow-cover anomalies lead predictably to significant wintertime anomalies in the surface thermal budget.

3.5 Summary

So, what is the likely interannual predictability of the wintertime (say December-January-February averaged) NAO? At present we can point to persistence from the previous winter to predict about 10% of the interannual variability and can gain perhaps another 5% or so from the QBO. The interannual persistence presumably results from a mixture of local and remote SST effects, with, as discussed above, a greater role for SST remote from the North Atlantic than has previously been appreciated. If these SST signals were better understood, especially the remote ones, perhaps they will provide a predictable evolution, not just persistence, of the NAO from year to year, and this may allow some additional variability to be predicted. Absent an increase in Earth's volcanism, however, we expect only a fifth of the year-to-year variability of the NAO to be predictable. Our community would be well advised to own up to the fact that the climate of the North Atlantic, and of Europe in particular, is dominated by a mode of climatic variability that is largely unpredictable. We can, perhaps, take comfort from the fact that recognizing the fundamental unpredictability of the atmosphere was arguably the greatest scientific achievement to emerge from our field in the past century (Lorenz 1963). The NAO is, above all, a feature intimately coupled to the chaotic dynamics of baroclinic systems and the storm track, and even when winter means are under consideration it must be kept in mind that "….most climatic elements, and certainly climatic means, are not predictable in the first sense at infinite range, since a non-periodic series cannot be made periodic through averaging" (Lorenz 1975). Forecasting the NAO is primarily an exercise in "prediction of the first kind." Such prediction is fundamentally limited by chaos, and chaos cannot be circumvented by choosing a prominent mode or by taking a seasonal average.

4. Climate predictability in the tropical Atlantic

4.1. The problem of TAV prediction

The most important signals of tropical Atlantic S/I climate variability are the variations in rainfall in the surrounding land regions and over the ocean, within the marine ITCZ. This variability is closely tied to two sources of forcing: El Niño and the anomalous distribution of SST within the tropical Atlantic (Chang *et al.* 2000; Saravanan and Chang 2000; Sutton *et al.* 2000). Other variables that affect society in this region are tropical storm activity, surface temperature, and lower-troposphere dust distribution (U.S. CLIVAR, 2003); these are also affected by El Niño and

Atlantic SST (Fontaine and Bigot 1993; Goldenberg and Shapiro 1996; Shapiro and Goldenberg 1998; Giannini *et al.* 2003b).

An illustration of how these two agents act to force TAV is shown in Figure 4.1. The figure displays a comparison between an observed and simulated index of Nordeste (in northeast Brazil) rainfall during boreal spring March-April-May (MAM, see also Figures 2.1 and 2.2). The atmospheric general circulation model used here is the Community Climate Model version 3.6.6 (CCM3) developed at the U.S. National Center for Atmospheric Research, Boulder, Colorado. When global SSTs from 1950 to 1994 are used to force the model (hereafter, Global Ocean-Global Atmosphere or GOGA experiment), the simulated rainfall index (red line) tracks closely the observed index (black line) and the correlation between the two is a rather high 0.76. When only tropical Pacific SST variability is specified, and SSTs in other ocean basins are kept at their climatological values (Pacific Ocean-Global Atmosphere or POGA experiment), the correlation between the observed and simulated indices (blue line) drops below 0.4, but when only tropical Atlantic SST variability is specified (Tropical Atlantic-Global Atmosphere or TAGA experiment), the correlation between the observed and simulated (green line), 0.65, is almost as high as in the GOGA experiment. This suggests that information on SST anomalies in the tropical Atlantic Ocean is crucial for seasonal climate forecasting in the region.

The reason for these results is that SST conditions in the tropical Atlantic depend on both local feedbacks and external influences from the tropical Pacific and other regions (Chang *et al.* 2000; Czaja *et al.* 2002). Therefore, while El Niño can affect TAV directly through an atmospheric bridge (Klein *et al.* 1999; Chiang and Sobel 2002) it also acts indirectly through interaction with local processes that modify tropical Atlantic SST (Chang *et al.* 2000; Chiang *et al.* 2002). In addition, climate variability that is generated in the extratropics also affects SST variability in the tropical Atlantic. Particularly important in this respect is the NAO, which forces SST variability in the subtropics with direct influence on the ITCZ, roughly in the same region affected by El Niño (Seager *et al.* 2000; Czaja *et al.* 2002; Visbeck *et al.* 2002). Thus, addressing the predictability of climate variability in the tropical Atlantic requires, in the first place, addressing the predictability of El Niño and the NAO. Lately, attention was also called to the importance to the tropics of climate variability originating from the Southern Hemisphere (Bareiro et al., submitted).

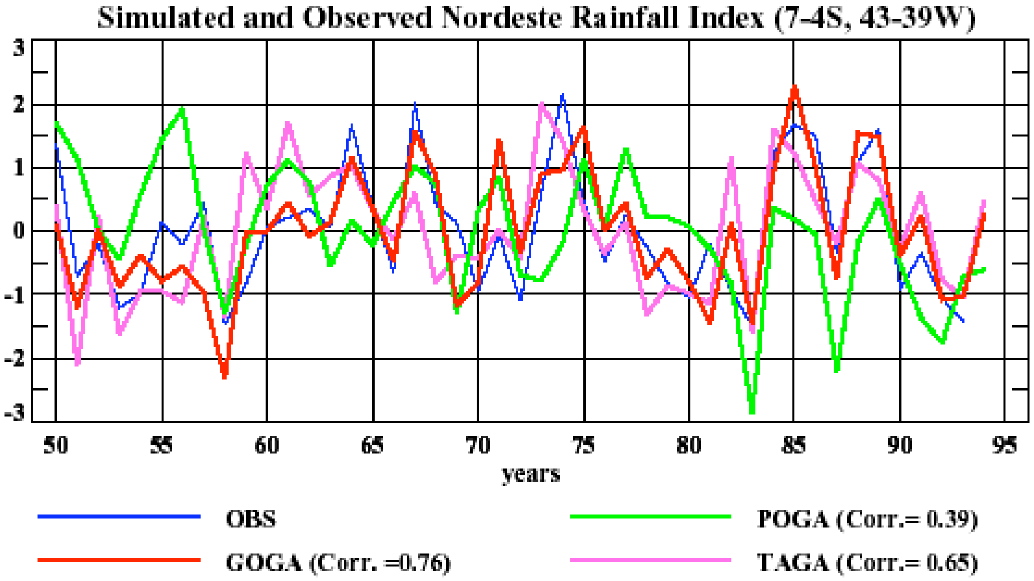


Figure 4.1: Simulated and observed NE Brazil rainfall index. Simulations are based on the CCM3 forced by observed SST in various ocean basins. Blue: Observation. Red: global SST. Green: Tropical Pacific-only SST. Magenta: Tropical Atlantic-only SST.

4.2 Patterns and mechanisms of tropical Atlantic SST variability

The complexity of ocean-atmosphere interaction dynamics in the tropical Atlantic is manifested in the multiple ways in which SST variability interacts with the atmosphere and this complexity affects the resulting climatic impacts. From the perspective of SST variability, we can identify two major patterns of variability with relevance for climate prediction hereafter referred to as the *gradient* and *equatorial* "modes" (Hastenrath 1978; Servain 1991; Ruiz-Barradas *et al.* 2000; Sutton *et al.* 2000).

The gradient mode:
This is a basin-wide pattern of interannual variability in the meridional temperature contrast between the Northern and Southern tradewind regions, recurrent during the boreal spring and early summer (Nobre and Shukla 1996). The pattern is often portrayed as a dipole, suggesting an out-of phase relationship between SST variability north and south of the equator (Servain 1991; Nobre and Shukla 1996). However, this appearance does not imply an instantaneous negative correlation (Houghton and Tourre 1992; Enfield *et al.* 1999) but rather that fluctuations in SST north and south of the equator can separately trigger a similar atmospheric response (Moura and Shukla 1981; Hastenrath 2002). The meridional SST gradient anomaly is statistically and dynamically coupled with an anomalous cross-equatorial circulation in the lower troposphere (Nobre and Shukla 1996; Ruiz-Barradas *et al.* 2000; Sutton *et al.* 2000). The pattern suggests the presence of a local interaction between SST, wind, and convection in the western equatorial Atlantic that affects the seasonal location of the marine ITCZ and climate along the northeastern seaboard of Brazil (Figure 4.2).

The interaction depicted by the gradient mode involves a positive feedback between the change in the surface wind circulation in the vicinity of the equator and the change in underlying SST (SST-wind-evaporation feedback). When a cross-equatorial, meridional wind anomaly arises in responds to the anomalous SST gradient, blowing in the direction of the warm anomaly, the related zonal wind anomaly, further away, is interacting with the prevailing trades to create changes in the windspeed that sustain the existing SST anomaly (Hastenrath 1984; Nobre and Shukla 1996; Kushnir *et al.* 2002a, see Figure 4.4). This wind-evaporation-SST (WES, see also Xie (1999)) feedback may affect the length of the rainy season in the semi-arid region of Northeast Brazil (Chang *et al.* 2000; Chiang *et al.* 2002).

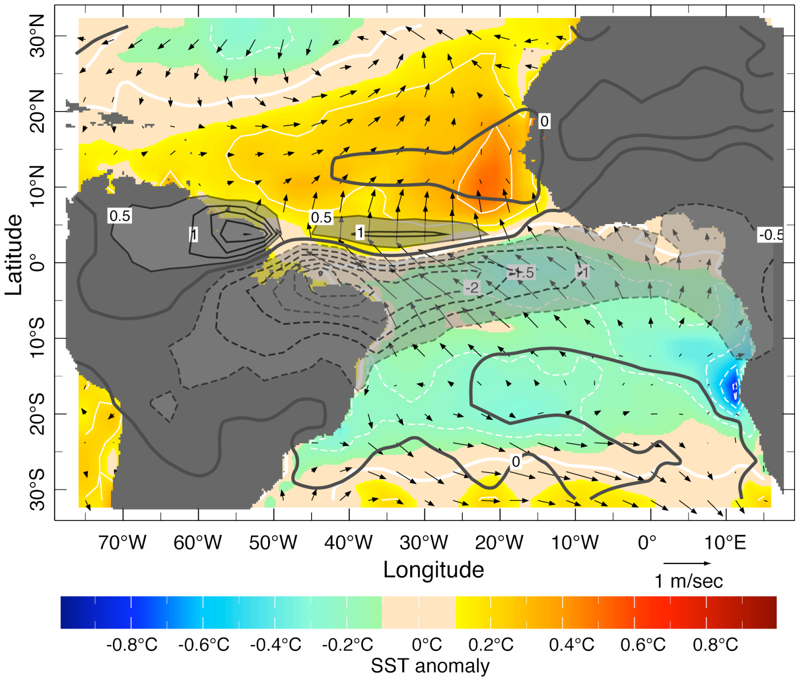


Figure 4.2: The tropical Atlantic gradient pattern – dominant pattern of surface ocean-atmosphere variability in the tropical Atlantic region during boreal spring. The black contours depict the first EOF of the regional March-April rainfall anomaly (from GPCP data, 1979-2001) in units of mm/day. This EOF explains 33% of the seasonal variance. The colored field is the March-April SST anomaly regressed on the principal component time series of the rainfall EOF (units are °C, see scale below; white contours every 0.2° are added for further clarity). Arrows depict the seasonal surface wind vector anomaly in m/sec, regressed on the same time series (see arrow scale below frame).

Observational and modeling evidence indicates that the gradient mode can be caused by atmospheric variability that originates outside of the tropical Atlantic region, primarily El Niño and the NAO (Enfield and Mayer 1997; Saravanan and Chang 2000; Chiang *et al.* 2002; Czaja *et al.* 2002). These remote influences can interfere with one another and with local feedbacks, affecting regional SST conditions, which in turn affect rainfall variability over northeast Brazil (Giannini *et al.* 2003a). El Niño's influence on the region is understood in terms of the atmospheric bridge created by the large perturbation in convective heating over the equatorial Pacific created by this phenomenon. This bridge takes two forms: a direct tropical influence related to the spreading of the Pacific tropospheric warming signal via tropical wave mechanisms and the related effect on tropical atmosphere stability and subsidence patterns (Klein *et al.* 1999; Hastenrath 2000; Saravanan and Chang 2000; Chiang *et al.* 2002; Chiang and Sobel 2002) and an indirect influence through the extratropical wavetrain response to El Niño known as the Pacific North American (PNA) pattern (Horel and Wallace 1981; Saravanan and Chang 2000), which influences the strength of the North Atlantic trades and – through turbulent heat flux exchange with the ocean – the underlying SST. Of these two effects, the direct response seems to act more quickly and is noticed earlier in the season (Saravanan and Chang 2000; Chiang *et al.* 2002). The NAO affects the gradient mode through its direct link to the strength of the Northern Hemisphere trades during winter (Hurrell *et al.* 2002).

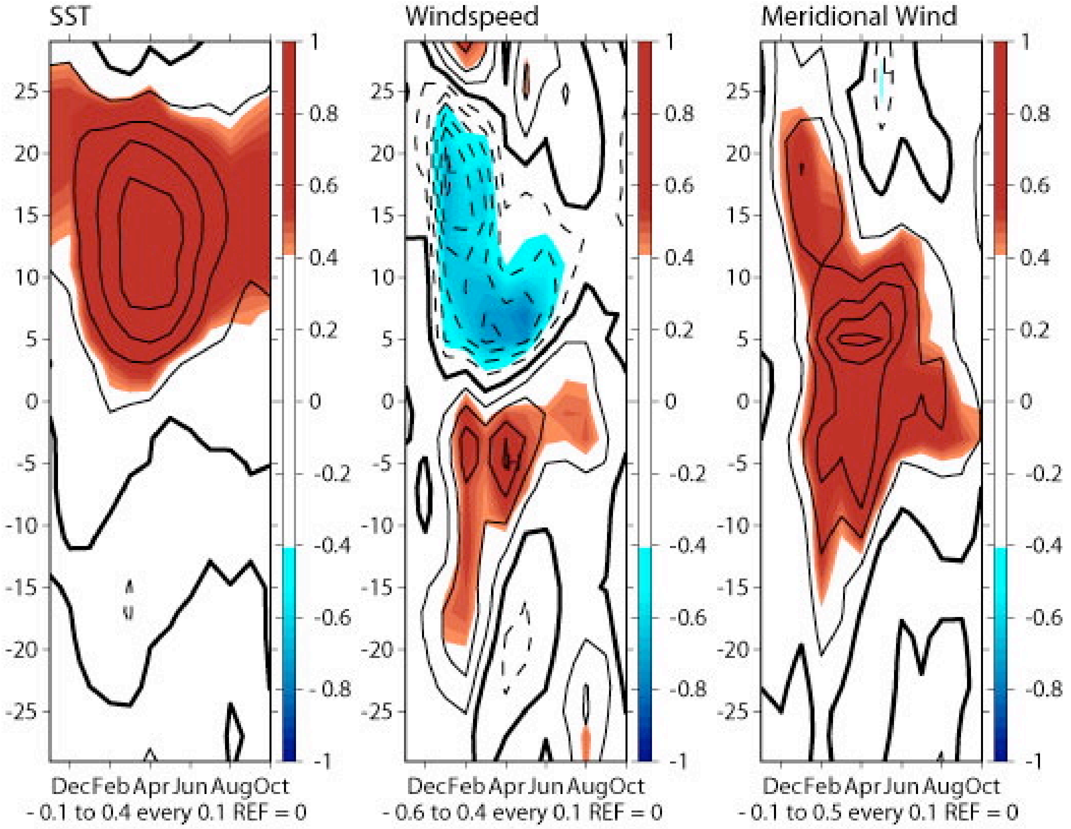


Figure 4.3: Combined EOF of SST, surface windspeed and surface meridional wind averaged over longitude, across the Atlantic Ocean. The analysis is performed after stratifying annual anomalies of the variables by latitude and calendar month, with time varying from 1965 to 2001 (see Kushnir et al., 2002 for further details). Color shaded regions indicate the correlation (significant values only) between the EOF time series and the related field.

The role of ocean dynamics in regulating tropical Atlantic SST anomalies associated with the gradient mode is less well resolved. A number of recent modeling studies (Chang *et al.* 2001; Seager *et al.* 2001) suggest that meridional ocean heat transport associated with the mean circulation in the tropical Atlantic tends to counteract the near-equatorial positive WES feedback, and weakens the anomalous cross-equatorial SST gradient of the boreal spring. But the importance of upper-ocean processes in the interannual variability of the gradient mode is unknown.

The equatorial mode:
This is a pattern of a largely equatorial SST anomaly coupled with an equatorial trade wind anomaly, which peaks in the boreal summer and into the fall (Figure 4.4). The equatorial mode (Zebiak 1993; Carton and Huang 1994; Ruiz-Barradas *et al.* 2000) bears a certain resemblance to the eastern equatorial Pacific expression of the El Niño – Southern Oscillation phenomenon. As in the Pacific, the Atlantic equatorial mode is associated with an SST anomaly in the cold-tongue region (Ruiz-Barradas *et al.* 2000) (see also Figure 4.5). Closely linked with this pattern are precipitation anomalies just south of the mean position of the summertime marine ITCZ (indicating an intensification and a slight shift towards the warm water) and along the coast of the Gulf of Guinea. The surface wind anomaly displays a convergence towards the anomalously warm patch in the eastern equatorial Atlantic.

In the Pacific, the phenomenon is explained primarily by the Bjerkne mechanism, in which upper-ocean wave dynamics changes the depth of the thermocline to affect the SST field, which interacts positively with a direct, baroclinic atmospheric response to create a growing disturbance with quasi-periodic regularity (Bjerknes 1966). It is possible, that a similar mechanism is responsible for the Atlantic equatorial mode. However, the detailed dynamics of the equatorial mode is still poorly understood, particularly with respect to the associated subsurface ocean processes and its connection with the remote influence of ENSO. The forecast skill of this phenomenon in coupled models is dismally low for reasons that remain to be resolved.

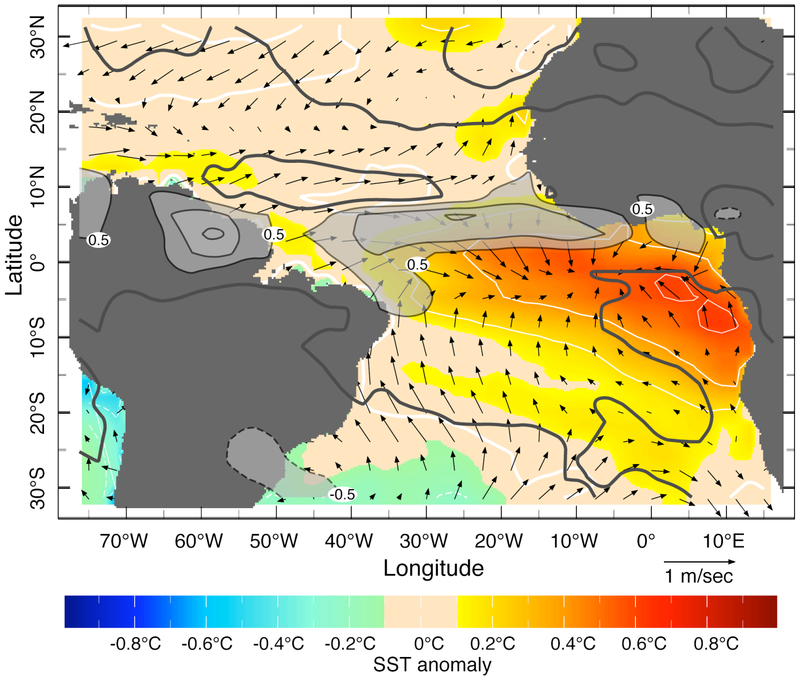


Figure 4.4: As in Figure 4.2 but for the boreal summer season (June-August). The rainfall EOF of this season explains 23% of the variance

The two tropical Atlantic modes are not necessarily independent of one another. Recent studies find a connection between them in ocean observations of the last 20 years and in an ocean model based on forcing data from the same period (Servain *et al.* 1999; Servain *et al.* 2000). This relationship appears however to be absent during the 1950s to 1970s (Murtugudde *et al.* 2001).

4.3 Predictability of TAV

As it turns out, and despite our general understanding of local and remote processes, our current ability to forecast tropical Atlantic SST anomalies is limited. This is partly due to the influence of forcing from the largely unpredictable extratropical variability, such as the NAO (see

Section 3), and partly due to the fact that the dynamics governing SST variability is complex and poorly understood. A third source of difficulty is the inability of the present generation of coupled global models to correctly simulate the underlying climate of the tropical Atlantic region (Davey *et al.* 2002).

An analysis of the effect of SST specification errors on the errors in rainfall prediction within the tropical Atlantic region in the context of a two-tiered prediction system is provided by Goddard and Mason (2002). The key figure from this study (Figure 4.5) shows the boreal spring and summer rainfall error pattern and the associated SST specification error resulting from assuming persistence of SST in a seasonal forecast with one season time lead. The errors in predicted spring rainfall are largest over northeastern Brazil and are linked with an error in specifying the SST gradient across the equator. In the summer, the precipitation forecast errors are largest over West Africa and are linked with an error in specifying SST along the equator.

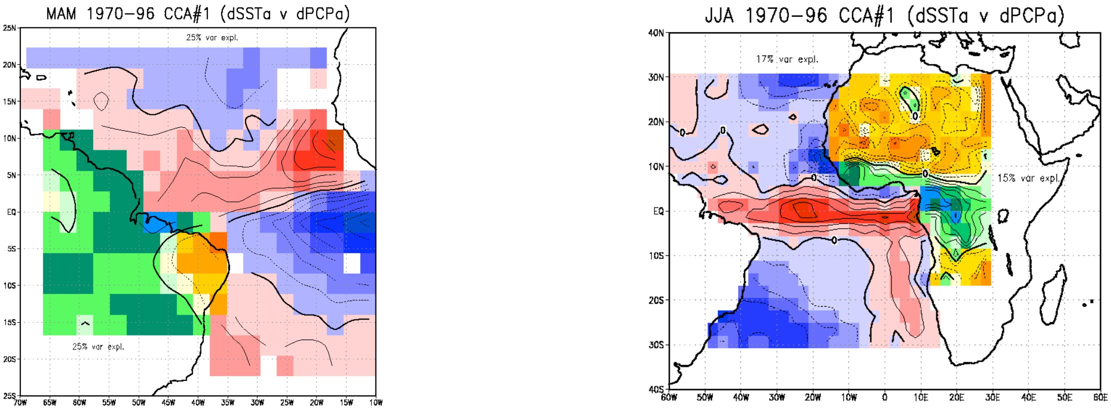


Figure 4.5: The dominant patterns of precipitation errors (over land) and their associated pattern of SST anomaly error for March-May (left) and June-August in a three month lead prediction with an atmospheric GCM forced with specified SST derived under the assumption of persistence. The experiment was performed for the years 1970–1996. The SST error is defined as the observed MAM (or JJA) SST – persisted February (or May) SST; the precipitation error is defined as the simulated precipitation – precipitation calculated with observed SST. Red/blue are for positive/negative SST error and green/yellow are for positive/negative precipitation error. Contour interval is 0.1 for both SST and precipitation patterns in relative (normalized) units (from Goddard and Mason, 2002).

There is a clear link between the error patterns in Figure 4.5 and the patterns of TAV described in the previous section. This is not surprising. The errors in rainfall are due to errors in correctly predicting the underlying dominant patterns of SST variability, which can be viewed as forcing the location and intensity of the marine ITCZ and its influences over the African and South American seaboards. The obstacle to prediction of rainfall in the tropical Atlantic can thus be linked to our ability to predict SST in the basin, as also supported by Figure 4.1. This however is a somewhat simplified view of regional processes that display evidence for coupled behavior in the form of thermodynamical and dynamical positive feedbacks. Such are the WES feedbacks in the western equatorial Atlantic during the boreal spring and the plausible Bjerknes feedback in the east during the summer. The presence of such feedbacks calls for the use of coupled models for prediction.

The thermodynamic feedback and the remote influence of El Niño are the two dominant factors affecting the predictability of TAV during the boreal winter and early spring – the time of year associated with the onset of the meridional mode. To first order, these processes can be captured with an atmospheric GCM coupled to a slab ocean and forced with Pacific SST anomalies. Missing in this approach is a way to incorporate the largely unpredictable effect of the Atlantic extratropics, north (e.g., NAO) and south of the equator. Chang *et al.* (2004) adopted such a model strategy. They conducted two sets of seasonal forecast experiments. In the first the mixed layer ocean was initialized with observed December SST everywhere in the global ocean (hereafter Global Initial Condition or GIC experiment) and the coupled model was integrated forward for 9 months. The experiment was conducted year-by-year over the 42-year interval 1959 to 2000 repeating each year's "hindcast" ten times, each starting with a slightly different initial December atmospheric state taken from the NCEP/NCAR reanalysis. The second set of experiments was identical to the first except that the observed SSTs used to initialize the mixed layer ocean were limited to the Atlantic Ocean only, between 30°S and 60°N (hereafter Atlantic Initial Condition or AIC experiment). In the latter set of runs, the SST anomalies were set to zero everywhere outside the Atlantic domain. The purpose of the second set of experiments was to examine the extent to which the predictability can be captured by the thermodynamic feedback between the atmosphere and the mixed layer ocean within the Atlantic basin in the absence of external forcing (El Niño in particular).

When validating the ensemble mean predictions against the observed SST, Chang *et al.* found that the coupled model has considerable skill in forecasting the SST anomaly in the tropical Atlantic during boreal spring. Off-equatorial SST anomalies, particularly those in the tropical north Atlantic, can be predicted two seasons in advance by the coupled model with a high degree of skill. Even in the absence of the remote El Niño influence (AIC experiment), the model skill is considerably superior to the skill of assuming the persistence of SST anomalies in that region.

Saravanan and Chang (2004) took a closer look at the role of thermodynamic air-sea feedback. They examined two thermodynamic feedback mechanisms: the reduced thermal damping mechanism (e.g., Barsugli and Battisti (2000)) and the WES feedback. The results show that thermodynamic coupling leads to amplification and increased persistence of surface wind variability in the deep tropical Atlantic. This effect is anisotropic, being stronger in the meridional component than in the zonal component of the surface wind. Since these features cannot be explained by the isotropic reduced thermal damping mechanism, it suggests that the WES feedback plays in an important role in enhancing the model's prediction skill, contributing to forecasts of north tropical Atlantic SST that are significantly better than persistence forecasts during the boreal spring.

4.4 A few comments on South Atlantic climate variability

There is emerging interest and research on the predictability of seasonal to interannual variability in the South Atlantic (SA). Variability over the tropical Atlantic has strong ties to the SA. The meteorological equator over the Atlantic, as given by the latitude of the ITCZ, is mostly north of 0^{o}N, so that the equatorial mode of TAV naturally belongs to the SA, bounded to the north by West Africa; a landmass with no counterpart in the eastern Pacific. The zonal mode extends southward along the Lower Guinea Coast where it represents fluctuations in the strength of the seasonal cold tongue. These are often dubbed "Bengula Niños," and play an important role in interannual precipitation variations over Africa. The potential influence of tropical SE Atlantic SSTs on Angolan and Namibian rainfall has been studied by Hirst and Hastenrath (1983) and Nicholson and Entekhabi (1987). More recently, Rouault *et al.* (Rouault *et al.* 2002) have drawn attention to the influence of SE Atlantic warm events on not just the coastal rainfall of tropical southwestern Africa but also, on occasion, over a much larger region of southern Africa. The southern pole of the gradient mode of TAV, located over the SA, appears to play an important preconditioning role on the impact of ENSO on NE Brazil rainfall during the February–May rainy season (Giannini, personal communication). Without a counterpart to the vigorous but relatively unpredictable wintertime NAO during December–February, the SA is relatively quiescent and thus has the potential to play a more-predictable preconditioning role on NE Brazil rainfall anomalies.

Ocean-atmosphere interaction over the subtropical SA is dominated by variability in the strength and position of the subtropical (St. Helena) anticyclone, together with dipolar SST anomalies with a nodal line near 30^{o}S (Venegas *et al.* 1997). The variability of SST tends to peak in austral summer–fall, with a red spectrum and a peak near 15 years (Venegas *et al.* 1997). Evidence, both observational (Venegas *et al.* 1997; Sterl and Hazeleger 2003), and from models (Haarsma *et al.* 2003), indicates that anomalous winds generate the SST pattern through anomalous latent heat fluxes as well as mixed-layer deepening. Anomalous Ekman transports appear to play a secondary role. There is observational evidence that this mode of covariability influences the equatorial mode during the austral winter (Robertson and Mechoso 2003), and the gradient mode during the austral fall (Barreiro *et al.* 2004). Coupled GCMs show analogous influence of the SA on TAV (Huang and Shukla 2004).

The SW South Atlantic atmosphere and ocean are characterized by important zones of convergence: the SA Convergence Zone (SACZ) in the atmosphere (near 20°S) is a major feature of the South American summer monsoon system, while the southward-flowing Brazil current meets the northward-flowing Malvinas current near 40°S in the Brazil-Malvinas Confluence Zone (BMCZ). The latter is one of the most turbulent regions of the global oceans in terms of mesoscale ocean eddies, but its influence on the atmosphere is not well documented. The SACZ is characterized by strong intrinsic variability on sub-seasonal timescales that projects onto the interannual timescale as "climate noise". Variability of the SACZ in the atmosphere is also linked to the SA (both show a strong interdecadal component), where again the dominant influence is of the atmosphere forcing the ocean (Barreiro *et al.* 2002; Robertson and Mechoso 2003). However, the South Pacific exerts a strong influence on the SACZ through the Pacific-South American (PSA) teleconnection patterns (Mo and Paegle 2001). ENSO influences the SACZ during austral spring (Cazes-Boezio *et al.* 2003), and may influence the SW Atlantic through this mechanism (Mo and Hakkinen 2001).

5. Conclusions

A broad-brush view of large-scale S/I climate anomalies in the Atlantic suggests that they can be divided into three types: internal to the basin are extratropical fluctuations driven by atmospheric chaotic dynamics that is to first order insensitive to surface anomalies and tropical variability where the atmosphere is sensitive, even coupled, to surface conditions, particularly SST variability, and is thus potentially predictable. The third kind are anomalies forced from outside the Basin, particularly from the equatorial Pacific.

In seeking to advance Atlantic Basin climate prediction in the extratropical regions, future research should focus on better quantifying and understanding the apparent marginal persistence of monthly and seasonal anomalies. Here we indicated the larger than expected (on the basis of relatively simple autoregressive models) NAO persistence during the winter season and the weak sensitivity of the lower troposphere to surface conditions (SST and soil moisture/cover) during the other seasons, particularly summer. While small, this marginal predictability can be useful to certain end users. The challenge in making forecasts of such variability is to prove that they are reliable. In addressing this problem it should be noted that the marginal "predictability" of extratropical S/I variability may be linked with more predictable decadal variations, including trends due to external (tropical) forcing and not only to intra-seasonal processes.

In the tropics the potentially predictable signal is large compared to the chaotic variability. Thus breakthroughs in tropical Atlantic climate prediction will be of high value to a broad range of social activities – from agriculture to water resources and to health and to the overall safety and well being of society. Future research should focus on developing better coupled models or new coupling strategies that can overcome the limitations of the present models in tracking the combined evolution of the atmosphere and the ocean.

Continued improvement of ENSO prediction methodology is clearly important to the cause of advancing Atlantic Sector prediction. Not enough is known on the interplay between local conditions and the remote forcing: how does it depend on the intensity of the remote forcing and the season? In the particular case of the tropical Atlantic, the influence from the relatively unpredictable extratropical dynamics can be thought of as an external source of variability, interfering with the more predictable ENSO influence. Better understanding of this interference is warranted.

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The Physical Basis for Prediction of Atlantic Sector Climate on Decadal Timescales

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This white paper discusses the physical basis and the potential for decadal climate predictability over the Atlantic and its adjacent land areas. Many observational and modelling studies describe pronounced decadal and multidecadal variability in the Atlantic Ocean. However, it needs still to be quantified to which extent the variations in the ocean drive variations in the atmosphere and over land. In particular, although a clear impact of the Tropics on the Midlatitudes has been demonstrated, it is unclear if and how the extra-tropical atmosphere responds to midlatitudinal sea surface temperature anomalies. Recent studies, however, indicate that there is indeed a discernable impact of the midlatitudinal ocean on the atmosphere at decadal timescales.

Although the mechanisms behind the decadal to multidecadal variability in the Atlantic Sector are still controversial, there is some consensus that the longer-term multidecadal variability is driven by variations in the thermohaline circulation. The variations in the thermohaline circulation appear to be predictable one to two decades ahead, as shown by a number of perfect model predictability experiments. The next few decades will be dominated by these multidecadal variations, although the effects of anthropogenic climate change are likely to introduce trends. A clear impact of the variations of the thermohaline circulation on the atmosphere can be demonstrated, so that useful decadal predictions with economic benefit are in reach.

1. Introduction

Over the last twenty years we have seen major developments in seasonal forecasting, and now many centers around the world routinely make seasonal forecasts. The success of these efforts is largely based on the predictability of the El Niño Southern Oscillation (ENSO) phenomenon, and in our ability to capture it in our models and statistical schemes. Process studies, observations and simple models have played a central role in the development of seasonal forecasting and have lead to the design and implementation of the TOGA/TAO observational array (McPhaden et al. 1998) which is integral in monitoring and prediction.

In contrast to seasonal forecasting, decadal to multidecadal climate predictions are at an infant stage[2]. Nonetheless, there are many things that can be learned from seasonal forecasting experience. Paramount among these is the recognition that better understanding of the physical mechanisms involved and better monitoring systems are needed for advances to be made. In terms of understanding decadal variability, we are handicapped much more significantly by a lack of adequate data, and we shall have to wait much longer to get it. Thus, in decadal variability studies there has been a heavy reliance on models. But models do not always agree with each other or with observations, and thus while models have been helpful in identifying possible mechanisms, the true mechanisms for decadal variability are still not known. However in this respect, observations can play a crucial role: They can be used to reduce model uncertainties, through improvements in model physics, especially those aspects believed important to decadal and multidecadal timescales, and on which models disagree.

As with seasonal forecasting, decadal to multidecadal climate prediction are of economic, political and public interest. Their value lies in planning the future in all fields that depend on

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[2] The term "decadal to multidecadal" is a rather loose definition of time scales usually covering anything from a few years to a few centuries. While this is somewhat inadequate, it pervades the literature and is used liberally in meetings and at conferences. Hence we accept its use in this paper and, when specific studies are quoted, every effort is made to be specific about the time scales and averaging periods used.

climate to some degree. This includes for example the choice of agricultural species, insurance fees, plans of infrastructure, the energy sector, or simply the diameter of gutters. Unlike seasonal forecasting, the relevant periods are longer than a single political reign, and anthropogenic forcing of climate becomes an issue.

This paper is organized as follows. We start in section 2 with a brief description of the global patterns of decadal predictability. In section 3, we describe briefly some observations of the decadal to multidecadal variability in the Atlantic sector. We discuss in section 4 what is known about the mechanisms that lead to climate variability in the Atlantic sector at decadal to multidecadal timescales, and in section 5 to which extent it can be predicted. Section 6 deals with ensemble prediction techniques. In section 7 the interference of the internal variability with anthropogenic climate change is discussed. The conclusions of this paper are presented in section 8.

2. Global pattern of decadal to multidecadal predictability

In this section we examine the global pattern of decadal predictability as found in potential (diagnostic) and classical (prognostic) predictability studies, which are two common methods for estimating decadal predictability. Decadal potential predictability is defined as the ratio of the variance on the decadal timescales to the total variance (Boer 2000). A value approaching one indicates an enhancement of variability on decadal timescales, and would argue for the presence of an oscillatory mode of variability and against the null hypothesis of the stochastic climate model (Hasselmann 1976, Frankignoul et al. 1997). Classical predictability studies consist of performing ensemble experiments with a single coupled model perturbing only the initial conditions (Griffies and Bryan 1997a and b, Grötzner et al. 1999, Boer 2000, Collins 2002, Collins and Sinha 2003, Pohlmann et al. 2004). In these studies, the predictability of a variable is given by the ratio of the ensemble variance to the actual signal variance. These experiments provide an upper limit of predictability, since they assume a perfect model and near perfect initial conditions. Although potential predictability can be estimated from observations, in practice data records are rather short and tend to be less reliable for earlier periods, and hence, it is often estimated from model simulations. Thus, both these predictability estimates rely heavily on models. A third method exists that is also model-based. This method compares the variability simulated with and without the inclusion of active ocean dynamics and identifies those regions in which ocean dynamics are important in generating the variability. It is likely that these regions are also the regions of high predictability potential (Park and Latif 2004).

All three methods, the potential predictability approach (Boer 2001), the classical predictability studies (e.g,. Pohlmann and Keenlyside 2004), and the ocean dynamics approach indicate four regions where predictability may exist at decadal timescales: The North Atlantic, the Southern Ocean, the North Pacific, and the Tropical Pacific. These regions are shown to be largely model independent by Boer (2001), where the potential predictability of decadal means of surface air temperature (SAT) from an ensemble of eleven climate models was calculated (Fig. 1). The most prominent regions are the North Atlantic and the Southern Ocean, where more than 50% of the variance exists in the decadal band. The North Pacific and Tropical Pacific also show a significant fraction of variability at decadal timescales. For the North Atlantic and Southern Ocean, the results of the Collins and Sinha (2003) and Pohlmann et al. (2004) classical predictability studies with coupled models are in good agreement with Boer's (2001) study, showing these regions are predictable out to ten years or longer. For the other two regions, the level of predictability weakens, but the patterns remain largely similar.

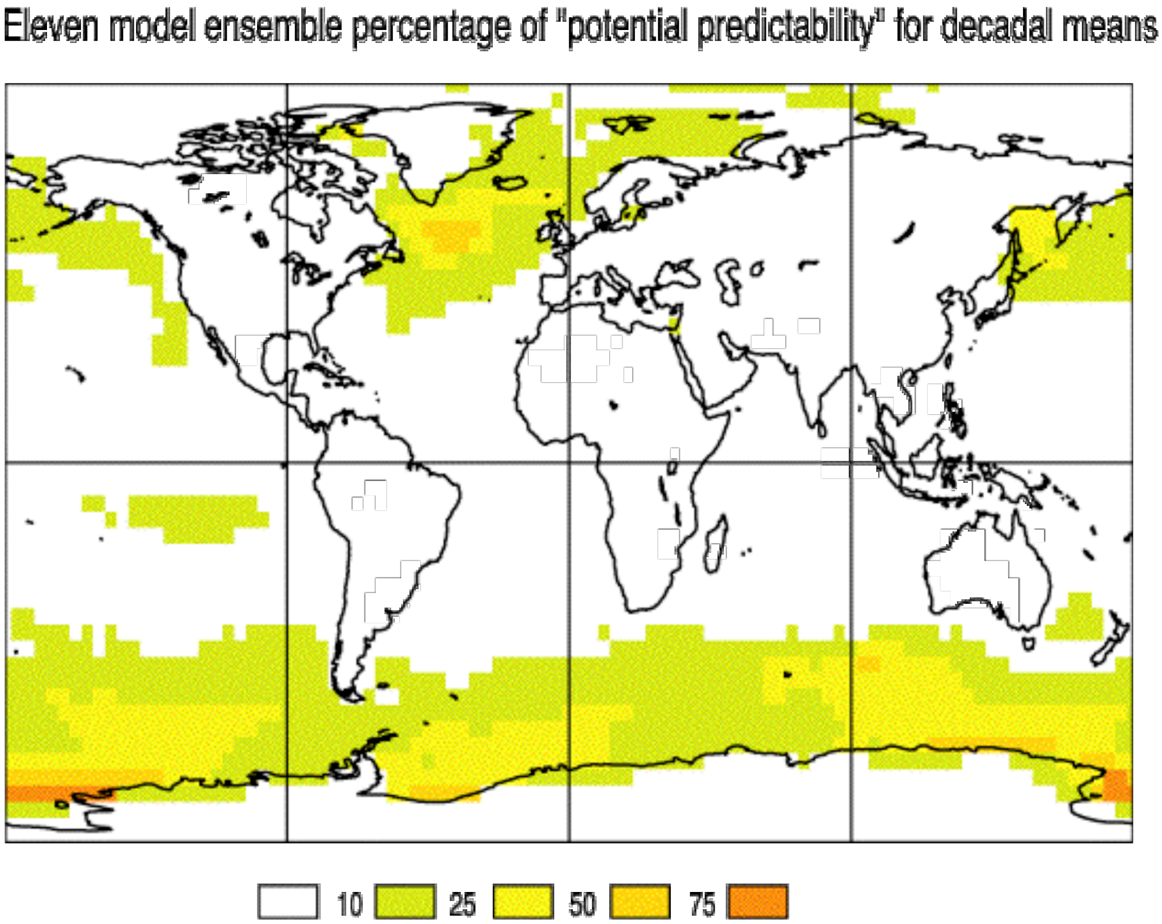

Figure 1: Map of potential decadal predictability as derived from extended-range control integrations with coupled ocean-atmosphere general circulation models. From Boer 2001.

The North Atlantic has received the largest amount of attention, since it shows the largest potential for decadal predictability and because of its potential influence on Western Europe and the Eastern United States. The Southern Ocean has received the least amount of attention, no doubt since it has little or no social or socioeconomic impact. Hence, the mechanisms for decadal predictability in this region are not yet well understood, and further work is required.

3. Observations in the Atlantic sector

A large number of observational studies exist concerning the decadal to multidecadal variability in the Atlantic sector. Bjerknes 1964, for instance, concluded from his analysis of the observations that the atmosphere drives the ocean at interannual timescales, while at the decadal to multidecadal timescales it is the ocean dynamics that matters. Many subsequent observational and modelling studies agree basically with this view, so that the predictability potential in the Atlantic sector is probably largest at the long-term decadal to multidecadal timescales.

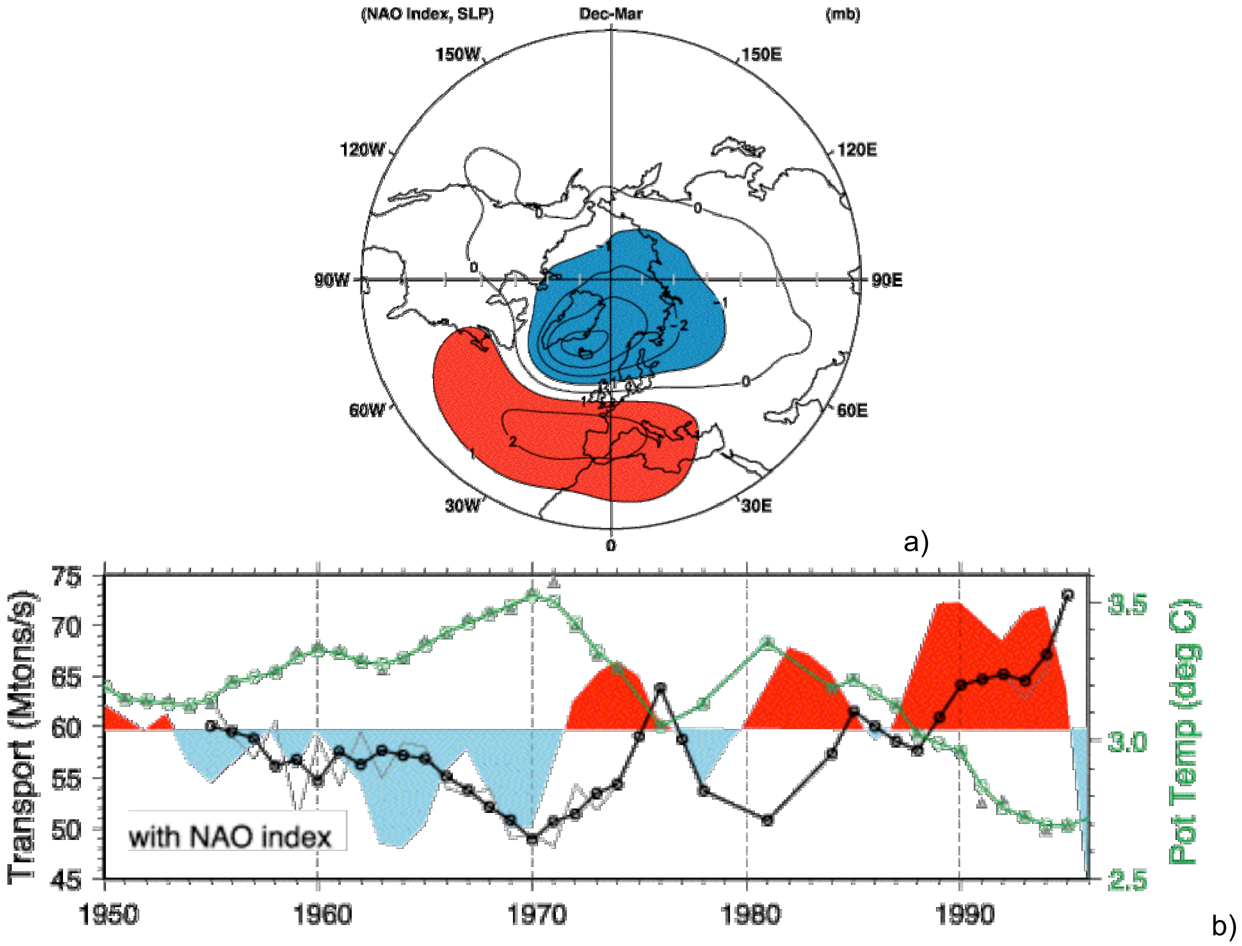

Figure 2: a) The pattern of the North Atlantic Oscillation (NAO) and b) timeseries of the NAO index, the temperature of the Labrador Sea Water (a measure of convection), and the Gulf Stream transport. After Curry et al. 1998.

The most prominent atmospheric phenomenon over the North Atlantic is the North Atlantic Oscillation (NAO, Hurrell 1995). The NAO is a seasaw in surface pressure, with coherent changes over the high and midlatitudes (Fig. 2a). A convenient index of the NAO is the normalized pressure difference between Iceland and the Azores (Fig. 2b). The NAO index exhibits rather strong interannual variability, but also some considerable decadal to multidecadal variability. The variations in the NAO have been clearly linked to surface temperature and precipitation variations over Europe and North America. In particular, the anomalously mild winters over Northern and Central Europe during the last few decades have been attributed to an intensification of the NAO. It has been shown that decadal to multidecadal variations coherent with those in the NAO can be also observed in the ocean (Fig. 2b, Curry et al. 1998), which implies the existence of some kind of air-sea interactions. We shall discuss below what is known about the nature of these interactions.

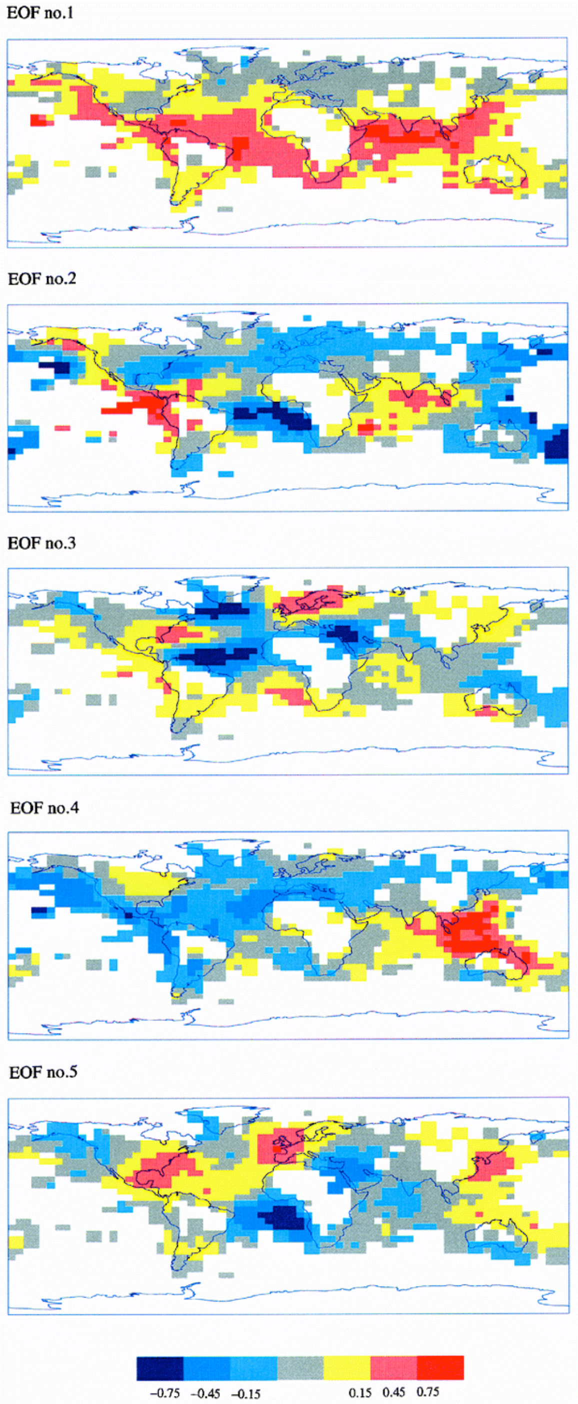

Figure 3: The first 5 rotated EOF patterns of global surface temperature for the last centuries as derived from paleoclimatic data. From Mann et al. 1998.

Folland et al. 1984 and Folland et al. 1986 describe multidcecadal variations in the Atlantic sea surface temperature (SST) and link them to West African (Sahelian) rainfall. Deser and Blackmon 1993 investigated the variability of the surface climate over the North Atlantic and described two modes that are relevant here: A quasi-decadal mode and a multidecadal mode. The latter was also described by Kushnir 1994. Mann et al. 1998 analyzed the global-scale temperature patterns during the past six centuries using proxy climate indicators. They identified an interannual to decadal mode in the Atlantic which is associated with the North Atlantic Oscillation. They also identified a multidecadal mode which resembles the interhemisperic contrast mode in the Atlantic described by Folland et al. 1984 and Folland et al. 1986. We show in Figs. 3 and 4 the first five reconstructed modes from the paleoclimatic reconstructions of global surface temperatures by Mann et al. 1998. The two figures demonstrate that the decadal to multidecadal variability in the Alantic Ocean (modes 3 and 5) existed throughout the last few centuries, so that they can be regarded as stable modes of the Atlantic climate system. The two modes represent basically the two types of Atlantic variability that were described in most observational papers. The first temperature mode (Mann`s EOF-3) is characterized by the well-known North Atlantic tripole (Visbeck et al. 1998) and the tropical Atlantic dipole (Chang et al. 1997) (Figs. 3c and 4c), while the second mode (Mann`s EOF-5) is the interhemispheric contrast mode (Figs. 3e and 4e), with uniform SST changes over most of the North Atlantic (see also Latif et al. 2004).

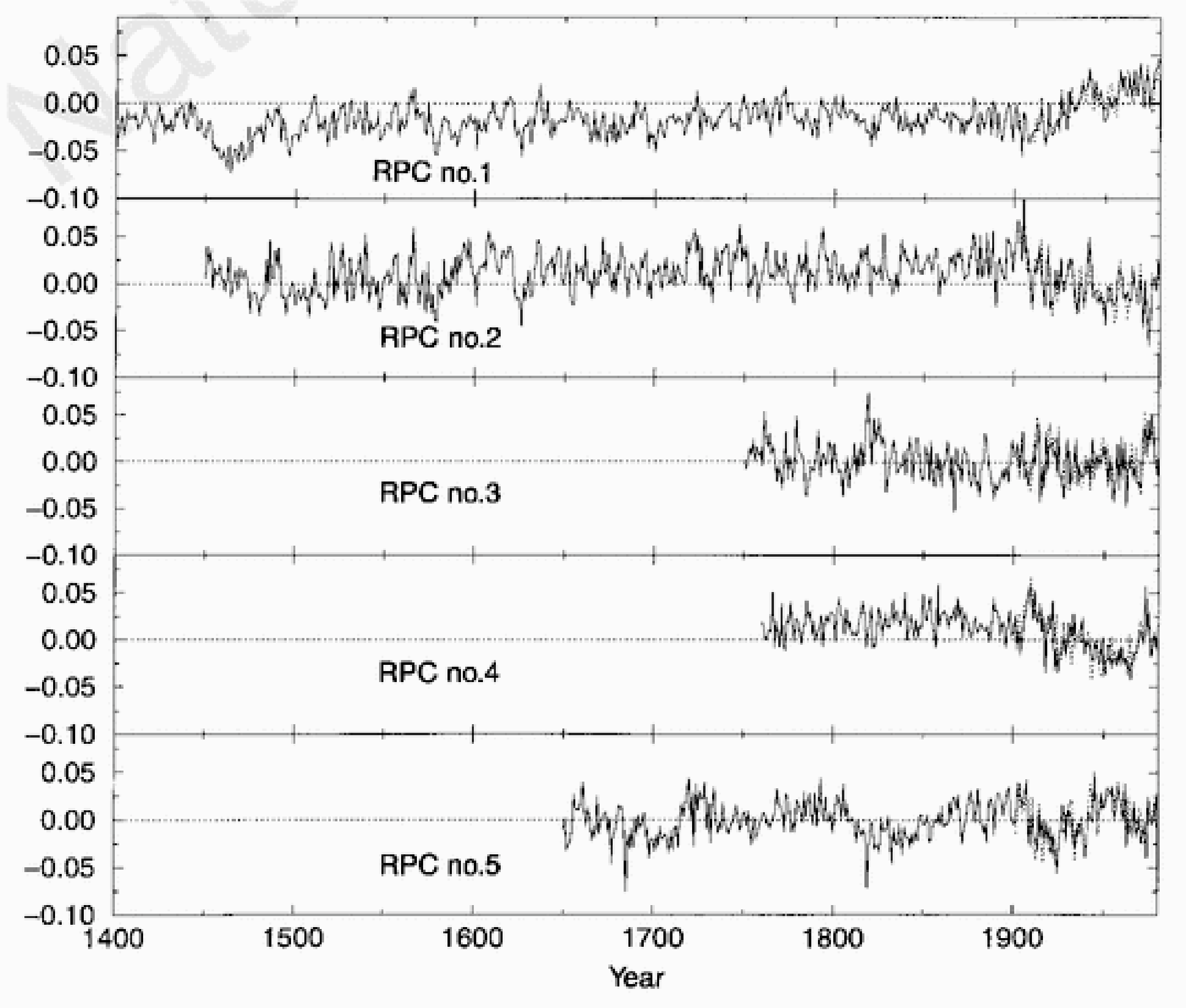

Figure 4: The first 5 rotated EOF timeseries of global surface temperature for the last centuries as derived from paleoclimatic data. From Mann et al. 1998

In this paper we concentrate on these two modes in the Atlantic which seem to be the most robust ones and which explain the most variance at the decadal timescales. Other types of variability in the Atlantic Ocean have been described in the literature, but we shall not discuss them here.

4. Dynamics of the decadal to multidecadal variability

We turn now to model simulations in order to address the mechanisms underlying the decadal to multidecadal variability and to discuss its predictability. We describe uncoupled simulations with atmosphere and ocean models forced by observed boundary conditions as well as coupled integrations.

Ocean forced atmospheric variability

Ensembles of uncoupled atmosphere general circulation model (AGCM) experiments forced by observed SSTs and sea ice distributions are used to identify atmospheric predictability under the assumption that the SSTs are themselves predictable. Different AGCMs forced by the observed time history of SST and sea ice simlulate successfully part of the decadal variabilty in the North Atlantic sector (e.g., Rodwell et al. 1999, Mehta et al. 2000, Latif et al. 2000), which indicates some ocean control on the atmosphere. However, it remains controversial which parts of the world ocean drive the low-frequency variations in the atmosphere, specifically in the NAO. While Rodwell et al. 1999, for instance, argue that it is mainly the North Atlantic SST, some more recent studies indicate a strong impact of the tropics, specifically the Indo-Pacific region, on the NAO at decadal to multidecadal timescales (e.g., Hoerling et al. 2001, Bader and Latif 2003). Bader and Latif 2003 show explicitly that it is the Indian Ocean that had a quite strong impact on the NAO during the last 40 years. The changes in the NAO forced by the Indian Ocean may even drive changes in the North Atlantic thermohaline circulation (Bader and Latif 2004), so that there is a direct and almost instantaneous response of the North Atlantic sector and an indirect and delayed response to Indian Ocean SST. Tropical Pacific SST influence not only the tropical Atlantic region, but also the extra-tropical Atlantic climate. It has been shown by Fraedrich and Müller 1992 anlyzing observations and by Merkel and Latif 2002 by conducting AGCM integrations that there is a significant response of the North Atlantic region to ENSO-related variations in tropical Pacific SST. In summary, there is definitely a potential for tropical SSTs to influence the Atlantic climate system.

Potential predictability is estimated from forced AGCM experiments by comparing external (ocean) forced and total climate variance (e.g., Rowell 1998). Although these studies have been criticized, since they exclude any feedback of the atmosphere on the ocean (Barsugli and Battisti 1998; Bretherton and Battisti 2000), they provide a first estimate of how much of the atmospheric variability may be predictable. Rowell and Zwiers 1999 indicate the tropics are generally more predictable than the extra-tropics. These results were further quantified in the PREDICATE project (Sutton et al. 2003), where the potential predictability of the North Atlantic - European region derived from four AGCMs forced by observed SST and sea ice distributions was systematically compared. The results showed that potential decadal predictability is highest in the summer season both for tropical and extra-tropical parts of the North Atlantic - European region. In summer (winter), roughly 60% (50%) and 30% (20%) of the variance is potentially predictable for the tropical and extra-tropical parts of the North Atlantic - European region, respectively. There are, however, significant differences between estimates of potential predictability from different atmosphere models, particularly in spring and autumn.

a) b) c)

Figure 5: Signal-to-noise maximizing analsysis of an ensemble of AGCM integrations with observed SSTs. Shown is the mode that reflects the multidecadal modulation of the North Atlantic Oscillation. a) SLP pattern, b) timeseries, and c) SST pattern. From Sutton and Hodson 2003.

In the PREDICATE project (Sutton et al. 2003) experiments were also carried out with different AGCMs forced by idealized patterns of Atlantic SST anomalies (Rodwell et al. 2004). The SST anomalies were identified from observations using a lagged maximum covariance analysis as those most likely to induce a significant response. A key finding was that, contrary to expectations, the response to the SST forcing was very consistent among the different atmosphere models. In many cases, the uncertainty was significantly less than the signal strength. The magnitude of the response was generally smaller than the interannual variability, but sufficient to be of clear importance for understanding and predicting decadal variability.

Similar conclusions were reached by Paeth et al. 2003 analyzing an ensemble of multidecadal AGCM integrations with observed SSTs.

Sutton and Hodson 2003 studied the influence of the ocean on atmospheric variability in the North Atlantic region by applying an optimal detection method to ensemble simulations of an AGCM forced by observed SST. They found that SST variability had a significant influence on the climate of the NA region during the period 1871-1999. Furthermore, SST variability influenced both interannual variations and longer timescale, multidecadal, variations of North Atlantic climate. An example from this study is shown in Fig. 5 which depicts the multidecadal modulation of the North Atlantic surface pressure by the multidecadal SST variations in the Atlantic. The timescale of this mode is clearly multidecadal (Fig. 5b) and the associated sea level pressure anomaly pattern resembles somewhat the NAO (Fig. 5a). The characteristic SST anomaly is that of the interhemispheric contrast mode (Fig. 5c, see also Fig. 4e). In summary, the various forced AGCM integrations indicate that both Atlantic SSTs and SSTs from outside the Atlantic have an impact on the climate of the Atlantic sector. This impact is stronger at decadal to interdecadal relative to the interannual timescales, which is important in view of decadal predictability. Thus, in order to exploit the full decadal predictability potential in the Atlantic sector, a global approach is required that considers forcings from both the tropics and the extra-tropics.

Atmosphere forced oceanic variability

The complementary problem was studied with different ocean general circulation models (OGCMs) forced by observed atmospheric boundary conditions. Most of these studies were performed by driving the OGCMs with reanalysis products. An example is given from the PREDICATE project (Sutton et al. 2003) in Fig. 6 which shows an ensemble of five model simulations with identical (NCEP reanalysis) forcing. Some of the model simulations were performed in ensemble mode by varying the initial conditions, but only the ensemble means are shown. Although the differences between the models are not small, some common features can be seen, e.g. a tendency for a reduced strength of the Atlantic meridional overturning circulation (AMOC) at 30°N until 1960 and slow increase thereafter (Fig. 6a).

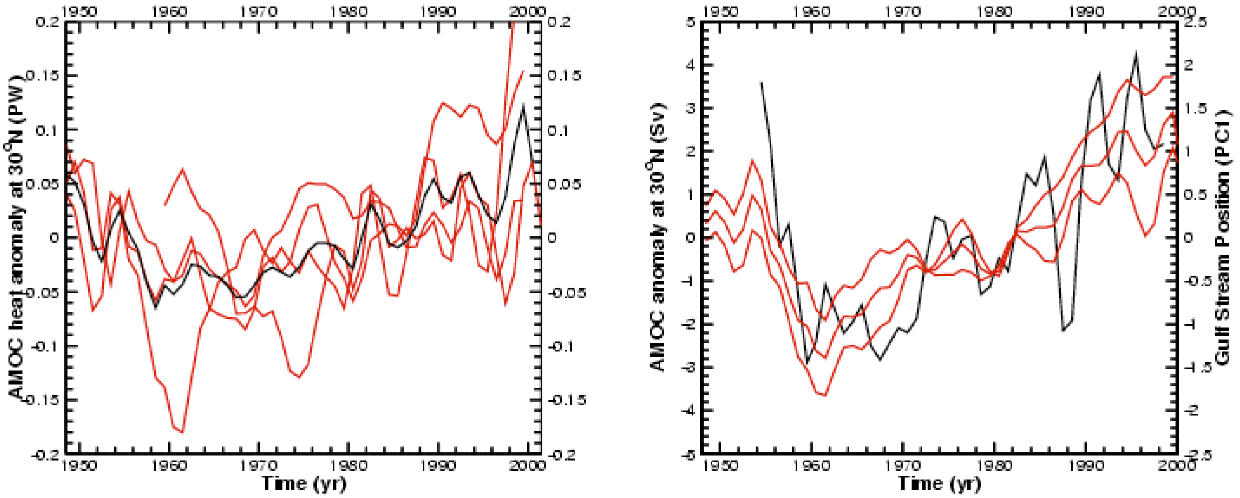

Figure 6: An North Atlantic overturning index simulated by several OGCMs forced by NCEP reanalyses. Left: The individual simulations (red) and the ensemble mean (black). Right: The ensembble means of two models which were run in ensemble mode and their mean (red) and a Gulf Sream index (black).

This result is very much in contrast to the expected reduction in THC strength which accompanies increases in greenhouse gases and highlights how natural variability can mask the anthropogenic signal. The two models that were run in ensemble mode are in shown in terms of their ensemble means in Fig. 6b together with the Gulf Stream index of Joyce et al. 2000 as used by Frankignoul et al. 2001. The latter index is constructed from XBT data at 200 m during 1954-1998 and respresents observed temperature anomalies along the mean Gulf Stream path. Since the variability of the AMOC is not known from observations, indices like the

Gulf Stream index may be taken as a proxy for the large-scale variability of the North Atlantic Ocean. It follows from Fig. 6b that the ensemble means of the two models broadly agree with the Gulf Stream index at the multidecadal timescale, yielding confidence to the simulated variability.

Coupled model variability: Internally generated variability

The uncoupled AGCM (OGCM) simulations described above indicate that the atmosphere (ocean) in the Atlantic sector is controlled at decadal and multidecadal timescales to some extent by the lower (upper) boundary conditions. This is important in view of decadal predictability, because this sensitivity to boundary conditions is necessary to “overcome” the strong unpredictable, internally generated, and chaotic component of the variability of the atmosphere and the ocean.

We turn now to the coupled model studies. Many of the proposed mechanisms for the decadal to multidecadal variability were derived from such coupled model simulations and some of them are summarized in the review paper of Latif 1998. There are two leading mechanisms for North Atlantic variability. One idea is that this variability is part of a thermohaline driven coupled atmosphere-ocean mode. Timmermann et al. 1998 found such a mode of variability, with a 35-year period, in a multicentury integration of the ECHAM3/LSG climate model. In their study, an anomalous strong North Atlantic THC drives positive SST anomalies. The atmospheric response to these SST anomalies involves a strengthened NAO, which leads to anomalously weak evaporation and Ekman transport off Newfoundland and in the Greenland Sea, and the generation of negative sea surface salinity (SSS) anomalies. These SSS anomalies weaken the deep convection in the oceanic sinking regions and subsequently the strength of the THC. This leads to a reduced oceanic poleward heat transport and the formation of negative SST anomalies, which completes the phase reversal.

A second idea is that multidecadal THC variability is driven by the low-frequency portion of the spectrum of atmospheric flux forcing. Delworth and Greatbatch 2000 investigating the multidecadal variability in the coupled model simulation of Delworth et al. 1993 with the GFDL R15 CGCM found such a mode in their analysis of a series of coupled and uncoupled OGCM integrations. The multidecadal variability simulated in the GFDL R15 CGCM discussed in Delworth et al. 1993 involves interactions of the gyre and thermohaline circulations, in which the anomalous salt advection into the sinking region plays a crucial role in determing deep convection. Delworth and Greatbatch 2000 show that the multidecadal THC fluctuations are driven by a spatial pattern of surface heat flux variations that bear a strong resemblance to the NAO. No conclusive evidence is found that the THC variability is part of a dynamically coupled atmosphere-ocean mode. The study of Saravanan et al. 2000 with an idealized model (with ocean-atmosphere coupling in an Atlantic like basin) agrees with the second idea. Saravanan et al. 2000 further conclude that midlatitude atmospheric predictability is modest compared to the predictability associated with tropical phenomena like El Niño, and that this predictability arises only from the atmospheric response to oceanic modes of variability, rather than from coupled modes. Whether decadal North Atlantic THC variability is truly coupled or not, the close correspondence between the North Atlantic SST and THC variability in conjunction with the dynamical inertia of the THC should allow for the prediction of the slowly varying component of the North Atlantic climate system (Latif et al. 2004).

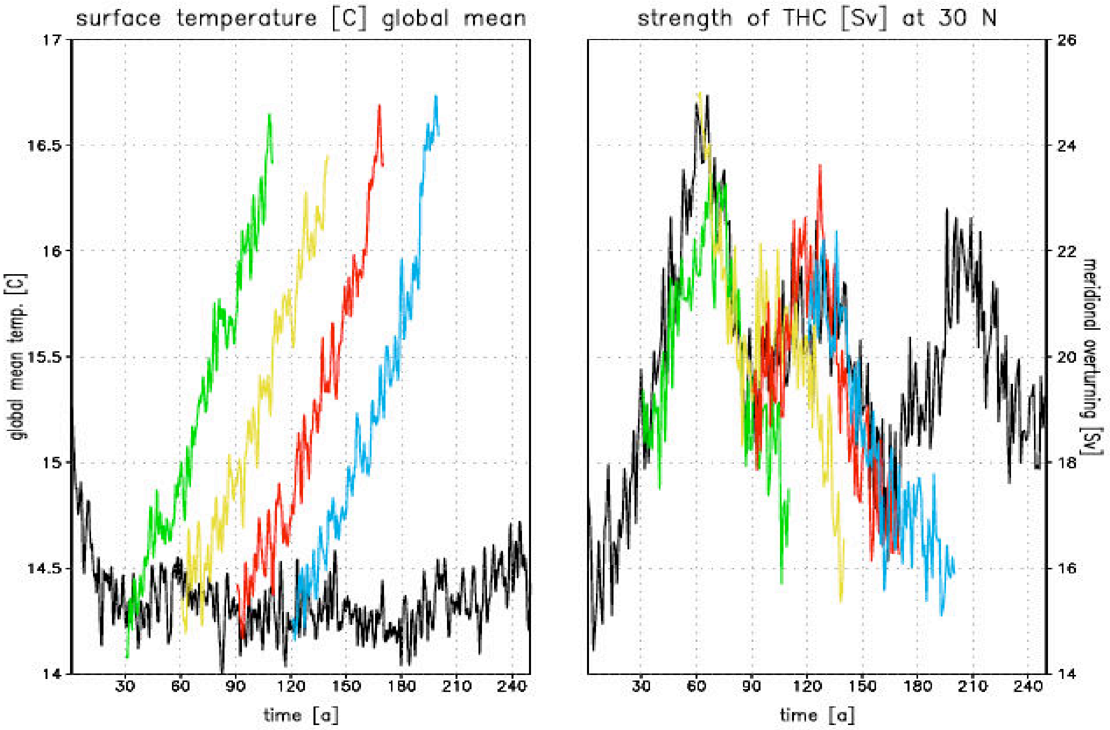

Figure 7: An ensemble of 1% CO_2 integrations with the MPI coupled ocean-atmosphere GCM initialized at different conditions of the control integration. Left: The evolution of globally averaged surface temperature. Right: The evolution of a North Atlantic overturning index. After Latif et al. 2004.

There is another important point associated with the dynamical inertia of the THC that is relevant for climate change detection: This interia implies that anthropogenically forced changes in THC strength (and North Atlantic SST) may be masked for several decades by natural multidecadal variability. This is clearly illustrated in greenhouse gas simulations with the ECHAM5/MPI-OM coupled model. In Fig. 7 four different greenhouse gas simulations (with an CO_2 increase of 1% per year) initialized from different states of a control integration are shown. While the global mean surface temperature exhibits a rather monotonic increase and virtually no sensitivity to the initial conditions (Fig. 7, left panel), THC evolution closely follows that of the control run for some decades (Fig. 7, right panel). Thus, the THC in this particular coupled model exhibits a rather strong sensitivity to the initial conditions, which is important in the light of decadal predictability. It should be noted, however, that the ECHAM5/MPI-OM coupled model may somewhat overestimate this sensitivity.

Coupled model variability: The role of external forcing

The studies described above indicate a significant role for internally generated decadal variability, but to what extent did external forcing influence the evolution of the climate in the Atlantic sector during the twentieth century? Many climate models were driven in ensemble integrations with observed greenhouse gas and aerosol concentrations for the twentieth century and were able to simulate realistically the observed long-term evolution of globally averaged surface air temperature (e.g., Stott et al. 2000, Meehl et al. 2003). In particular, the observed warming trend and the superimposed multidecadal variability of globally averaged SAT could be reproduced by prescribing observed forcings. The picture changes, however, when regional climate indices over the North Atlantic are analysed. The time evolution of the observed North Atlantic SST during the twentieth century, for instance, cannot be reproduced in the ensemble integations with the HadCM3 climate model (Fig. 8). This indicates that the climate over the North Atlantic was strongly governed by internal variability during the twentieth century and that external forcing played a minor role. This is, however, somewhat in conflict with simulations of the last millenium. Some models show quite some skill in reproducing the recontructed multidecadal to centennial variability in Northern Hemisphere surface temperature when driven with external forcings. In particular, multidecadal to centennial changes in the solar input explain a large part of the variability. Thus, the relative roles of internally generated and externally forced variability need still to be quantified more precisely.

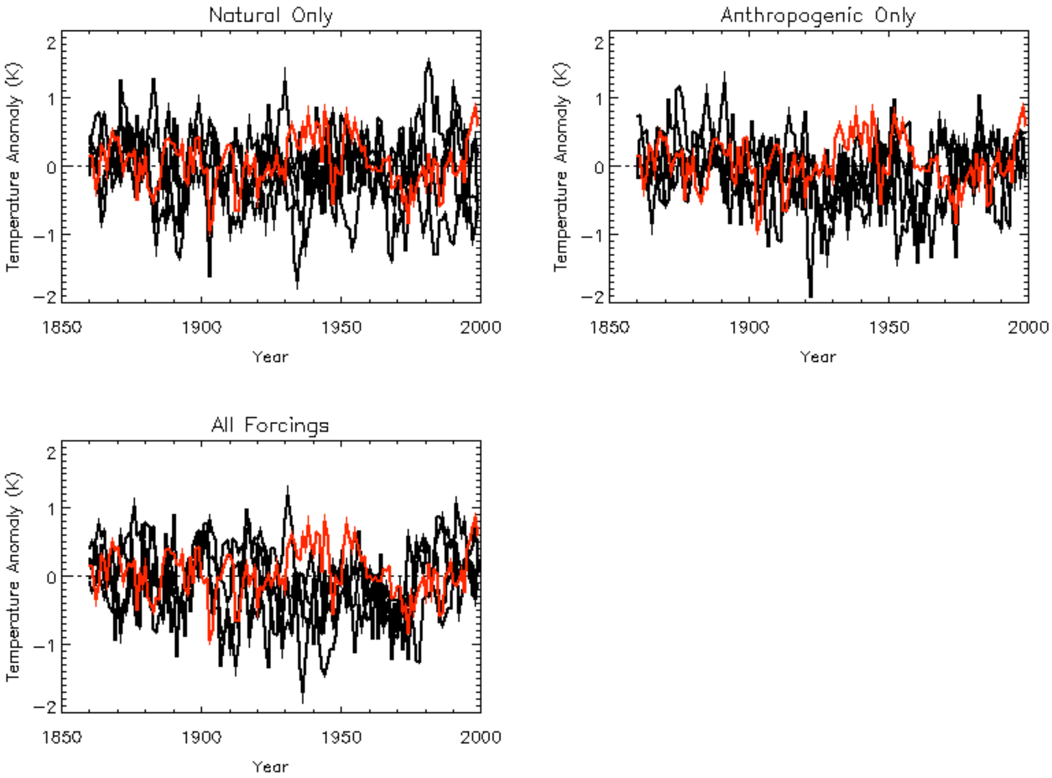

Figure 8 : Simulation of North Atlantic SST from 1860-2000 in three different ensemble integrations with the Hadley Centre coupled ocean-atmosphere GCM with only natural forcings, with only anthropogenic forcings, and with natural and anthropogenic forcings

5. Decadal climate predictability in the North Atlantic-European region

There have been several classical decadal predictability studies of North Atlantic variability. As discussed below, they all seem to indicate that North Atlantic THC variations are predictable out to a decade or more However, there are major disagreements on the level and extent of predictability of SST and atmospheric quantities, such as SAT and SLP. But there are some positive indications of decadal predictability of SAT and SLP over Europe.

In the PREDICATE project (Sutton et al. 2003) a systematic comparison of the predictability of five state-of-the-art European CGCMs (HadCM3, ECHAM5/MPI-OM, ARPEGE3/ORCA, BCM, ECHAM4/ORCA) was made. The results indicate that in general the strength of the Atlantic THC is potentially predictable at least a decade in advance and, in some situations, multidecadal predictions of the THC may be possible (Fig. 9, left panel). In addition, THC-related variations in SST and SAT are potentially predictable one or two decades in advance (Fig. 9, right panel). The exact level of predictability is dependent on the oceanic initial conditions and on the coupled model used.

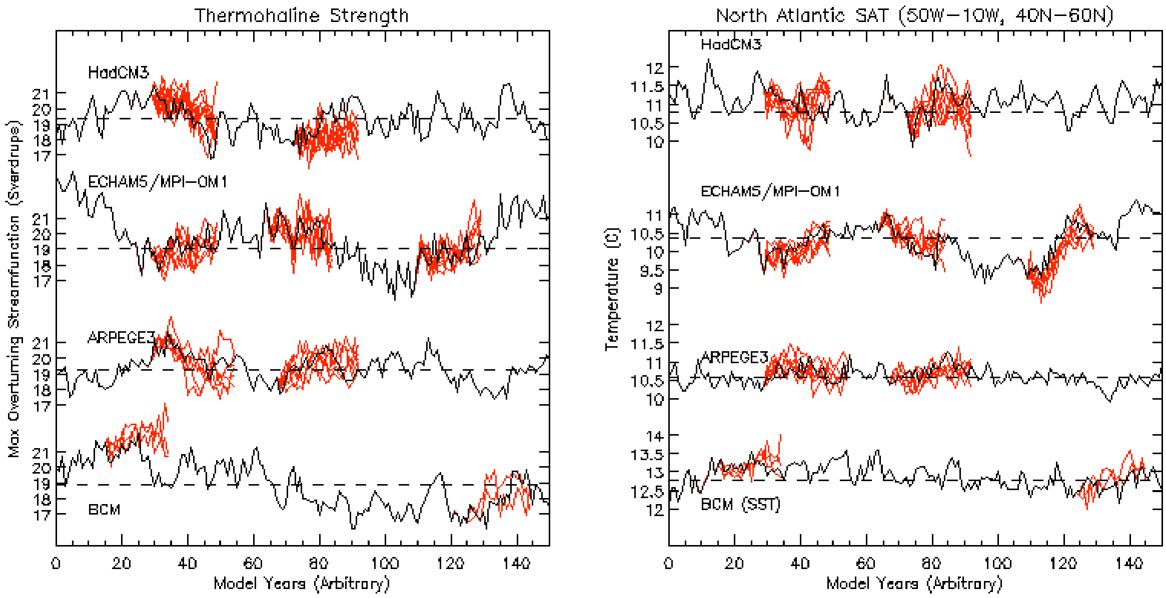

Figure 9: Classical predictability experiments with different European coupled ocean-atmosphere GCMs. Left: Prediction of thermohaline strength. Right: Prediction of North Atlantic SST. Only the atmospheric initial conditions were perturbed in these experiments.

The results of Griffies and Bryan 1997a and Griffies and Bryan 1997b with the GFDL R15 CGCM also suggest that variations of North Atlantic SST are predictable at multidecadal timescales. Grötzner et al. 1999 used the ECHAM3/LSG climate model and found that the North Atlantic THC is predictable about one decade in advance, but North Atlantic SST only about one year. Boer 2000 analyzed simulations with the CCCma climate model and found that at multidecadal timescales predictability of SAT was mainly restricted to the Southern Ocean. Collins (2002) used the HadCM3 climate model and found that SAT is predictable over the North Atlantic at decadal timescales. Collins and Sinha 2003 have shown that the multidecadal THC predictability in the HadCM3 model leads to some predictability of western European climate (Fig. 10). The predicted probability density functions (PDFs) of western European SAT were shown to be significantly different to that of the control integration in the analyzed forecast ensembles. A probabilistic approach for decadal forecasting seems therefore promising.

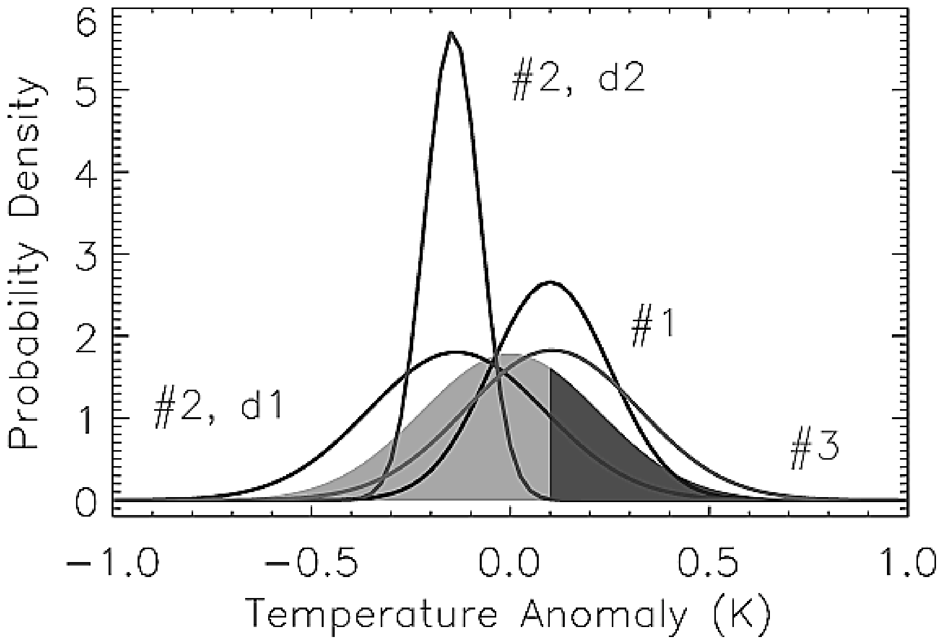

Figure 10: Probability density functions (PDFs) of western European surface air temperature (SAT) in different predictability ensembles produced by the Hadley Centre coupled ocean-atmosphere GCM. After Collins and Sinha 2003

6. Ensemble prediction

The value of ensemble prediction is well established in the fields of numerical weather forecasting and seasonal prediction. Ensemble predictions are generally realized by varying the initial conditions. It was shown more recently that multi-model ensembles may be another promising aproach for ensemble climate prediction.

ENSEMBLES (Ensemble-based Predictions of Climate Changes and their Impacts) is a large EU funded project, commencing May 2004, that aims to develop and test an end-to-end seasonal to decadal and longer timescales forecast system, which also accounts for anthropogenic climate change. The project will build on three previously funded EU projects: PREDICATE (Sutton et al. 2003; discussed above); DEMETER (Development of an European Multi-model Ensemble System for Seasonal to Interannual Prediction, Palmer et al. 2004; described below); and ENACT (Enhanced Ocean Assimilation and Climate Prediction, Davey et al. 2002). ENACT will contribute comprehensive ocean data assimilation schemes for initializing multidecadal hindcasts.

The DEMETER project (Palmer et al. 2004; http://www.ecmwf.int/research/demeter) addressed the issue of sampling model uncertainty in making predictions. In this project a multi-model ensemble for seasonal forecasting was constructed and tested: Seven comprehensive coupled ocean atmosphere models from research centers around Europe were used to make six-month long hindcasts over an extended period (of at least 29 years). An important outcome of the project is the demonstration of the superiority of the multi-model ensemble over any single model. This feature, although poorly understood, is quite universal and not restricted to any particular region or variable (Palmer et al. 2004). An important outcome from DEMETER is the demonstration that a multi-model ensemble is an effective method for sampling model uncertainties and for making more reliable forecasts, a result that should carry over to decadal-to-multidecadal predictions.

7. Predicting global change

The “Intergovernmental Panel on Climate Change” (IPCC 2001) has been established to assess scientific, technical and socioeconomic information relevant for the understanding of anthropogenic climate change, its potential impacts, and options for adaptation and mitigation. The results of this report show a wide range in both, projections of atmospheric concentrations of greenhouse gases/aerosols and model dependence of global and local response on the forcing. The reason global change scenarios are discussed here is two fold. First, anthropogenic changes in greenhouse gases/aerosols are an important forcing for climate on longer timescales and thus need to be taken into account when making multidecadal forecasts. Second, natural climate variability, since it can mask anthropogenic climate change, is an important consideration in predicting global climate change, particular at a regional level (see also Fig. 7). The main point we wish to convey is the large uncertainties involved. This is further illustrated in Fig. 11 which shows European SAT in three global change simulations. Apparently, the evolution of European SAT during the next few decades is dominated by the strong internal decadal to multidecadal variability, but some bias towards higher temperatures is introduced by the more abundant greenhouse gases.

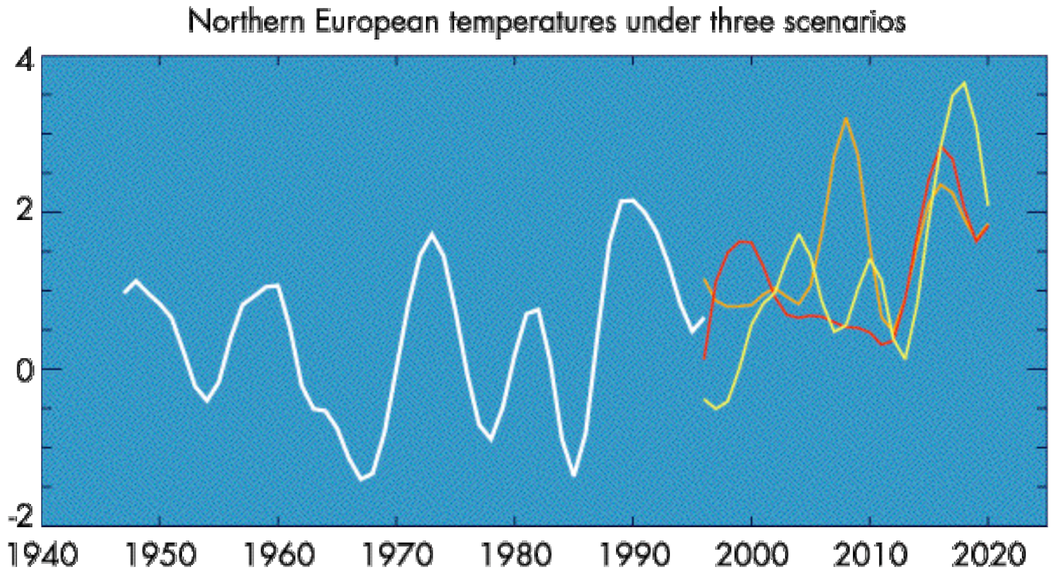

Figure 11: Northern European SAT during the next 20 years under three different greenhouse warming scenarios as simulated by the Hadley Centre coupled ocean-atmosphere GCM. Apparently, the evolution of Northern European SAT during the next few decades is dominated by the strong internal decadal to multidecadal variability, but some bias towards higher temperatures is introduced by the more abundant greenhouse gases.

The Atlantic sector may be particularly sensitive to anthropogenic climate change. This is due to the presence of the THC, which was shown in a number of studies to be sensitive to external forcing. It is likely that strong changes in the strength of the THC will have direct consequences on North American and European climates. In order to make projections of future climate, models incorporate past, as well as future emissions of greenhouse gases and aerosols. Hence, they include estimates of warming to date and the commitment to future warming from past emissions. The globally averaged surface air temperature is projected to increase by 1.4 to 5.8°C (Fig. 12) over the period 1990 to 2100 (IPCC 2001).

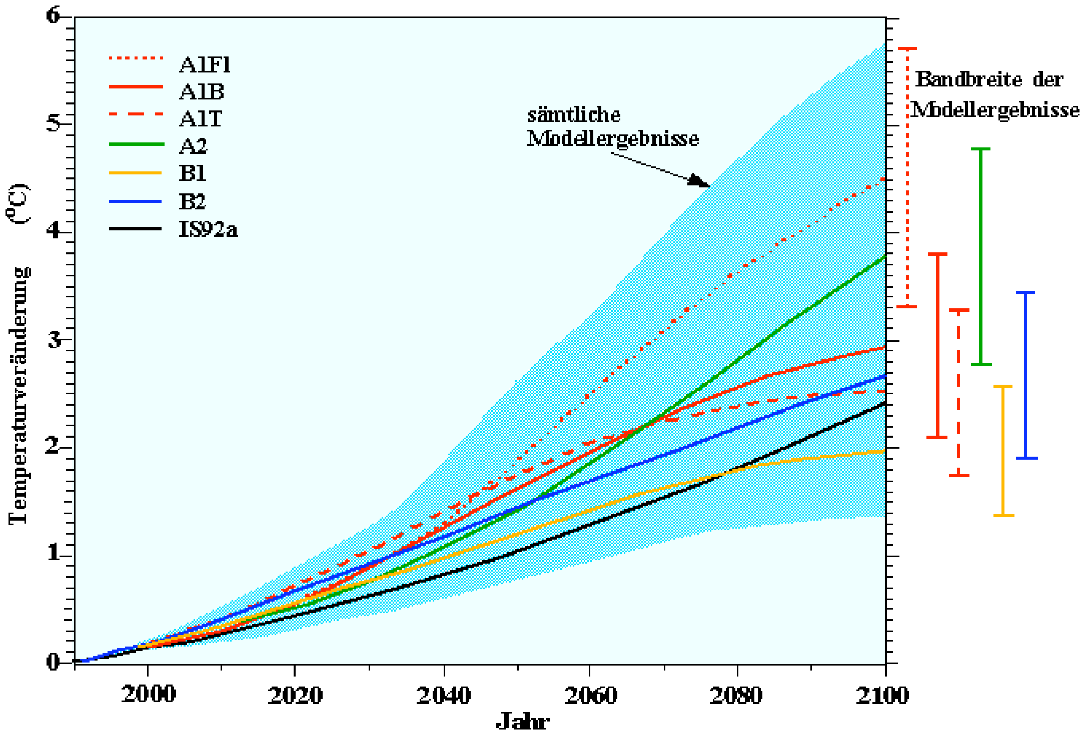

Figure 12: Evolution of globally averaged SAT for different scenarios and models. From IPCC 2001.

These results are for the full range of SRES scenarios, based on a number of climate models. The projected rate of warming is much larger than the observed changes during the 20th century and is very likely to be without precedent during at least the last 10,000 years, based on palaeo-climate data. By 2100, the range in the surface temperature response across the group of climate models run with a given scenario is comparable to the range obtained from a single model run with the different SRES scenarios.

A wide range of THC behavior is simulated by the ensemble of models collected in CMIP (Coupled Model Intercomparison Project), even when the models are forced by the same scenario, indicating a rather large uncertainty in the response to forcing (Fig. 13). Most climate models predict a gradual weakening of the thermohaline circulation in response to global warming under the assumption of some kind of a "bussiness as usual" (BAU) scenario.

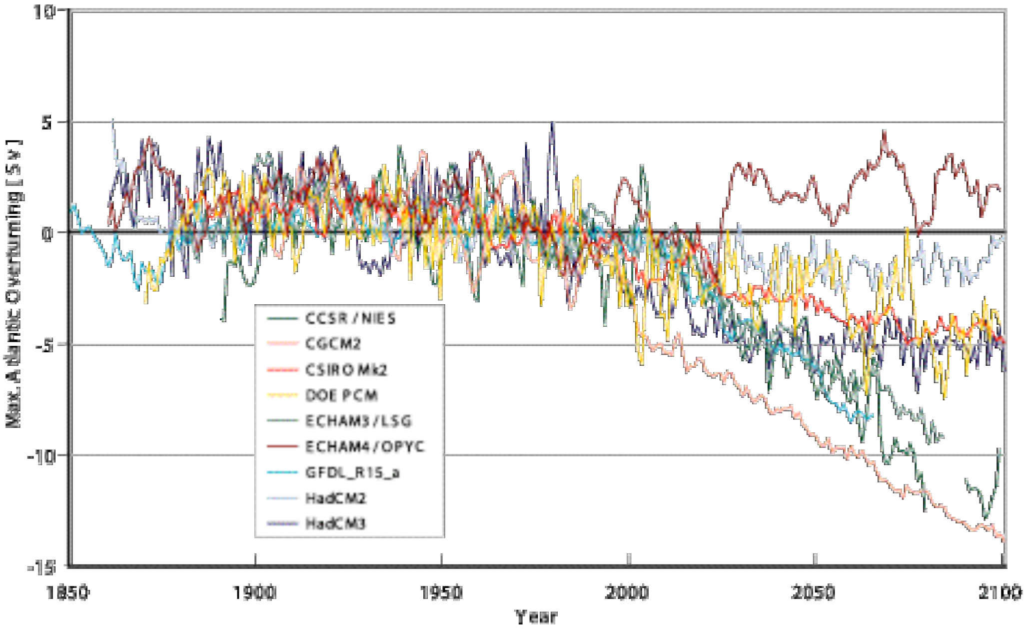

Figure 13: Evolution of the thermohaline circulation in greenhouse warming simulations with different coupled ocean-atmosphere GCMs. From IPCC 2001.

This, however, does not lead to a cooling over the North Atlantic or the adjacent land areas, but to a local minimum in the warming (Fig. 14). A few models simulate a rather stable THC (e.g., Latif et al. 2000). The role of the tropics in stabilizing the THC through anomalous fresh water fluxes has to be considered in this context. In particular, the anomalous export of fresh water from the Alantic to the Indopacific region appears to play a crucial role in the stabilization of the THC. None of the complex climate models simulates some kind of abrupt change in the THC until 2100 when forced by increased levels of greenhouse gases. Thus, it may be concluded that the system is still far beyond a bifurcation point. This is also supported by a multimillenial control integration with fixed greenhouse gas concentrations performed with the GFDL R15 climate model, in which regional abrupt climate change is an extremely rare event (e.g., Hall and Stouffer 2001).

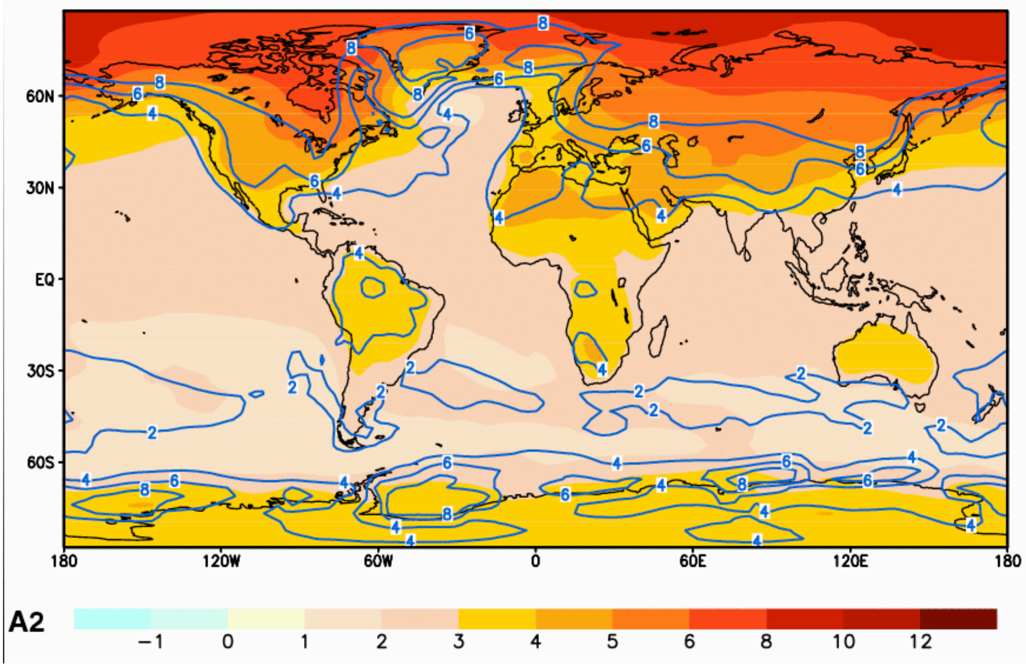

Figure 14: Multi-model projection of SAT for the year 2100 and scenario A2. From IPCC 2001

8. Summary

The climate in the Atlantic sector exhibits strong decadal to multidecadal variability. Part of this variability appears to be potentially predictable, especially the part that is related to variations of the thermohaline circulation. The variations of the THC may be predictable a few decades ahead, as shown by a number of coupled model studies. There is no consensus on the mechanisms responsible for decadal to multidecadal variability in the North Atlantic. In general the models fall into two camps, either the variability is the response of the ocean to stochastic forcing or it is part of a coupled ocean-atmosphere mode of variability. Clearly the latter has the most potential for predictability. However, where the ocean response to stochastic forcing has an oscillatory character, the inertia of these variations still offers the potential for decadal predictability. Nonetheless, understanding the true mechanisms for decadal variability is important with respect to developing decadal predictions systems. But the lack of data and the timescales involved makes this a challenge.

Although there is some consensus that predictability at decadal timescales exists in the Atlantic Ocean, to what extent does this predictability carry over to the atmosphere, especially over land, is still controversial. It is also uncertain whether the strength of the atmospheric response relative to internal atmospheric variability is significant enough to be of practical use. Most of the effort in understanding these issues has focused on the North Atlantic/European region. The more recent studies would tend to indicate that the climate of Western Europe does exhibit useful decadal predictability (Sutton et al. 2003; Collins and Sinha 2003; Pohlmann et al. 2004). Results from ensembles of AGCM forced by observed SST experiments also suggest reasonable agreement between atmospheric model responses (Rodwell et al. 2003). Although predictability in decadal mean surface air temperature is mostly restricted to ocean regions, the probablility density fuctions of surface temperaure over land (e.g., Europe) are shown to be affected in some models by the decadal to multidecadal variability of the large-scale ocean circulation. Thus, some useful decadal predictbability of economic value may exist in the Atlantic sector. To exploit this decadal predictability, however, a suitable ocean observing system must be installed, since the memory of the climate system resides in the North Atlantic Ocean. In particular, the thermohaline circulation should be monitored carefully, since its variations are most interesting in the light of decadal predictability in the Atlantic sector.

Until the end of this century, climate models predict that anthropogenic climate change will become more and more important. How precisely global and regional climate will evolve, however, is highly uncertain. The strong internal decadal to multidecadal variability is likely to mask the anthropogenic climate signal during the next few decades. Likewise the regional climate of the Atlantic sector during the twentieth century was, in contrast to global climate, dominated by the internal variability. Global warming will, however, introduce a warm bias on the multidecadal timescale. The strength of this warming depends on the selected scenario and the selected climate model. The warming may well override the amplitude of the internal decadal to multidecadal variability on the global scale. Regionally, however, changes in the ocean circulation may provide important feedbacks. For the Atlantic sector, the fate of the thermohaline circulation will be important in shaping regional climate change. There exists, however, a large uncertainty concerning the response of the THC to global warming. Most models predict some weakening of the THC and a corresponding reduced northward heat transport in the North Atlantic, but the spread in the model results is extremely large. A weakening of the THC may mediate somewhat the warming over the North Atlantic, but the models still predict considerable warming over land. According to the model simulations, abrupt climate change is not to be expected over the Atlantic sector during this century. Instead the bulk of the climate models simulate rather gradual changes when forced by increased levels of greenhouse gases.

A multi-model approach may be an effective way of sampling model uncertainties. Dealing with the uncertainties of anthropogenic climate forcing seems a bigger problem. But as 20 years ago people may have wondered if seasonal forecasting would ever be possible, in 20 years from now routine decadal-to-mutlidecadal predictions may have become accepted.

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Climate Observing System for the Atlantic Sector

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I. Overview of Basin-Scale Observations

A. Ocean Based Observations

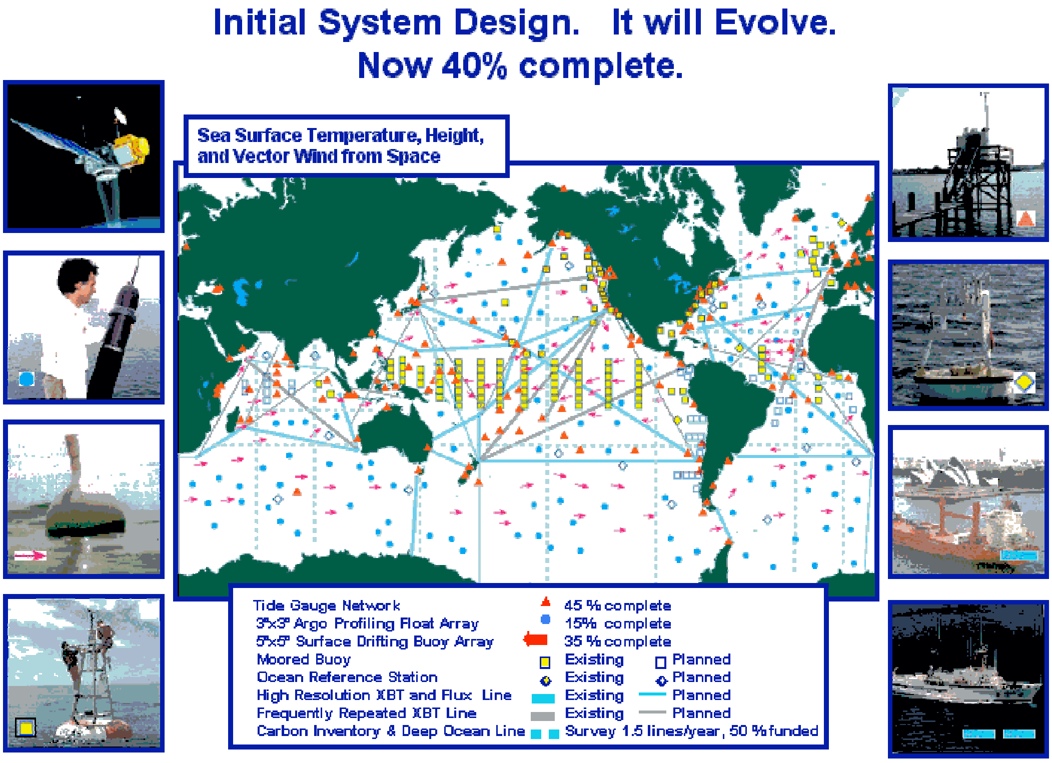


Figure 1: Initial Global Observing System design.

The current existing components of the international effort comprise *in situ* 1) fixed point time series 2) Global Surface drifting Buoy Array; 3) Global Ships of Opportunity Network; 4) Tropical Moored Buoy Network; 5) ARGO profiling float array; 6) Global Tide gauge Network; 7) Dedicated Ship Operations 8) Moored Buoy.

Several elements are part of the Sustained Ocean Observing System for Climate (fig.1) while the rest are short-term measurements as part of specific process studies. More information can be found at: http://www.clivar.org/organization/atlantic/IMPL/index.htm
http://www.clivar.org/organization/atlantic/IMPL/proc-stud.html

For the purpose of this white paper, we will consider the region comprising between 80°N and 60°S.

A.1 Fixed Point Time Series

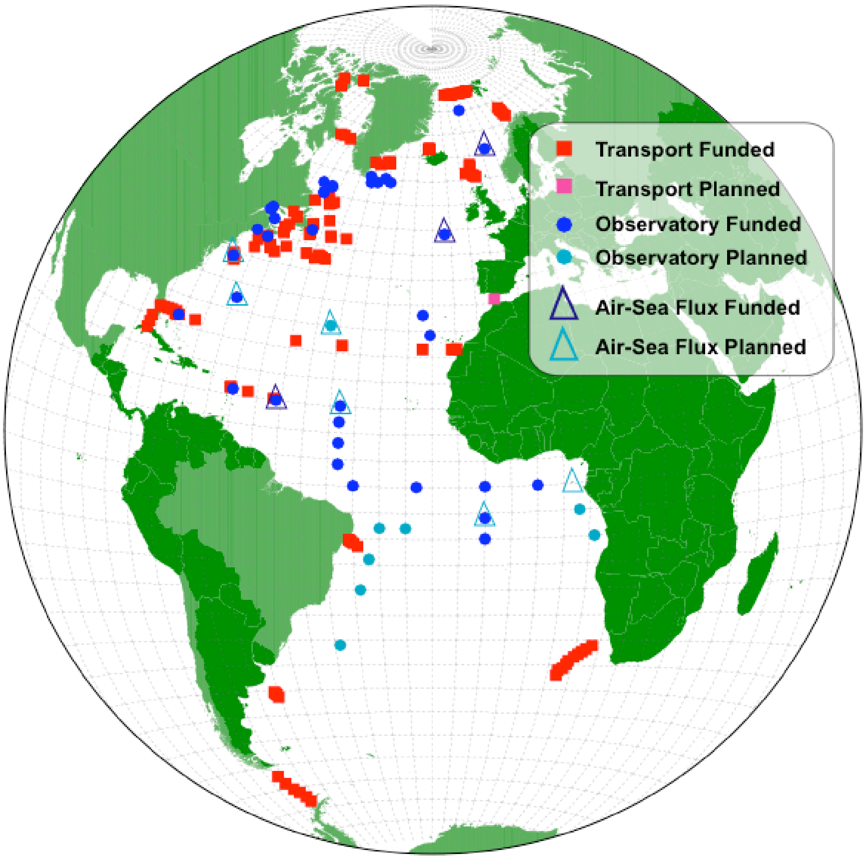


Figure 2: Positions of moorings arrays for transport measurements, observatories long-term series and PIRATA array. Sites are listed with positions and brief descriptions in Table 1.

Fixed-point time series are an essential element of the global ocean observing system. These Eulerian Observatories are uniquely suited for fully sampling 2 of the 4 dimensions (depth and time), thus complementing other components of the observing system (satellites, floats, ships). They resolve a wide range of temporal variability and sample the water column from the surface to the bottom. Fixed-point stations will resolve multi-disciplinary variability and processes like fluxes of heat, freshwater momentum and other properties between the ocean and atmosphere.
Moorings are uniquely suited for sampling critical regions, in adverse conditions, and over extended periods. They can be used in passages and boundary currents, under the ice, in abyssal layers, during storm seasons, and to capture transient events like convection.

The definition of an ocean time series site in the global system is that it has the following characteristics:

- in-situ observations of ocean/climate related quantities at a fixed geographic location/region
- sustained and continuous, contributing to a long-term record at the site
- autonomous moored sampling should be pursued to resolve high- frequency variability, to achieve high vertical resolution, and to obtain coincident multi- disciplinary sampling
- as an alternate to a mooring, shipboard observations from regular occupation of a site as at Ocean Weather Stations, historical sites or sites where moorings have not been established provide an alternate method
- site selection is determined by the value of the site as representative of one, and where possible more, meteorological, physical, or chemical area of interest.

Figure 2 shows the positions of current and planned fixed point stations in the Atlantic. A brief description is available in Table 1.

Lat/Long	Description	OB	FL	TR
75N/3.5W	Deep Ventilation in the Greenland Sea (AWI)	X		
66N/2E	OWS M, Norwegian Sea (Norway)	X	X	
59.7N/39.6W	CIS, Central Irminger Sea (EU)	X	X	
57N/53W	Bravo Station, Labrador Sea (BIO, IfMK)	X		
49N/16.5W	PAP Porcupine Abyssal Plain (EU)	X	X	
60N/40W	Irminger Sea Circulation and Convection (WHOI)	X		
59N/36W	Irminger Sea (Netherlands)	X		
40N/70W	Station W (WHOI)	X	X	
39N/70W	DWBC Along New England and Bermuda (WHOI)			X
43N/60W	North Atlantic Western Margin (UK)			X
33N/22W	K276 Azores Front/Madeira Abyss. Plain (IfMK)	X		
32N/65W	BATS Station S (USA)	X	X	
29N/16W	ESTOC Canary Islands (EU)	X	X	
27N/77W	Abaco Bahamas (RSMAS)	X		X
16N/60W	CLIVAR MOVE western site (IfMK)	X		
15N/51W	NTAS and MOVE eastern site	X	X	
15N-10S/38W-0	PIRATA	X	X	
78N/9E-5W	Fram Strait (EU ASOF)			X
72-73N/19E	Fluxes Across the Barent slope (Norway)			X
68-66N/21	Denmark Strait Overflow (EU ASOF and Iceland)			X
63N/3640W	Freshwater and dense fluxes SE Greenland			X
64-59N/3-9W	Iceland-Scotland overflows (EU ASOF)			X
53N/50-53W	Labrador Sea Export (IfMK)			X
44-41N/45-49W	Grand Banks Boundary current (BIO and IfMK)			X
27N/77-81W	Florida Strait Transport (RSMAS)			X
26.5N	MOC monitoring (UK Rapid)			X
16N/50-60W	CLIVAR MOVE deep transport (IfMK)			X
9-13S/33-36W	Upper Transport (IfMK)			X
40-41S/56-55W	Malvinas Current transport			X

Table 1. Atlantic Ocean Sites. OB=Observatory, FL=Air-Sea Flux and TR=Transport Site. More information can be found at http://www.oceantimeseries.org/

A.2 Global Surface Drifting Buoys Array.

The primary goal of this project is to assemble and provide uniform quality control of sea surface temperature (SST) and surface velocity measurements. These measurements are obtained as part of an international program designed to make this data available in an effort to improve climate prediction. Climate prediction models require accurate estimates of SST to initialize their ocean component. Drifting buoys provide essential ground truth SST data. The Global Drifter Center is located at AOML in Miami, Florida. The center manages the deployment of drifting buoys around the world. Using research ships, Volunteer Observation Ships (VOS), and U.S. Navy aircraft, Global Lagrangian Drifters (GLD) are placed in areas of interest. Once verified operational, they are reported to AOML's Data Assembly Center (DAC). Incoming data from the drifters are then placed on the Global Telecommunications System (GTS) for distribution to meteorological services everywhere. More information can be found at: http://www.aoml.noaa.gov/phod/dac/dac.html

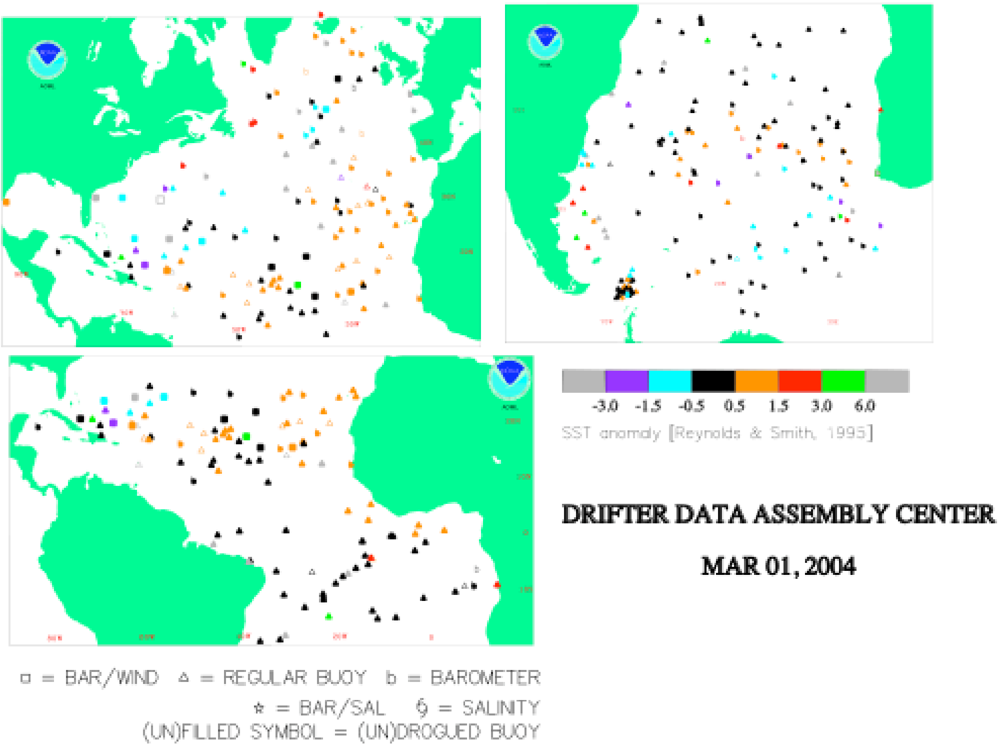


Figure 3. Drifters population and positions in the North, South and Tropical Atlantic in March 1st 2004. Colours indicate SST anomaly.

The primary goal of this project is to assemble and provide uniform quality control of sea surface temperature (SST) and surface velocity measurements. These measurements are obtained as part of an international program designed to make this data available in an effort to improve climate prediction. Climate prediction models require accurate estimates of SST to initialize their ocean component. Drifting buoys provide essential ground truth SST data. The Global Drifter Center is located at AOML in Miami, Florida. The center manages the deployment of drifting buoys around the world. Using research ships, Volunteer Observation Ships (VOS), and U.S. Navy aircraft, Global Lagrangian Drifters (GLD) are placed in areas of interest. Once verified operational, they are reported to AOML's Data Assembly Center (DAC). Incoming data from the drifters are then placed on the Global Telecommunications System (GTS) for distribution to meteorological services everywhere. More information can be found at: http://www.aoml.noaa.gov/phod/dac/dac.html

A.3 Subsurface Floats and ARGO Project

Argo is a new method of collecting information from the upper ocean using a fleet of robotic floats. Argo data complement other in-situ observations (many restricted to shipping routes) and data from earth-observing satellites.

Argo floats drift at depths between 1 and 2 km. Every 10 days each float surfaces and measures a profile of temperature and salinity. Argo has the unique capacity to provide measurements throughout the ice-free regions of the deep ocean and especially at high latitudes in winter. These data and the float's position are transmitted to satellites and the float then dives to start a new cycle. The sub-surface drift enables the currents that transport heat and water to be estimated across entire ocean basins. The 3000 floats Argo array (spaced about 300 km apart) will deliver 100,000 profiles per year. Over 25% of the array is now operating. Completion is expected by 2006. Objectives of Argo fall into several categories. Argo will provide a quantitative description of the evolving state of the upper ocean and the patterns of ocean climate variability, including heat and freshwater storage and transport. The data will enhance the value of the Jason altimeter through measurement of subsurface vertical structure (T(z), S(z)) and reference velocity, with sufficient coverage and resolution for interpretation of altimetry sea surface height variability. Argo data will be used for initialization of ocean and coupled forecast models, data assimilation and dynamical model testing. A primary focus of Argo is seasonal to decadal climate variability and predictability, but a wide range of applications for high-quality global ocean analyses is anticipated.

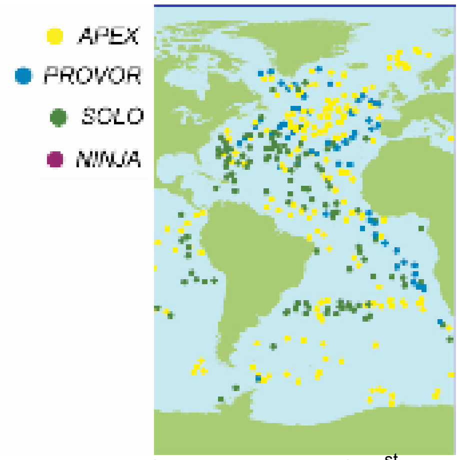


Figure 4. Active ARGO floats in the Atlantic by float model, as of 31st January 2004

The initial design of the Argo network is based on experience from the present observing system, on newly gained knowledge of variability from the TOPEX/Poseidon altimeter, and on estimated requirements for climate and high-resolution ocean models. Argo will provide 100,000 T/S profiles and reference velocity measurements per year from about 3000 floats distributed over the global oceans at 3-degree spacing. Floats will cycle to 2000 m depth every 10 days, with a 4-5 year lifetime for individual instruments. All Argo data will be publicly available in near real-time via the GTS, and in scientifically quality-controlled form with a few months delay.

More information can be found at: http://w3.jcommops.org/cgi-bin/WebObjects/Argo

A.4 Global Tide Gauge Network

The tide gauge data from the international program Global Sea Level Observing System (GLOSS) aims at the establishment of high quality global and regional sea level networks, including the South and tropical Atlantic Ocean, in an evenly distributed spatial sampling. The NODC and the University of Hawaii provide access to the sea level data through the Join Archive for Sea Level (JASL). These data, primarily since 1980, are hourly, daily and monthly from stations in tropical and subtropical areas of all ocean basins, including the South and tropical Atlantic. However present data are measured with different standards and have a Northern Hemisphere bias. Most data belong to tide gauges although some are derived from bottom-mounted pressure gauges. The observations obtained from them are used to conduct research activities that include interannual and decadal sea level fluctuations and tropical ocean dynamics. Within this context, the archive of long-term data records, as provided by NODC, is a key to complement observations by altimetry that began in 1985 with the launch of the GEOSAT mission, to estimate long-term modulation of events, to determine the temporal characteristics of the record covered by altimetry, and to monitor ocean circulation. Moreover, these tide gauge data records are needed to calibrate altimeters, to provide information where altimetry has data gaps in time and space, to provide long-term records on coastal and in high latitude regions.

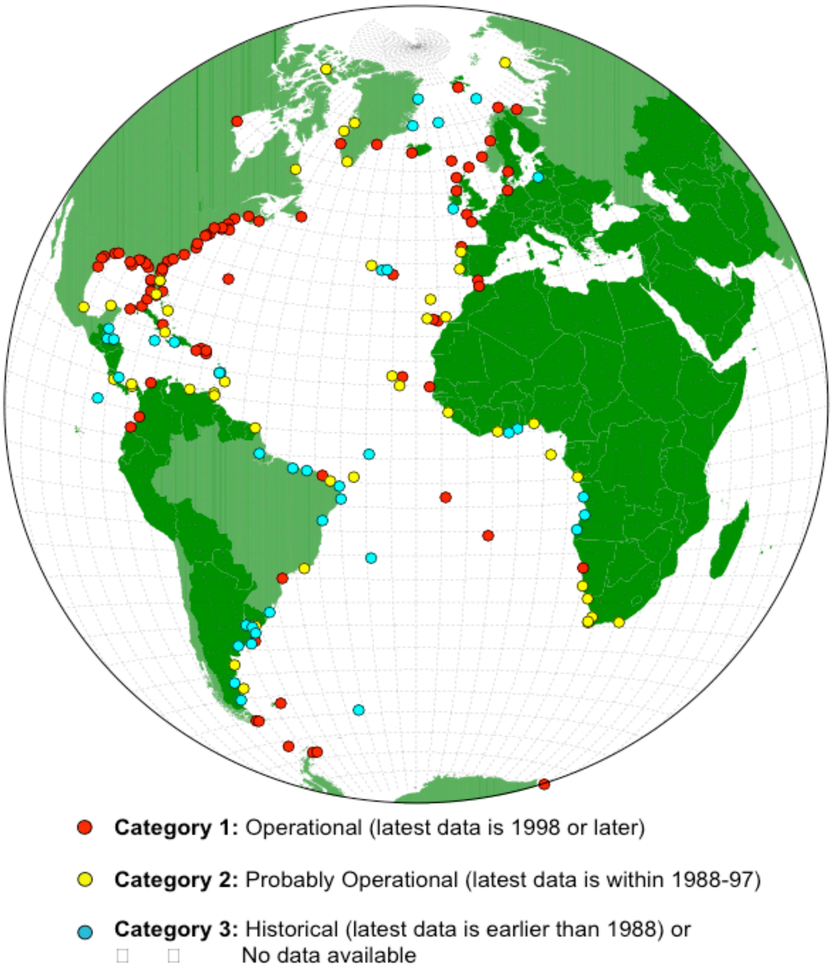


Figure 5. Atlantic Sea level network by category

More information on the Global Sea Level Network can be found at:
http://badc.nerc.ac.uk/data/gloss/
http://lwf.ncdc.noaa.gov/oa/climate/research/slp/index.html

A.5 Global Ships of Opportunity Network

The Ship-of-Opportunity Program (SOOP) is an international effort directed primarily towards the continued operational maintenance and co-ordination of the XBT ship of opportunity network but other types of measurements are being made (e.g. TSG, XCTD, CTD, ADCP, pCO2, phytoplankton concentration).

In conjunction with SOOP, a program developed by National Oceanic and Atmospheric Administration (NOAA) SEAS (http://seas.amverseas.noaa.gov/seas/) was created to provide accurate meteorological and oceanographic data in real time from ships at sea through the use of satellite data transmission techniques. The system transmits data through either the GOES or INMARSAT C satellites to NOAA for use in weather, climatological and ocean models such as in the Fleet Numerical Oceanography and Meteorology Center (FNMOC) OTIS SST analysis above. Its goal on the World Wide Web is to provide information on the past and current activities of the NOAA SEAS XBT program.

An example of the present SOOP network is shown in Figure 6.

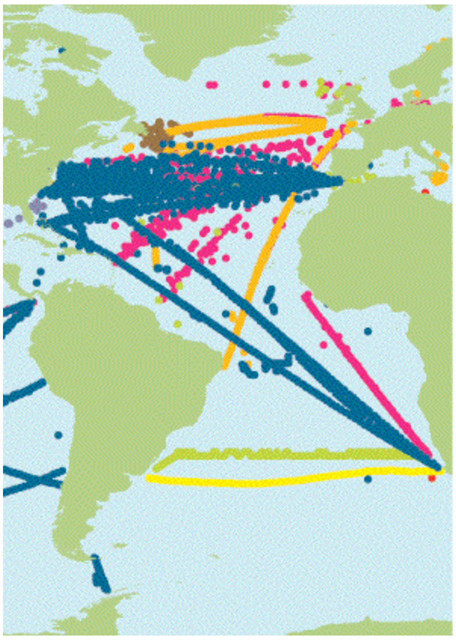


Figure 6: Example of the international XBT lines conducted for the period January-2002 to December 2002. Full lines correspond to high density lines and point lines correspond to low density sampling.

The XBT sampling is performed at three different resolutions:

- Low-resolution sampling, targeted the large-scale, low frequency modes of climate variability and making no attempt to resolve the energetic, mesoscale eddies that are prevalent in much of the ocean. The low-resolution lines are maintained through an international consortium with oversight by the SOOP Implementation Panel and data are frequently available in real-time for operational climate forecasts and analyses.
- Frequently repeated XBT (FRX) lines are mostly located in tropical regions to monitor strong seasonal to inter-annual thermal variability in the presence of intra-seasonal oscillations and other small scale geophysical noise. They are intended to capture the large-scale thermal response to changes in equatorial and extra-equatorial winds. The lines are (ideally) covered 18 times per year with an XBT drop every 100 to 150 km.
- High resolution XBT (HRX) lines are those whose sampling criteria require boundary-to-boundary profiling, with closely spaced XBTs to resolve the spatial structure of mesoscale eddies, fronts and boundary currents. The repetition frequency is about four times per year.

More information can be found at: http://www.ifremer.fr/ird/soopip/index.html

A.6 Ocean Carbon Monitoring Network

Between 1990 and 1998 the WOCE Hydrographic Programme (WHP) occupied a grid of 20000 full depth hydrographic stations (the WHP One Time Survey). Together with other occupations of some of these sections (repeat hydrography), these sections document changes in oceanic properties and circulation on decadal timescales based on physical, chemical and transient tracer measurements. They also form the basis for determining oceanic heat and freshwater transports. During the WHP, collaboration between WOCE and JGOFS led to the complementary measurement of parameters to enable ocean carbon storage and transports to be determined. CLIVAR is concerned with further refining the WOCE determinations of oceanic heat and freshwater transports and with documenting decadal and shorter period ocean changes based in large part on the reoccupation of a subset of the hydrographic sections that formed the WHP.

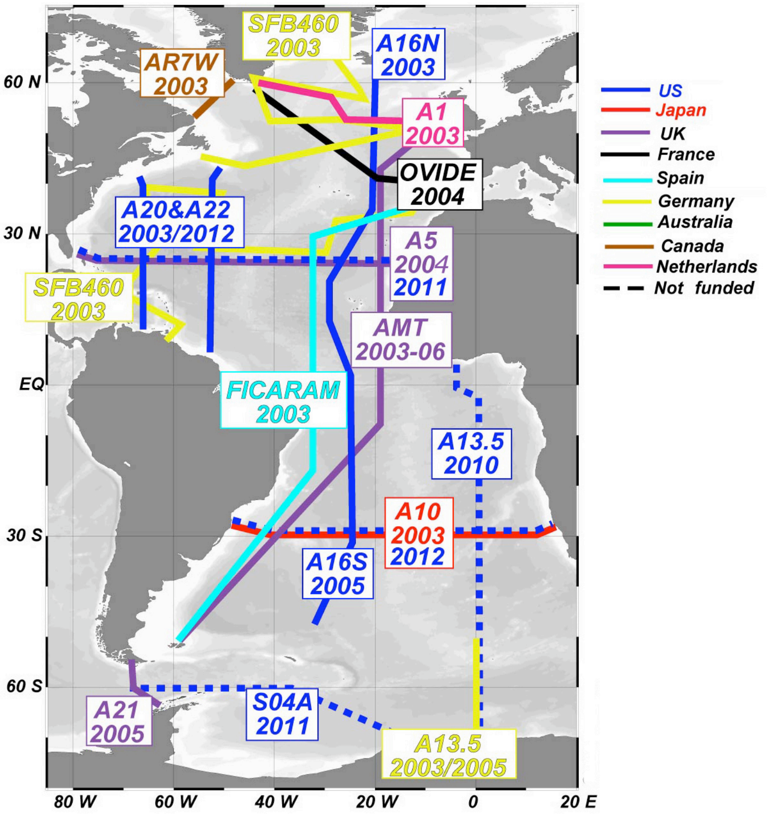


Figure 7: International CLIVAR/ CO_2 lines in the Atlantic, repeated every 7-10 years

In similar fashion there are a number of national and international initiatives aimed at better assessing the role of the oceans in storing and distributing carbon, particularly in light of rapidly rising atmospheric CO_2 levels. Reoccupations of WHP sections form a key component of these ocean carbon strategies. The International Ocean Carbon Coordination Project (IOCCP) is co-sponsored by the SCOR/IOC CO2 panel and the Global Carbon Project. It has been set up to work with national, regional and international carbon programs and data centres to provide a global view of ocean carbon.

Thus the reoccupations need to be closely coordinated between CLIVAR and the IOCCP to ensure that:

- the essential suite of measurements are made to serve both CLIVAR and ocean carbon requirements
- agreed standards are set for the determination of each parameter
- an effective system is developed to quality-control, safeguard, distribute and archive the resulting data sets.

More information can be found at: http://www.clivar.org/carbon_hydro/

A.7 VOS Surface Marine Network

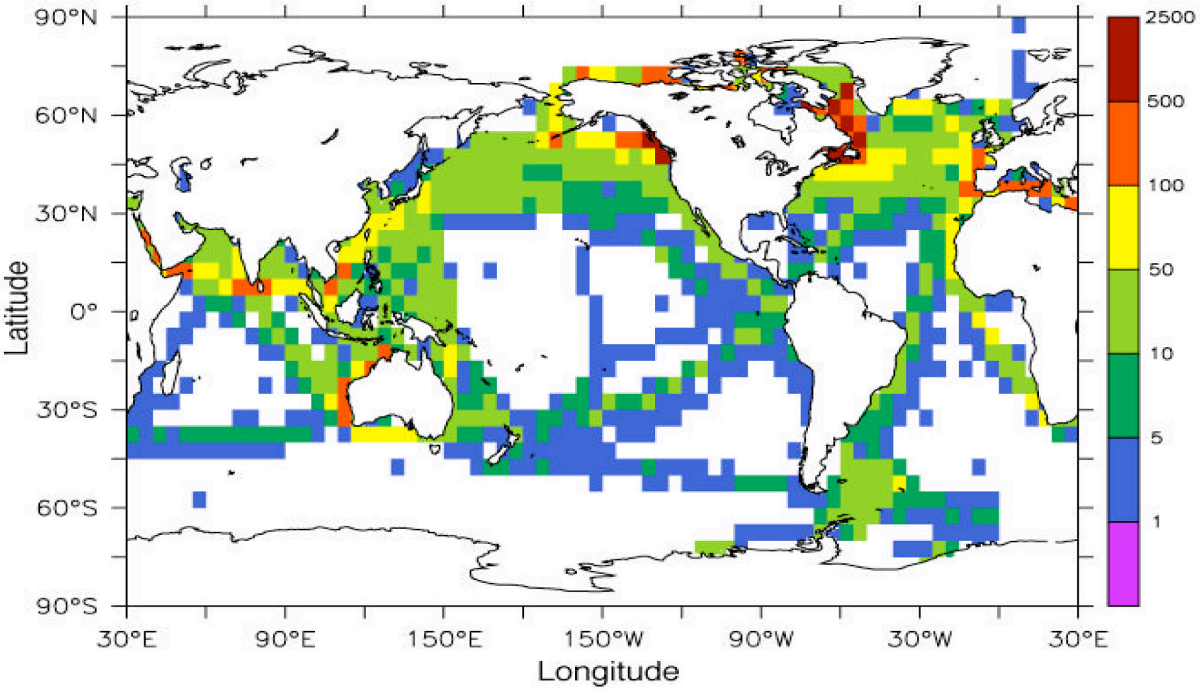


Figure 8. Map of the observation density for ships real-time data during the period Feb 2002 to April 2003.

The international scheme by which ships plying the various oceans and seas of the world are recruited by National Meteorological Services (NMSs) for taking and transmitting meteorological observations is called the World Meteorological Organization (WMO) Voluntary Observing Ships' (VOS) scheme. During the past few decades, the increasing recognition of the role of the oceans in the global climate system has placed even greater emphasis on the importance of marine meteorological and oceanographical observing systems. One of the major continuing problems facing meteorology is the scarcity of data from vast areas of the world's oceans (the so-called 'data sparse areas') in support of basic weather forecasting, and climate analysis and research. While the new generation of meteorological satellites help to overcome these problems, data from more conventional platforms, in particular the voluntary observing ships, remain essential. These ship observations provide ground truth for the satellite observations, important information which the satellites cannot observe, and essential contributions to the data input for the numerical weather prediction (NWP) models. As might be expected, real-time reports from the VOS are heavily concentrated along the major shipping routes, primarily in the North Atlantic and North Pacific Oceans. Of course, as VOS reports are part of a global data capture program, their reports are of value from all the oceans and seas of the world, and even the well frequented North Atlantic and North Pacific Oceans require more observational data.

The VOS Climate Project (VOSClim) is an ongoing project within JCOMM's Voluntary Observing Ships' Scheme. It aims to provide a high-quality subset of marine meteorological data, with extensive associated metadata, to be available in both real-time and delayed mode to support global climate studies. VOSClim is a follow-up to the earlier VOS Special Observing Project North Atlantic (VSOP-NA) which was conducted on behalf of the World Climate Research Project (WCRP) from 1988 to 1990.
Data from the project will be invaluable for climate change studies and research. In particular it will be used to:

- input directly into air-sea flux computations, as part of coupled atmosphere-ocean climate models;
- provide ground truth for calibrating satellite observations;
- provide a high quality reference data set for possible re-calibration of observations from the entire VOS fleet.

The project is now in its implementation phase with almost 100 ships having been recruited to participate so far. Figure 8 gives an indication of the level of coverage likely to be achieved by the project ships.
The project website: http://lwf.ncdc.noaa.gov/oa/climate/vosclim/vosclim.html is now active and the valuable incoming data from project ships are now being monitored and analyzed.

A.8 Moored Buoy Network

Moored buoys are deployed in the coastal and offshore waters to measure and transmit barometric pressure; wind direction, speed, and gust; air and sea temperature; and wave energy spectra from which significant wave height, dominant wave period, and average wave period are derived. Even the direction of wave propagation is measured on many moored buoys. In addition to their use in operational forecasting, warnings, and atmospheric models, moored buoy data are used for scientific and research programs. The NOAA National Data Buoy Center (http://seaboard.ndbc.noaa.gov/), the Environment Canada (http://sebulba.pyr.ec.gc.ca/~wbs/bplatstat.html) and the European Group on Ocean Stations (http://www.meteo.shom.fr/egos/) are in charge:

- To maintain an operational network of moored buoys in data sparse areas in the North Atlantic.
- To coordinate data dissemination and monitor data quality.
- To provide information on the operational status of the buoys on a regular basis.

PIRATA (Pilot Research Moored Array in the Tropical Atlantic, http://www.pmel.noaa.gov/pirata/) is a project designed by a group of scientists involved in CLIVAR, and is implemented by the group through multi-national cooperation (cf. section III). The purpose of PIRATA is to study ocean-atmosphere interactions in the tropical Atlantic that are relevant to regional climate variability on seasonal, interannual and longer time scales.

The scientific goals of the PIRATA array are: to provide a description of the seasonal-to-interannual variability in the upper ocean and at the air-sea interface in the Tropical Atlantic; to improve our understanding of the relative contributions of the different components of the surface heat flux and ocean dynamics to the seasonal to interannual variability of SST within the tropical Atlantic basin; and to provide a data set that can be used to develop and improve predictive models of the coupled Atlantic climate system. (PIRATA Science and Implementation Plan, 1996). To achieve the objectives PIRATA designed, deployed and maintain a pilot array of ATLAS moored oceanic buoys that measure a set of oceanic and atmospheric parameters. Data is collected and transmitted in real time via satellite and posted in a web page. The location of the PIRATA moorings is given in Figure 10.

Figure 9. Position of the operational Moored Buoys, the PIRATA array and the Northwest Tropical Atlantic Station (NTAS).

The Northwest Tropical Atlantic Station (NTAS) project for air-sea flux measurement was conceived in order to investigate surface forcing and oceanographic response in a region of the tropical Atlantic with strong SST anomalies and the likelihood of significant local air-sea interaction. The primary science objectives of the NTAS project are to determine the in-situ fluxes of heat, moisture and momentum, and then to use these in-situ fluxes to make a regional assessment of flux components from numerical weather prediction models and satellites, and to determine the degree to which the oceanic budgets of heat and momentum are locally balanced. The scientific objectives are addressed through analysis of observations from a surface mooring deployed near 15° N, 51°W. The NTAS site is at the eastern edge of the Guiana Abyssal Gyre/Meridional Overturning Variability (GAGE/MOVE) Experiment mooring array and can be considered a westward extension of the Pilot Research Moored Array in the Tropical Atlantic (PIRATA). Hourly meteorological data for the current deployment of the NTAS buoy are received via Service Argos four times daily. Data is displayed as time series and available for download as ASCII files from http://uop.whoi.edu/ntas/index.html

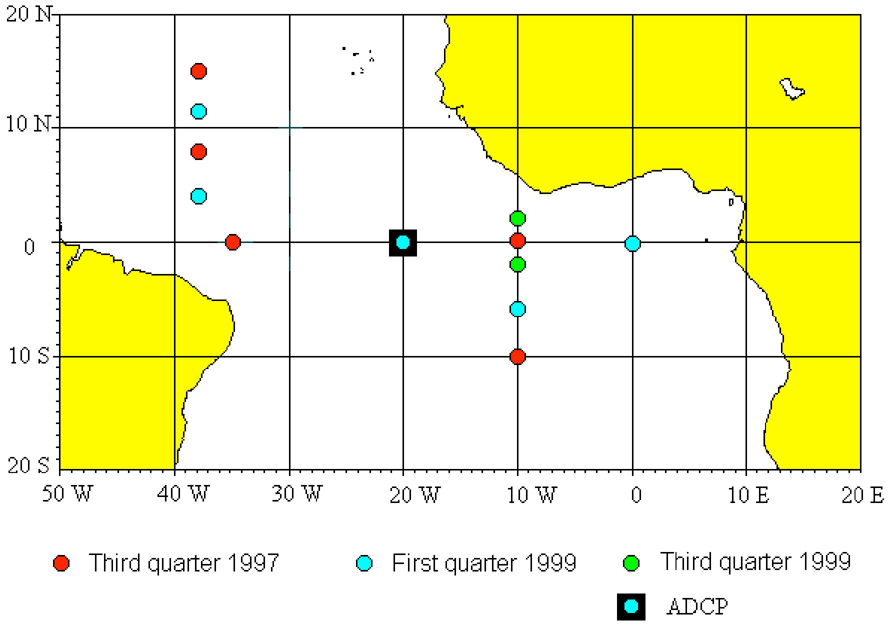


Figure 10: Location of the PIRATA moorings.

B. Land Based Observations

The Global Climate Observing System (GCOS) established in 1992, identified the needs to facilitate the establishment or enhancement of networks to obtain observations in the areas of meteorology and atmospheric chemistry. Toward this end, it has defined two networks as sub-systems of the WWW Global Observing System. The GCOS Upper-Air Network (GUAN) has been established to ensure that appropriate upper-atmospheric observations for climate purposes will be available. One hundred and fifty stations were selected from the roughly 1000 WWW upper-air stations on the basis of their location, quality and record length. Similarly, for surface observations, GCOS worked with climate change detection experts to define a global network of high-quality stations for monitoring global temperatures. The GCOS Surface Network (GSN) consists of 989 stations.

B.1 GCOS Upper Air Network (GUAN)

The principal aims of the GUAN project are to ensure a relatively homogenous distribution of upper air stations that meet specific record length and homogeneity requirements outlined by GCOS and to develop, and make available, their current and historical data. A total of 150 sites have been selected, with a further 15 sites for use as a standby network, network upgrades, or furthering monitoring in the Indian and African regions, for their reliable prior records and the potential to provide data in the future. The Met Office, Hadley Centre (http://www.metoffice.gov.uk/research/hadleycentre/guan/index.html) and NOAA/NCDC have been nominated as joint data analysis centres for GUAN. ECMWF have also been asked to provide reports on the quality and availability of real time data. GUAN should provide a data set of both daily data at standard and significant levels, and monthly data at the standard pressure levels with an accompanying metadata base. The network will be, temporally and spatially, as homogenous as possible, with complex quality control procedures and bias corrections applied to the time series. Some grid products will be available on line, while daily and monthly data will be provided by the respective institutions on request only.

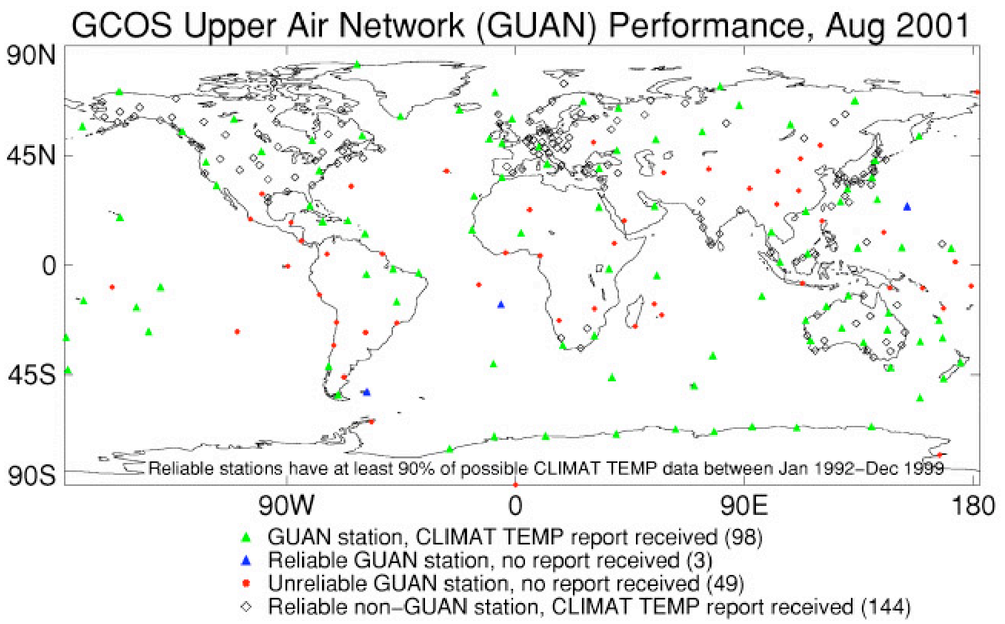


Figure 11. Map of reporting GUAN Stations (MetOffice) based on CLIMAT TEMP reports received over the GTS within one calendar month of the reference date.

A.2 GCOS Surface Network

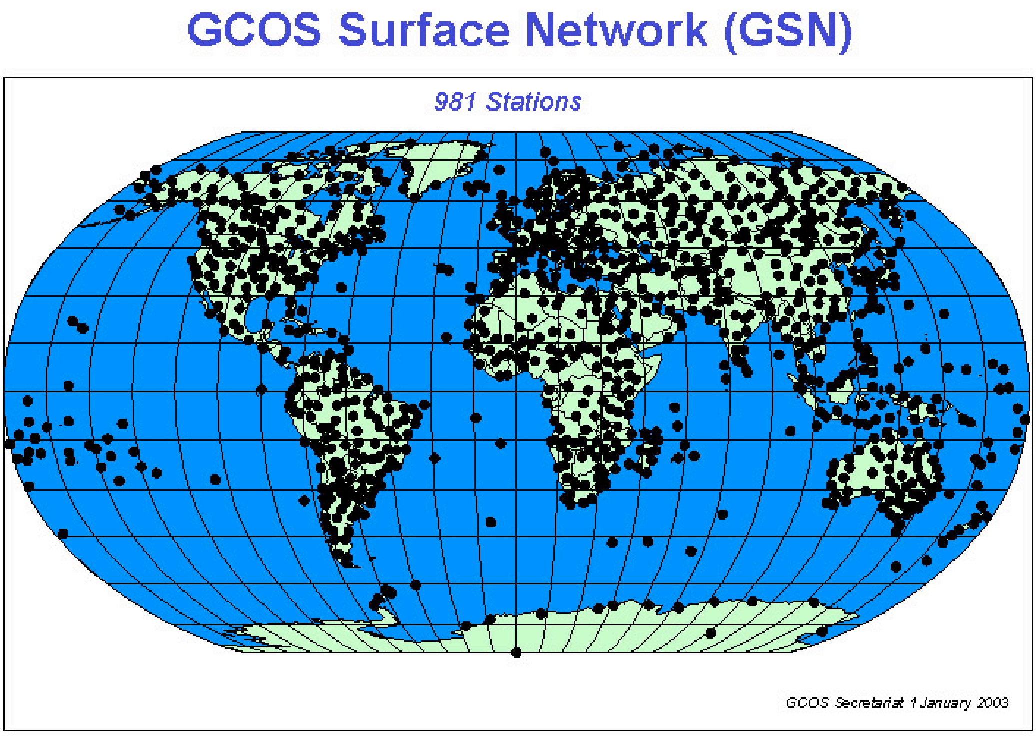


Figure 12. Spatial distribution of GSN Stations.

The Initial selection of a GSN was initiated in 1997. Ranking and selecting by use of an objective method led to about 1000 stations to be included in the GSN. Based on results from the monitoring centres the GSN is beeing under review and some changes have been introduced meanwhile (deletion of stations, placement, new stations). The most recent GSN station map can be view in Figure 12. Germany (http://www.gsnmc.dwd.de/GSNMC.htm) and Japan officially offered to serve as GSN Monitoring Centres.

II. North Atlantic MOC Observations and Link to Arctic

A. Scientific Background

It has long been recognized that the Atlantic meridional overturning circulation (MOC) is potentially sensitive to greenhouse gas and other climatic forcing, and that changes in the MOC have the potential to cause abrupt and perhaps global climate change. Though the mechanisms remain poorly understood, the two-way exchanges of heat, mass and salt between the North Atlantic and the Arctic Ocean are known to be implicated, and their interplay and variability are becoming known from two main data sets:- first, from standard hydrographic sections worked across the main gateways of exchange for periods of over a Century; second, from direct flux measurements conducted across each of the main choke-points by the multinational VEINS (1997-2000), ASOF (2000- present) and other programs [see eg Hansen and Østerhus, 2000; Hansen et al 2001; Fahrbach et al 2001, 2003; Schauer et al in press; Ingvaldsen et al 2002; Jonsson and Briem, 2003; Melling 2000 and 2004; Prinsenberg and Bennett, 1987; Prinsenberg & Hamilton 2004]. From this long-sustained effort, we would now recognise that the entire ocean-atmosphere system of Arctic and subarctic seas is involved in driving the multi decadal changes we observe, and as our understanding has grown, we have begun to appreciate both the complexity and the systematic nature of these changes.

A.1 Relevant aspects to the Climate System in the Atlantic Sector

1. Discounting recent claims to the contrary by Seager et al (2002), Rhines and Hakkinen (2003) re-establish the case that the northward flux of heat by the ocean is of major importance to the climate of Europe. Their case hinges less on re-interpreting the experimental results of Seager et al --though in fact a substantial cooling over northern seas *does* seem to follow the suppression of the ocean circulation in their GISS model -- but on the more substantive issue that heat and freshwater transports are intimately coupled, so that removal of only one of them renders the problem meaningless. In other words, the northward transport of salt, the accumulation or redistribution of freshwater at or from high latitudes, the growth and decay of ice-cover and the uptake and release of heat by the ocean are so intimately related as to preclude any simpler approach to modelling the problem.

2. We have understood for some time that the warm, moist southerly airflow directed along the eastern boundary of the North Atlantic under the increasingly NAO-positive conditions of recent decades has in some way been responsible for driving a warmer (Dickson et al 2000), stronger (Dye 1999; Mork and Blindheim, 2000; Orvik et al 2001) and probably narrower (Blindheim et al 2000) flow of Atlantic water northwards to the Barents Sea and into the Arctic Ocean since the 1960s (Quadfasel, 1991; Carmack et al 1995; Aagaard et al, 1996; Tereschenko, 1996; Swift et al, 1997; Carmack et al, 1997; Grotefendt et al 1998; Morison, Aagaard and Steele, 1998; Karcher et al 2003). We have more recently understood that the spread of warmth to the Barents Sea might be attributable to a mix of both local- (Adlandsvik, 1989; Adlandsvik and Loeng, 1991; Loeng, Ozhigin and Adlandsvik, 1997) and remote- forcing (Orvik and Skagseth, 2003). Orvik and Skagseth suggest in fact that the volume transport of the Norwegian Atlantic Current passing Svinoy (62°N) is most closely correlated with the Atlantic wind stress curl at 55°N, 15 months earlier, conveying some possibility of prediction; they suggest that the barotropic nature of the flow might also be imposed upstream along the Irish-Scottish shelf. The various possible constituents for overflow through Denmark Strait have gradually been assembled into a current recipe and mixing scheme (Mauritzen, 1996a,b; Rudels et al 2002), revealing the interconnected nature of inflow and outflow through the Nordic Seas. Simply, the Atlantic Water which inflows to the Arctic across the Barents Sea shelf --subsequently transformed into upper Polar Deep Water (uPDW)-- forms the bulk of the contribution which the Arctic Ocean makes to Denmark Strait Overflow and hence to the deep limb of the MOC. (Eurasian Basin Deep Water will always be too dense to contribute to overflow through Denmark Strait, and Canada Basin Deep Water is currently too dense to do so; Rudels et al., 2002). Second,

recirculation from the Norwegian Atlantic Current in eastern Fram Strait (the other Atlantic Water branch passing northwards to the Arctic Ocean) forms the other main contribution to DSOW. Though new candidate pathways for overflow are still being put forward (eg Jonsson and Valdimarsson, 2004), the long spreading time from Fram Strait to overflow has already been used successfully to predict the changing hydrographic characteristics of DSOW and of the DSOW-derived abyssal layer of the Labrador Sea downstream (Dickson, Curry and Yashayaev, 2003).

4. From the gateway arrays supported by models it has been possible for the first time to quantify the main fluxes of freshwater passing south from the Arctic Ocean to the Atlantic either side of Greenland. It is the anticipated increase in these freshwater outflows under greenhouse-gas forcing that has been implicated in model experiments with a slowdown of the MOC and associated effects on climate (eg Mauritzen and Hakkinen, 1997; Rahmstorf and Ganopolski, 1999; Delworth and Dixon 2000; Marotzke, 2000; IPCC 2001; Stocker et al 2001; Rahmstorf 1996, 2002; Vellinga and Wood, 2002). Thermohaline effects of the Great Salinity Anomaly(ies) provide a case in point (Hakkinen, 1999; Haak et al 2003). Since our present records are rarely long enough yet to determine variability, and since they include the direct measurement of vigorous flows in remote ice-covered passageways through the Canadian Arctic where the scales of motion are small, where moving ice and icebergs pose a hazard to moored gear and where proximity to the magnetic pole complicates even the measurement of flow direction, comprehensive simultaneous coverage has understandably been difficult to achieve. However the available freshwater flux estimates seem self-consistent, with approx. 0.1 Sv (each) passing south through Davis Strait and Denmark Strait. A comparison of model-based and hydro-based estimates provides an initial indication that the freshwater gained by the water column of the NW Atlantic since the 1960s is of a similar order to that lost from the Arctic Ocean (NAOSIM model estimate by Karcher; see Dickson, Yashayaev and Dye, op cit).

5. In most cases, our estimates of freshwater flux from high latitudes are too short to describe variability and the factors that might control it. However historic hydrography from Arctic and subarctic seas, and a relative wealth of new fieldwork (in SHEBA, SBI, CASES, CATS, ASOF, CHAMP and other programs) has provided a conceptual framework for these controls, which is now under test. A range of authors describe how freshwater storage within the Arctic Ocean has changed with time (Anderson et al 2004; Schlosser et al 2002; Steele and Boyd, 1998), and at least three candidate mechanisms describe the time-dependent ‘switchgear’ that directs the freshwater outflow along different pathways to lower latitudes, typically in response to different modes of the Arctic Oscillation (Proshutinsky and Johnson 1997; McLaughlin et al 2002; Steele et al 2003; see also Dukhovskoy, Johnson and Proshutinsky, 2004). The notion that such a ’switchgear’ mechanism exists is important to the predictability of the system, since it carries the implication that there is some sort of discoverable shared time-dependence between the two main freshwater transports passing south either side of Greenland. However even if such a switchgear exists, it is unlikely that the freshwater supply to the Atlantic MOC is simply or solely controlled by processes at the point of outflow. As Hakkinen reminds us (Hakkinen pers comm; Hakkinen and Proshutinsky, 2004), the oceanic exchanges between high- and mid-latitudes are effected by the overlap between two quite different sets of processes, with different time-scales, either side of the Nordic sills, --an immediate barotropic ocean response to the Arctic Oscillation in Arctic and Nordic seas, and a delayed baroclinic response to thermal and wind forcing by the AO/NAO in the Atlantic subpolar gyre and Nordic Seas (Isachsen et al 2003). Interaction between these nearly-independent ‘loops’ of circulation will determine the changes in freshwater content to which the MOC will respond.

6. Although, with few exceptions, our direct measures of freshwater flux have not yet been extended into time series, we maintain long-term salinity records of decade-to-century scale at a scatter of standard stations and sections throughout our northern seas. The

evidence from these is of a recent rapid increase in the outflow of freshwater from the Arctic to the N Atlantic. e.g. (1) a 40-year increase in the offshore density gradient in the upper ocean between the Labrador shelf and the central Labrador Sea (WOCE AR7W line; Dickson, Curry and Yashayaev, 2003) suggests a 20% increase in the southgoing flux of the relatively fresh waters of the shelf and upper-slope around the margins of the Labrador Sea since the mid-1960s. (2) Time series from OWS Mike in the Norwegian Sea (Østerhus, pers comm.) and standard section data west of Norway (Blindheim et al 2000) provide evidence of a broadscale freshening of the upper 1-1.5 km of the Nordic Seas over the past 4-5 decades (3) Tapping-off the freshening upper layer of the Nordic Seas, the entire system of overflow and entrainment that ventilates the deep North Atlantic has undergone a remarkably rapid, persistent and uniform freshening by about 0.010 - 0.015 per decade over the past 4 decades (Dickson et al 2002; Turrell et al 1999). (4) As the 'receiving volume' for these freshening inputs, the entire watercolumn of the Labrador Sea has undergone radical change over the past 3-4 decades; between 1966 and 1992, the overall freshening of the watercolumn of the Labrador Sea has been equivalent to mixing-in an extra 6m of fresh water at the sea surface (Lazier 1995 and pers comm). (6) Discharged into the Deep Western Boundary Current, this deep freshening had been tracked down the American seaboard to 8ºN by 2000 (Ruth Curry, WHOI pers comm).

A.2 Global Connectivity

The link to global change remains to be established. In the literature, two general types of variability are expected to accompany conditions of anthropogenic global warming. These are 1) a slowing of MOC overturning in the North Atlantic, and 2) an intensification of the global water cycle. An initial study by Dickson, Curry and Yashayaev (2003) suggests that there has been little sustained, significant or concerted change in the trans-ocean gradients of steric height in recent decades, either for a long meridional transect through the deep basins of the western Atlantic from 32S to 60N (closely correlated with MOC overturning in HadCM3 experiments; Thorpe et al 2001), or for the latitude of maximum ocean heat transport at 24N (the basis of the NERC-RAPID MOC Monitoring Array by Marotzke). On the other hand, there is evidence of a concerted and large-scale change in salinity between the late 1950s–early 60s and the 1990s along a similar meridional transect from 50S to 60N through the South and North Atlantic, thus covering the main centres of SSS, steric height and E-P in both hemispheres (Curry et al 2003). Though the hydrographic data set from the South Atlantic is less complete and dependable, the evidence is of long term freshening towards both poleward limits of the section, and a more saline upper ocean in the tropics of both hemispheres. A similar structure of change in recent decades has been reported from the North and South Pacific and Indian Ocean (Wong et al 1999, 2001; Bindoff and McDougall, 2000), suggesting that the Ocean may already be registering an amplification of the global water cycle.

As regards future change, three main factors seem set to dominate changes in the freshwater budget at high latitudes

- The discharge of the major Eurasian rivers to the Arctic Ocean is expected to increase with Arctic warming. Peterson et al (2002) have derived an empirical relationship between recent warming and past Russian riverflow amounting to +0.007 Sv per ºC. Citing present predictions of a global rise in surface air temperature of between 1.4 ºC and 5.8 ºC by 2100 (IPCC TAR, 2001), they therefore predict that the "discharge from the six largest Eurasian rivers alone would increase by 0.01 to 0.04 Sv (315 -1260 km^3/year) by 2100".
- Arctic Ocean sea-ice is expected to decrease steadily in volume over the 21st Century. Weaver's group at U Victoria, Canada predict a loss of some 8500 km ^{3} (46%) of ice by 2100, the freshwater equivalent of 0.0027 Sv.
- The freshwater flux from Greenland is expected to increase. As one recent example, simulations by Fichefet et al (2003) suggest that the annual mean total freshwater flux from Greenland will increase by 0.015 Sv over the period 1970-2080. The total area of Greenland ice shrinks by 1%, the total volume is reduced by an amount equivalent to a 5.5 cm rise in global sea level. If correct, a *combined* increase of this order (+0.04Sv)

is not insignificant. Peterson et al (2002) cite freshwater sensitivity experiments with a range of ocean and climate models as predicting that the critical additional freshwater flux to the northern Atlantic 'after which the THC cannot be sustained' lies between 0.06 and 0.15 Sv. In a more recent so-called 'Common Hosing Experiment' in which + 0.1 Sv of freshwater was added to the Atlantic at 50N-70N for 100 years, four AOGCMs showed a variable response, the MOC reducing by up to 10 Sv before recovering (see http://www-pcmdi.llnl.gov/cmip/coord_expt.html and http://www.gfdl.noaa.gov/~kd/CMIP.html; Jonathan Gregory, Hadley Centre, pers comm.)

B. Atlantic MOC Observations

A substantial portfolio of process studies and observations targeting the Atlantic MOC in the Northern Hemisphere is now taking shape (http://www.clivar.org/organization/atlantic/IMPL/proc-stud.html#moc). This includes ongoing national CLIVAR programs in Canada, Norway, France, Germany, and USA as well as two international thematic programs:

1 The activities under and associated with the Arctic - Subarctic Ocean Fluxes study (ASOF; http://asof.npolar.no/). ASOF programme is structured around 7 main tasks: warm water inflow to Nordic Seas, exchanges with Arctic Ocean, ice and freshwater outflow, Greenland-Scotland Ridge exchanges, overflows and storage basins to Deep Western Boundary Current (DWBC), Canadian Arctic Archipelago (CAA) throughflow and modelling processes and predictions. ASOF is an international programme funded mainly by NSF, NOAA, ONR and EC Framework V. ASOF has received the status of a CLIVAR endorsed project by the CLIVAR SSG.

2 The activities under and associated to the UK RAPID Climate Change programme (http://www.nerc.ac.uk/funding/thematics/rcc/). In particular a moored array at 26.5°N to measure directly the meridional mass flux, time series of transient tracers in North Atlantic deep waters, an array along the western margin of the Atlantic to look at boundary wave signals, and an array between New England and Bermuda has been jointly funded by the UK and USA.

B.1 Arctic-Subarctic Ocean Fluxes Study

In the above statements, many of the areas of present uncertainty concern the ocean, more specifically the ocean exchanges which connect the climatically sensitive Arctic Ocean with the world ocean via the subarctic seas. It is the aim of ASOF to supply these missing observations. More specifically: to measure the variability of the fluxes between the Arctic Ocean and the Atlantic Ocean with a view to implementing a longer-term system of critical measurements needed to understand the high-latitude ocean's steering role in decadal climate variability.

Elements of the ASOF observing system that are in place are:

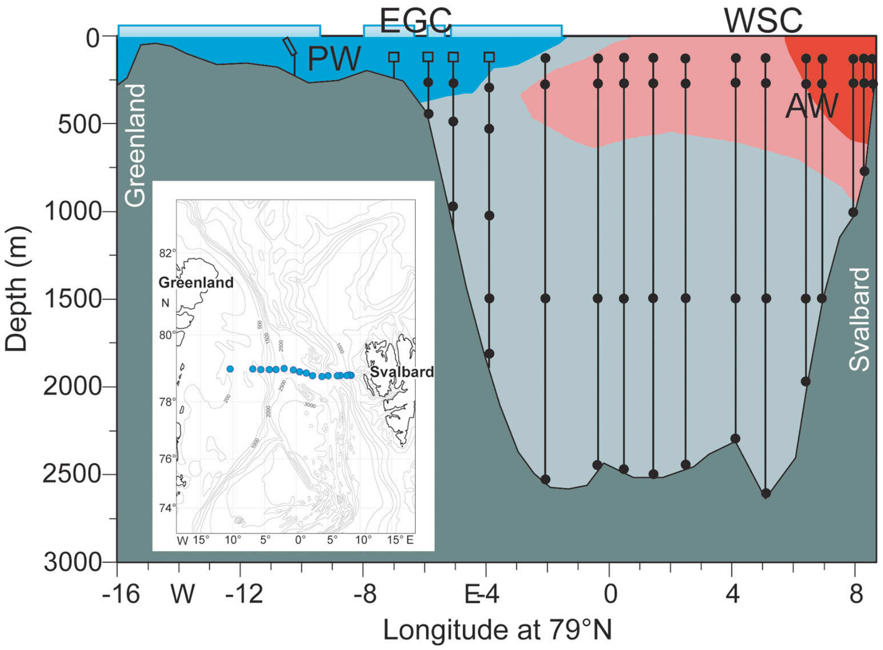


Figure 13. Fram Strait Array: 79N, 10E-10W

To measure:

- *Heat Flux.* Part of the northward flow of warm Atlantic Water reaches the Arctic Ocean through Fram Strait. Since Fram Strait is the only deep passage to the Arctic Ocean, it plays a significant role in the exchange between the Nordic Seas and the Arctic Ocean. Deployment of moorings will allow to monitor and understand the flow of Atlantic Water into the Arctic Ocean. In particular the recirculation within Fram Strait affects the net heat transport significantly.
- *Freshwater*. Sea ice and Polar Water of low salinity provide the freshwater flux from the Arctic. Deployment of moorings will allow to monitor and understand the flow of Polar Water and sea ice from the Arctic Ocean into the Nordic Seas. The techniques to measure the ice-bound freshwater will be further developed to obtain time-series measurements of the salinity profile from underneath the ice to the bottom. They are presently available as a prototype

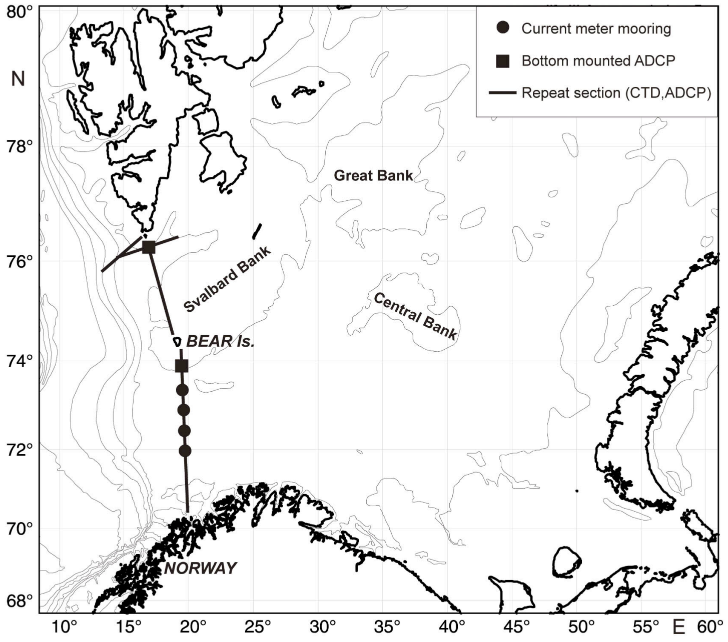


Figure 14. Barent Sea Array: 72-74N, 20E

Fluxes across the western Barents Slope. Part of the northward flow of warm Atlantic Water reaches the Arctic Ocean through Barents Sea. Deployment of moorings will allow to monitor and understand the flow of Atlantic Water into the Barents Sea. In particular the recirculation from the Barents Sea affects the net heat transport significantly.

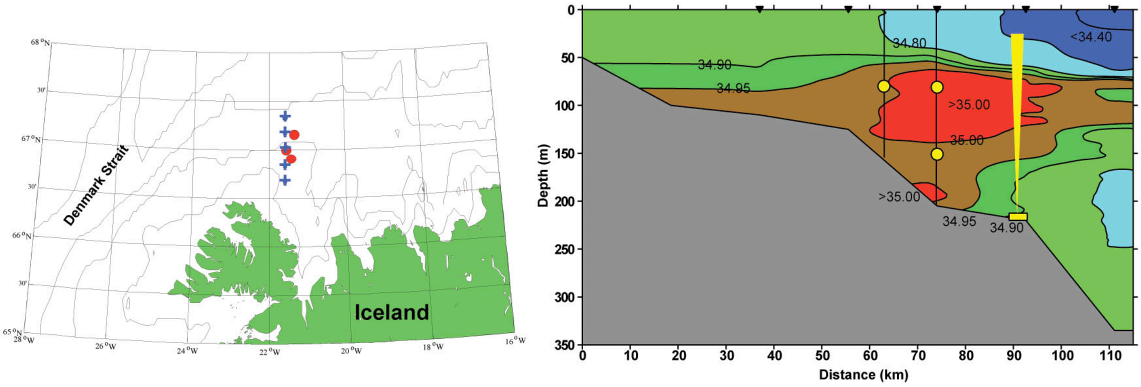


Figure 15. Icelandic Atlantic Inflow: 67N-21.5W

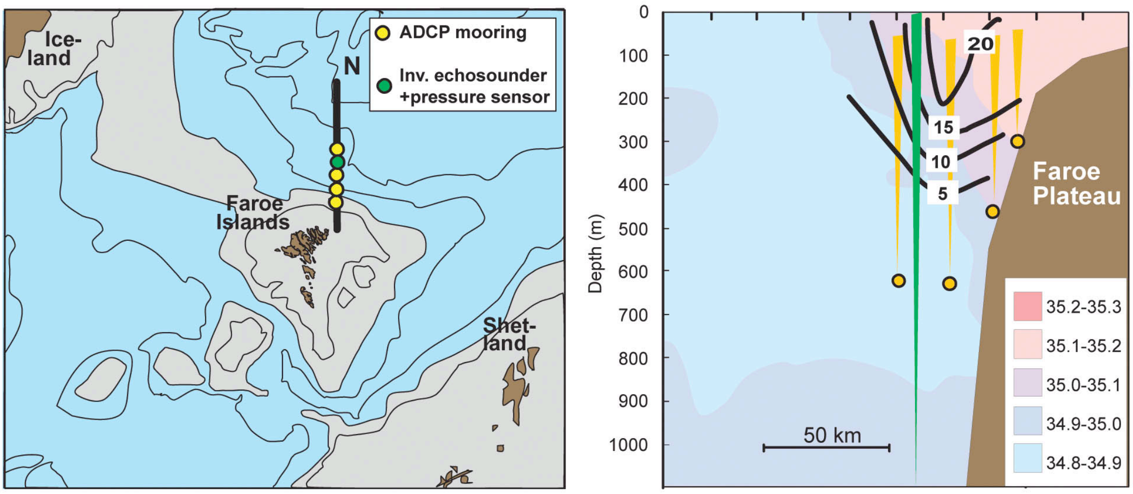


Figure 16. Faroese Atlantic Inflow: 63.3-62.7N, 6.1W

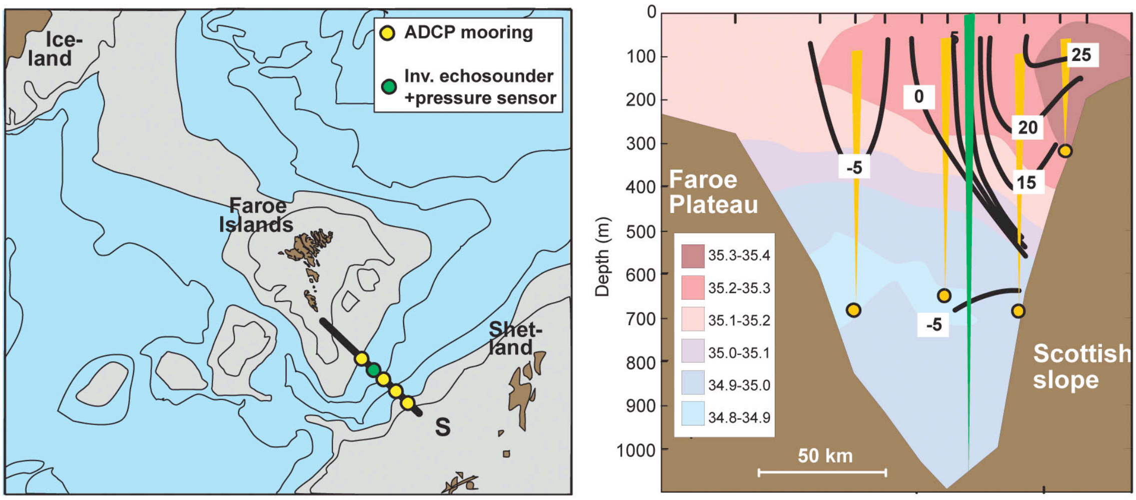


Figure 17. Shetland-Atlantic Inflow: 61-60.5N, 6-4.5W

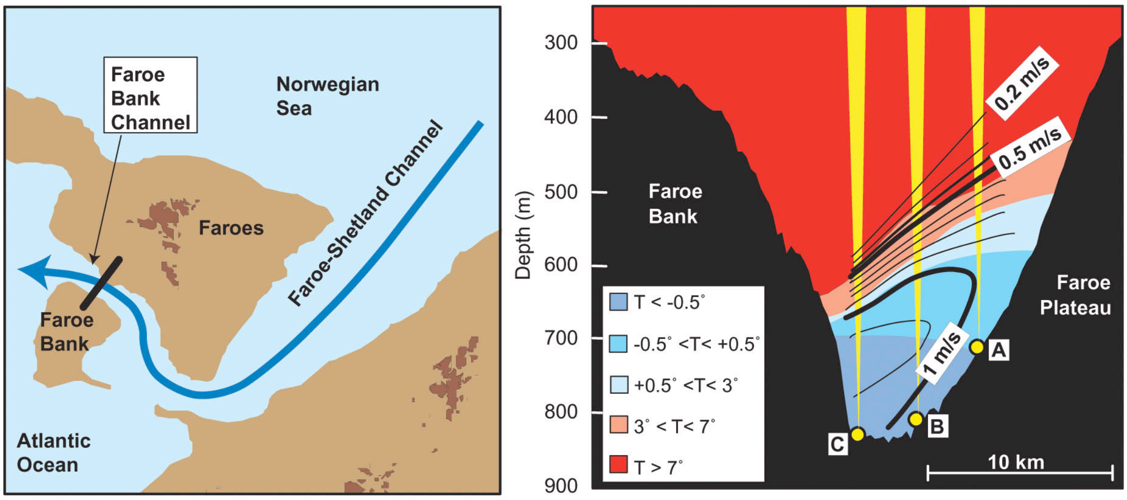


Figure 18. Faroes Bank Channel Overflow: 61.5N, 8.25W

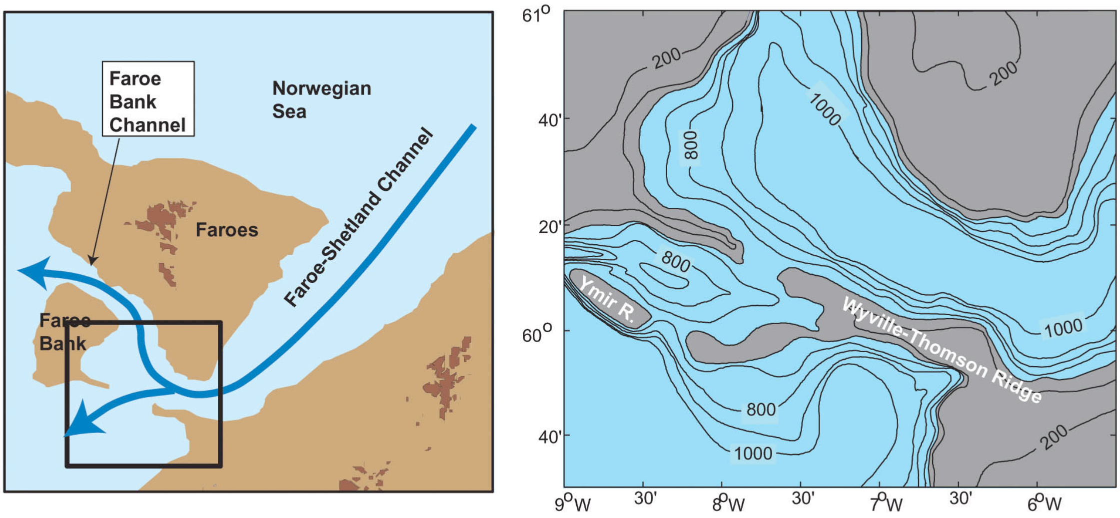
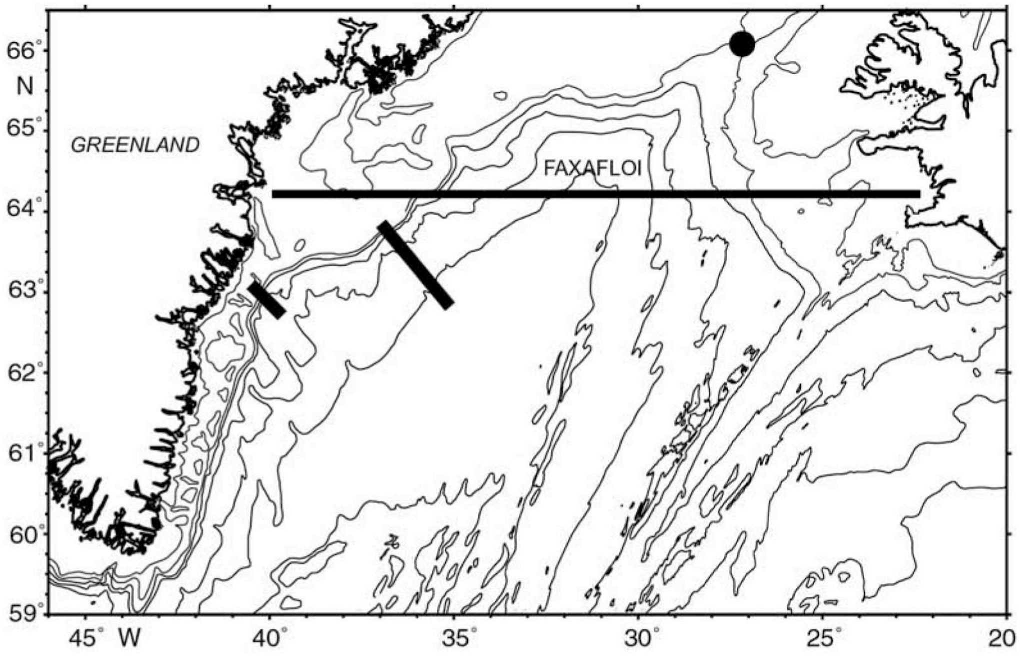


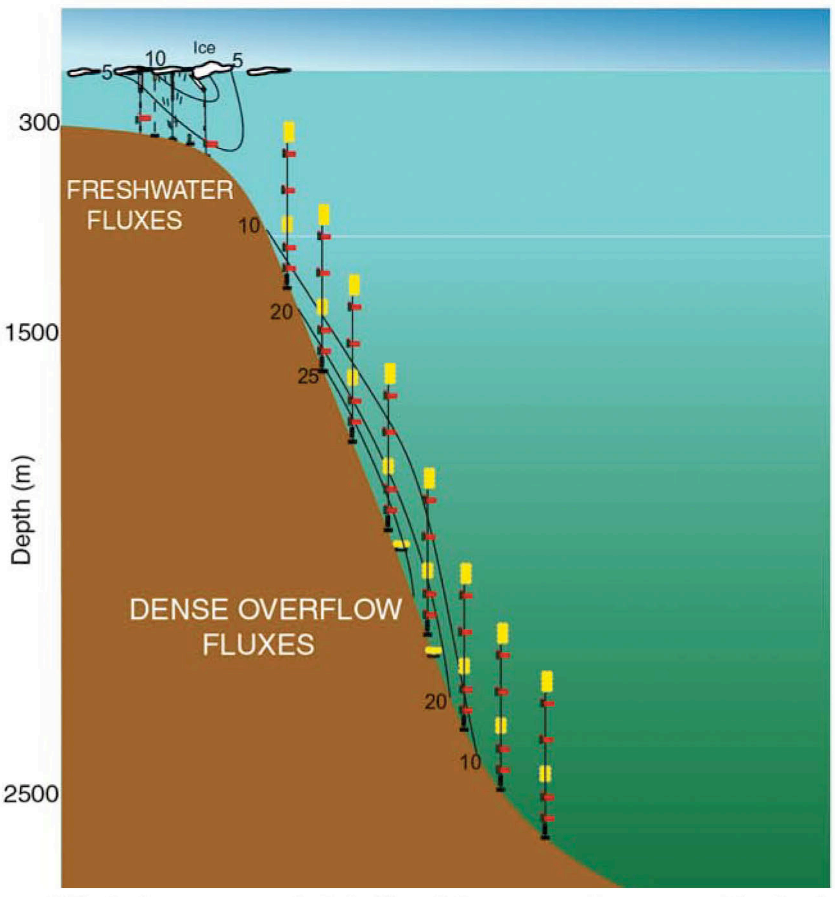
Figure 19. Wyville-Thompson Ridge overflow

The axis of the freshwater flow from the Nordic Seas to the Atlantic closely follows the East Greenland shelf and upper-Slope. The East Greenland Shelf south of Denmark Strait is therefore the critical location for monitoring the net transport and phase of the freshwater flux, and is an area where both are almost totally unknown. A new array has been designed to provide such a measure under the ice of the SE Greenland shelf.



Measurement area of ASOF - W

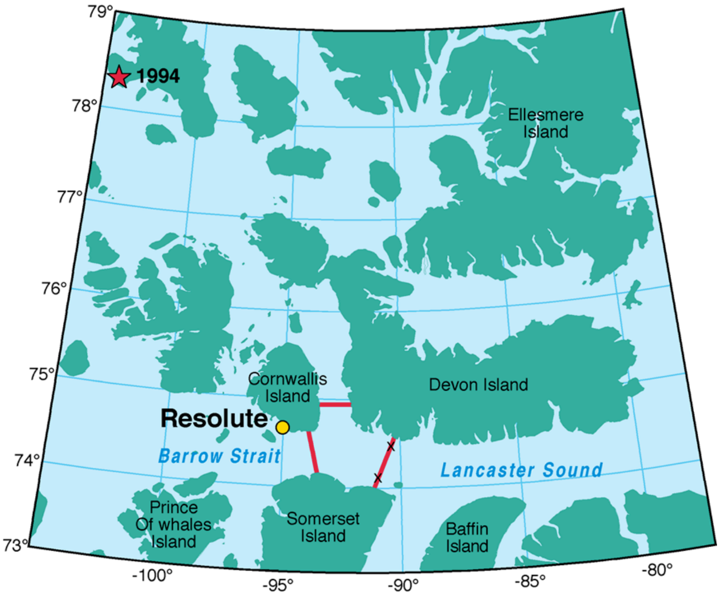
Figure 20. SE-Greenland Freshwater fluxes: 62.8N, 40-41W



Principal arrangement of shelf and slope arrays to measure freshwater and dense overflow fluxes

Figure 21. SE Greenland Slope Overflow: 63-63.5N, 35.5-36.8W

The core of the Denmark Strait Overflow is found at depths between 1000 and 2500m in a layer up to 300m from the bottom.



Work area for the Barrow Strait Flow-through Study. The X's denote the northern and southern mooring sites. The red lines represent the CTD lines completed.

Figure 22. Arctic Freshwater Flux through western Lancaster Sound. 74-75N, 92W

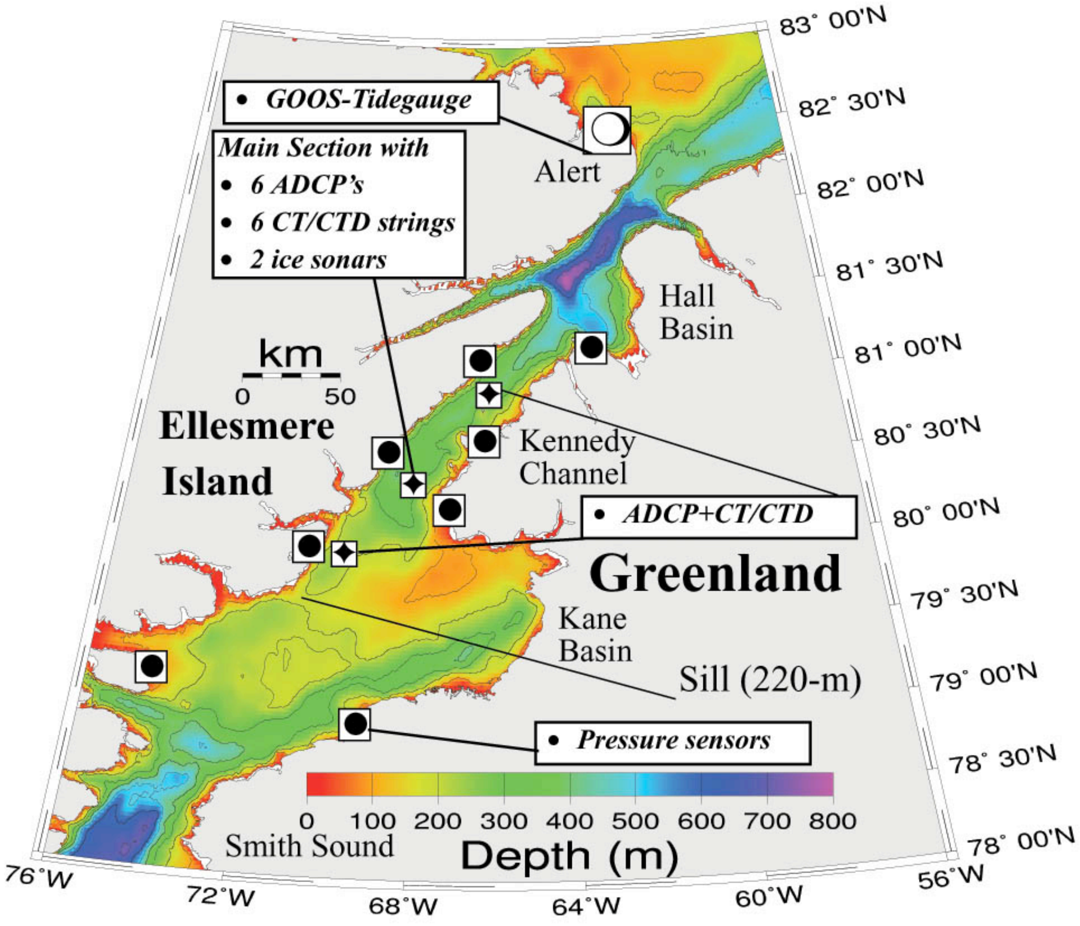


Figure 23. NARES STRAIT AND JONES SOUND MOORING ARRAYS
80N – 68W and 78N – 90W

B.2 RAPID-MOC Monitoring the Atlantic Meridional Overturning Circulation

A number of projects have been funded by UK NERC to monitor the MOC, some of which are collaborations with US NSF funded projects.

Monitoring the Atlantic Meridional Overturning Circulation at 26.5°N

Much of the heat transported northward in the Atlantic is given off to the atmosphere over the Gulf Stream extension from where it is transported north-eastward toward Europe by the atmosphere. Fluctuations in heat transport (and, by implication, transports of other quantities such as freshwater and carbon) are expected to be dominated by fluctuations in the transporting velocity field, and only to a lesser extent by variability in heat (or property) content. As one consequence, the basic monitoring of the MOC should occur near the heat transport maximum. 26.5°N has the triple advantage of being close to the heat transport maximum in the Atlantic, of being the latitude of four modern hydrographic occupations, and of offering a long time series of boundary current observations not existing anywhere else. At 26.5°N the western boundary current (flow through Florida Strait) can be measured relatively straightforwardly by cable (existing long-term programme by the US) and regular calibration cruises. This makes the monitoring of the entire MOC equivalent to the task of monitoring the depth profile at which the flow through the Florida Straits returns southward. Currently, its contribution to the MOC returns southward at depths between 1000m and 4000m.

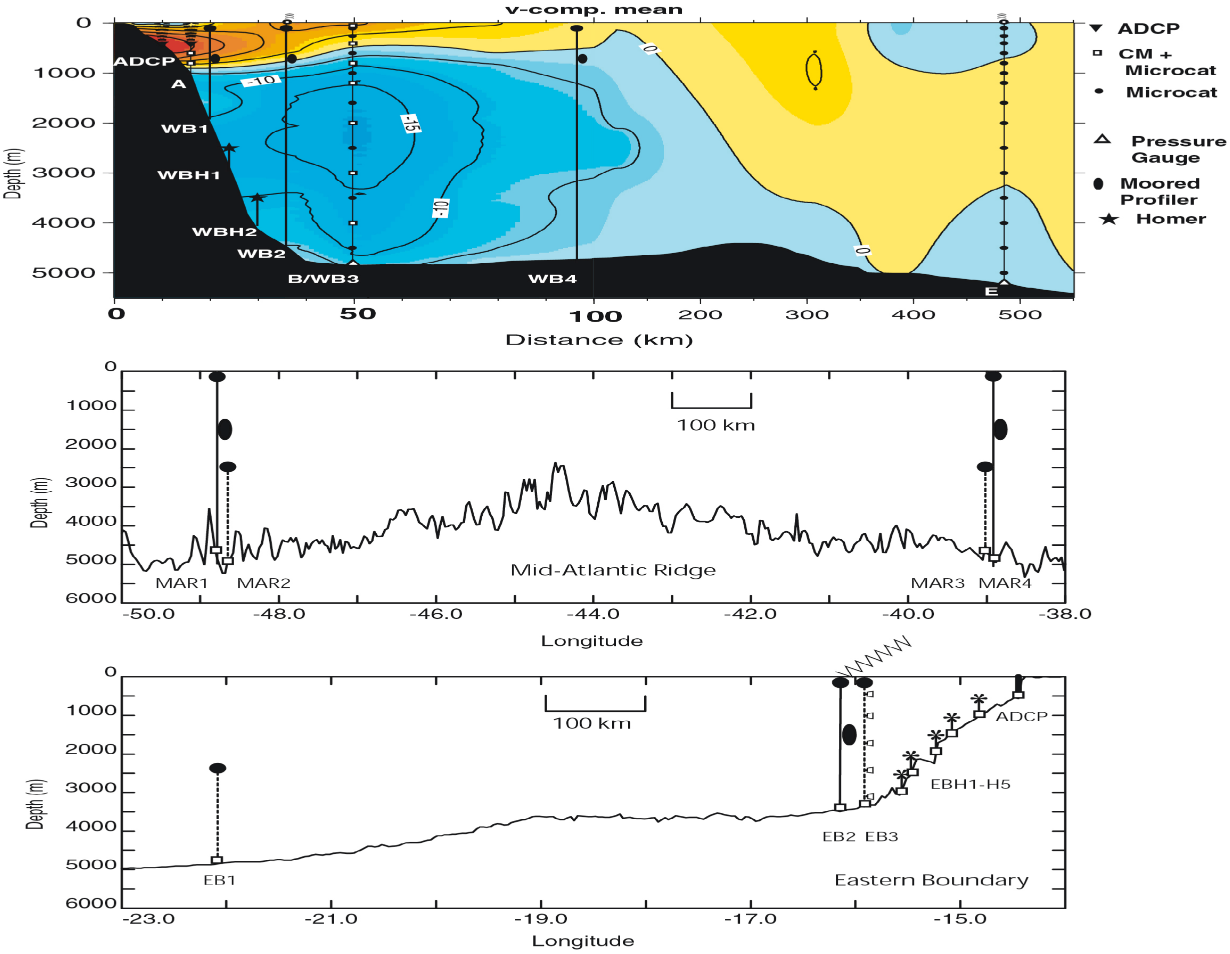


Figure 1: Mooring array for monitoring the Atlantic meridional overturning circulation at 26.5 N. a) Western boundary; b) Mid-Atlantic Ridge; c) Eastern boundary

Figure 24. MOC monitoring at 26.5^{o}N.

The monitoring consists of continuous full-depth density profiles at and near the eastern and western boundaries. In total, 8 full-depth moorings, six of which equipped with a McLane Moored Profiler (MMP) taking roughly one CTD profile every other day. The use of profilers has the big advantage over individual, fixed-location CTD sensors that only a single instrument needs to be calibrated. Several moorings are deployed near each boundary, for obtaining boundary current measurements through thermal wind, improving the signal-to-noise ratio, and as failsafe measures. All moorings are equipped not only with CTDs but also with bottom pressure sensors, and some with current meters. This gives added information for estimating the depth-independent part of the MOC that is not in thermal wind balance but is rather dominated by high-frequency barotropic dynamics. The presence of the Mid-Atlantic Ridge (MAR) complicates the endpoint monitoring of the MOC, because a pressure drop may exist across the ridge. Below the ridge crest, the sub-basins to the east and west therefore are monitored separately. The array consist of one MMP mooring on each side of the MAR, but the back-up fixed-depth CTD moorings only reach to the ridge crest. The MMP moorings will tell us how the shallow Gulf Stream return flow is divided between eastern and western basins. In addition to the full-depth sampling, the sloping shelfbreak topography is instrumented, from the deep water to shallow depths, with CTDs, bottom pressure recorders (BPR), and current meters (CM), to obtain continuous observations at fixed depths. This provides an alternative vertical sampling strategy, and also help solve the bottom triangle problem

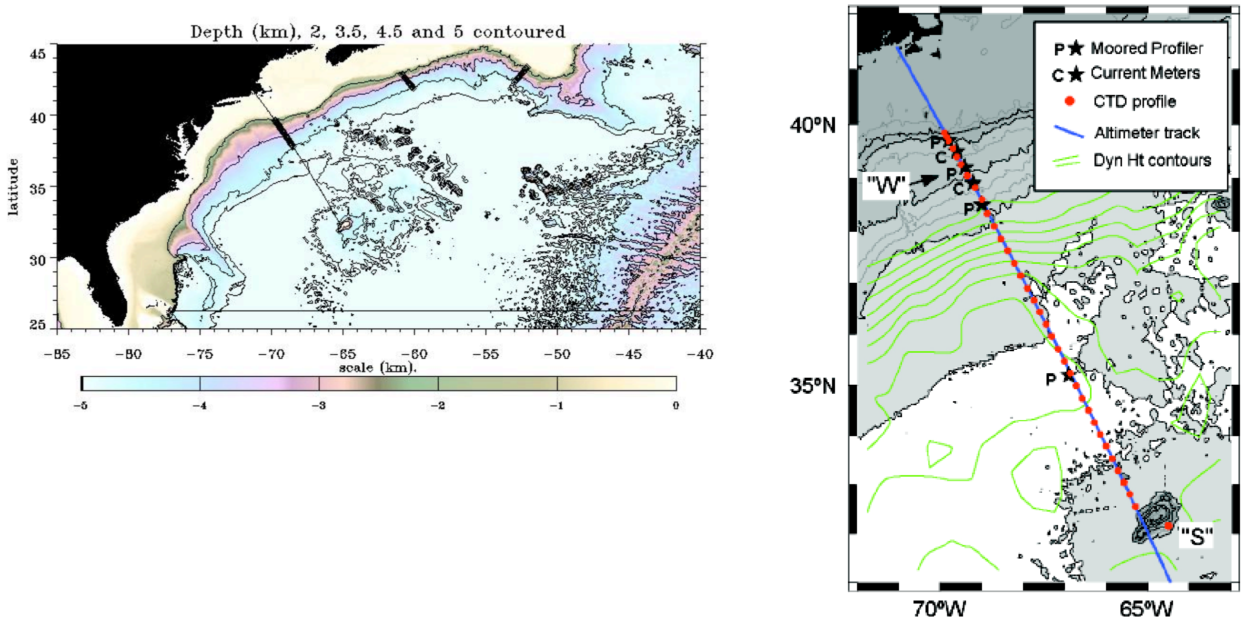


Figure 25a and b. A monitoring array along the western margin of the North Atlantic

The aim of this observing system is to monitor the communication of MOC signals along the western margin of the Atlantic on time-scales of months to years. There are a number of motivations for focusing on this boundary communication:

- The boundary waves represent the rapid, integrated response of the mid- and low-latitude ocean to deepwater formation events at high latitudes, and should allow changes in MOC at mid-latitudes to be attributed to their high-latitude sources.
- With the boundary wave signal taking weeks to propagate between sites along the US continental slope, it is possible to identify the coherent part of the signal within a four-year dataset. Contrast this with a tracer signal that takes years to propagate and is strongly modified by mixing and recirculations.
- The well-defined speed of propagation facilitates the identification of the relevant signal amongst the "noise" and aliasing of more localized ocean processes, for example generated through local wind forcing.
- the observing system is designed to capture the propagation of information from the Grand Banks to the Gulf Stream where the continental slope is steep and comparatively uncomplicated, and thus the wave signals propagates in a relatively well-ordered manner.

The prototype array of instruments is designed to measure both integrated and local properties of the ocean circulation in this region, with the aim of identifying propagation of signals along the western boundary, and of attributing these propagating signals to variability in the thermohaline circulation. This array doesn't represent a complete monitoring system in itself for the MOC. However such an array is essential component of any complete monitoring system, which would ideally include a MOC monitoring line at 26N.

III. The in-situ observing system in the tropical Atlantic

In Section I a basin-scale overview was provided of Atlantic sector observations. This section is focused more specifically on these observation with respect to their relevance and status in the tropical Atlantic. During the past few decades, real-time observations from the tropical Atlantic in-situ observing system were derived primarily from volunteer observing ship (VOS) program, coastal and island tide-gauges, and a small number of drifting buoys. Considered as a second priority during the Tropical Ocean and Global Atmosphere (TOGA) program (1985-1994), which was mainly focused on the Pacific Ocean and El Niño – Southern Oscillation (ENSO) climatic features, the in-situ observing system in the tropical Atlantic registered progress only from the mid-1990s. This progress was first dedicated to increasing the number of classical expendable instrumentation (surface drifters, XBT, HD-XBT, …) launched by the VOS system and other oceanographic vessels. Regarded as the centre piece of the tropical Atlantic observing system, the Pilot Research moored Array in the Tropical Atlantic (PIRATA) (Servain et al., 1998) is a network of in-situ observations enable to monitor changes in oceanic weather conditions in the tropical Atlantic. It completes the similar system already set up in the Pacific during the TOGA's years and known as TAO/TRITON (Tropical Atmosphere-ocean Array/TRIangle Trans-Ocean buoy Network). In the year 2000, a new and important component was added, the Argo program. As discussed in Section I, Argo is an international program whose goal is to deploy in the global ocean an array of 3,000 free-drifting profiling floats that measure the temperature and salinity of the upper 2000 m in a period of 5 years. Approximately 700 floats were operating in 2003 in the Atlantic, of which about one third in the tropical basin.

A. Surface meteorology, surface and subsurface temperature and salinity observations

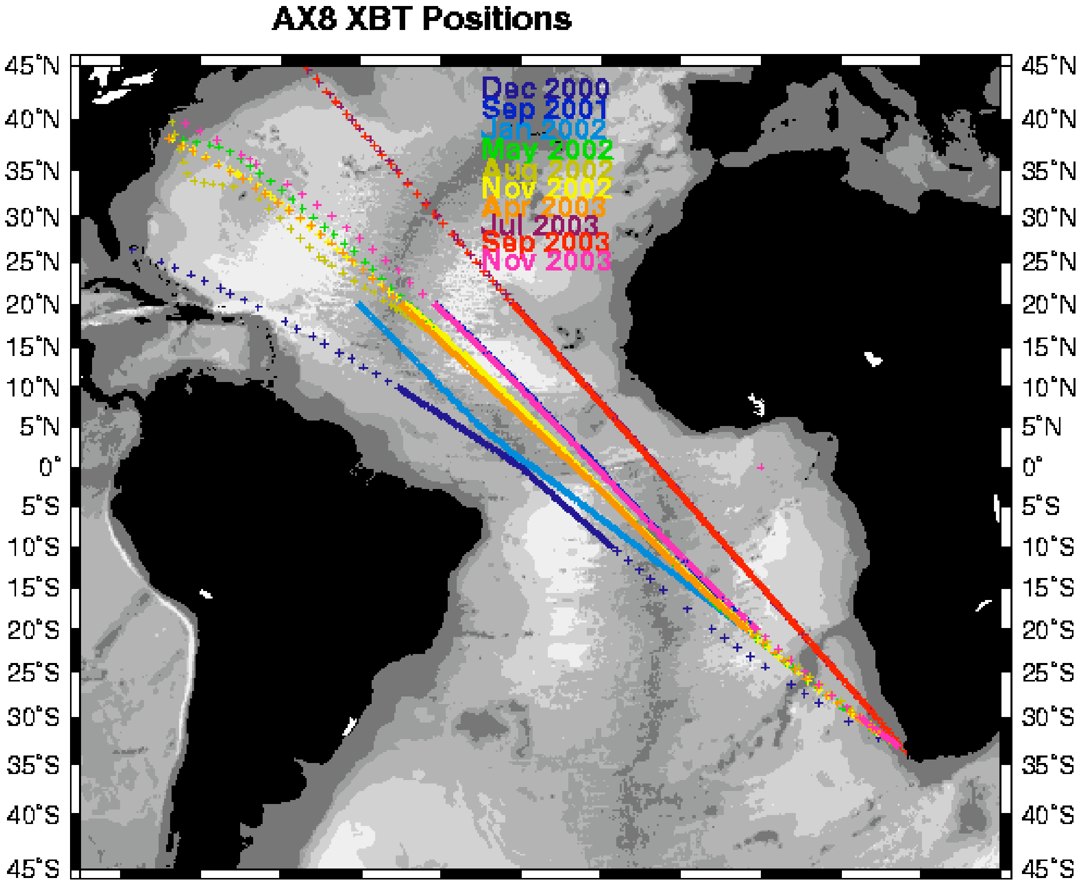
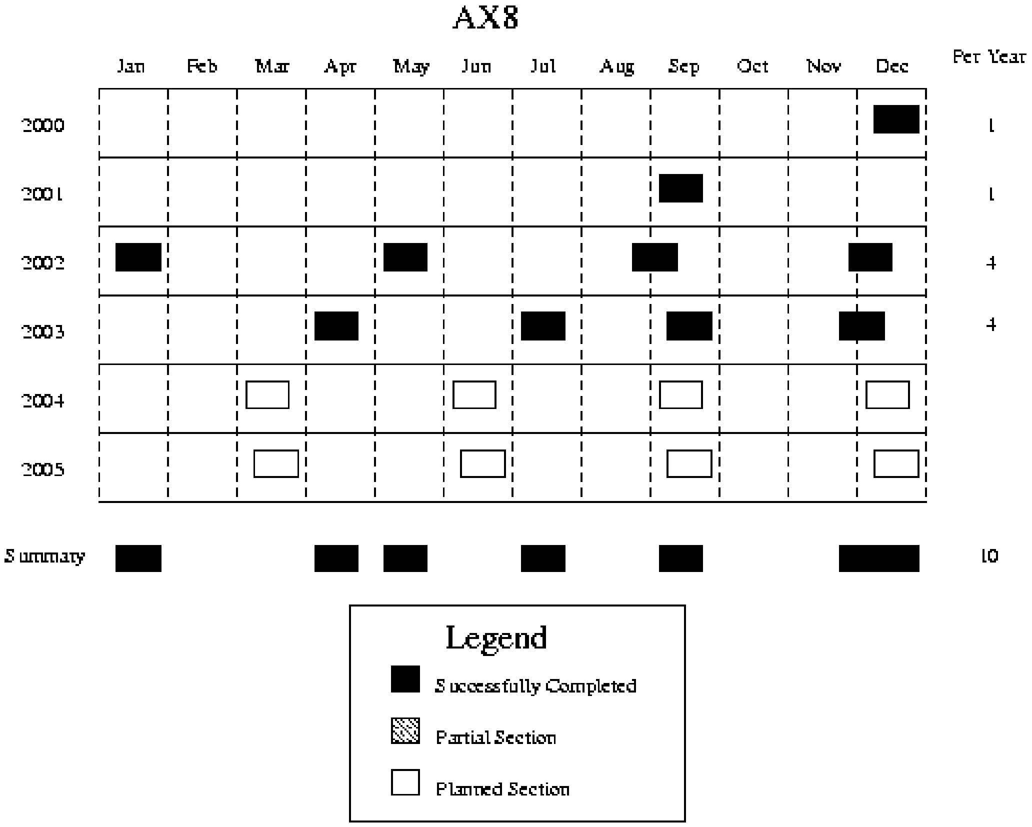


Figure 26. AX8 XBT positions 2000-2003.

The international VOS measurements of surface meteorology (SST, wind, SLP, …) account for 6,000 to 8,000 observations per month from 30°N to 30°S in the Atlantic. Such a relatively high data density permit monthly objective analysis (i.e. Smith et al., 2003 for the wind) and possible blending with satellite data for weekly resolution or better for SST. However the data quality is not guaranteed and coarse temporal and spatial resolution remains in some areas, especially in the Southern Hemisphere. Furthermore, the blending of VOS/satellite SST data has limited accuracy in cloudy tropical zones away from the major ship tracks. The surface Thermosalinograph (TSG) and subsurface (0-700 m) temperature and salinity data (XBT, HD-XBT) are obviously concentrated along the well-traveled shipping routes. In the tropical Atlantic, there are four main ship tracks which are presently operational: AX8 from north-east coast of USA to South Africa, AX11 from Europe to Brazil, AX20 from Europe to French Guyana, and AX15 from Europe to South Africa. AX8 is mainly managed by the US NOAA/AOML, and the three other ones by the French IRD. The XBT and TSG measurements generally allow a section per month along the ship track. The HD-XBT observations (30 km resolution between ± 10° latitude, and 40 km resolution between ± 10° and 20° latitude) allow a section per quarter along the AX8 track (Goni and Baringer, 2002). The TSG data set is managed by the Gosud program (Global Ocean Surface Underway Data). For the tropical Atlantic the TSG data are under the responsibility of the French IRD.


AX8

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Per Year
2000												■	1
2001									■				1
2002	■				■			■				■	4
2003				■			■		■			■	4
2004			□			□			□			□	
2005			□			□			□			□	
Summary	■			■	■		■		■		■	■	10

Legend

■ Successfully Completed

▨ Partial Section

□ Planned Section

Figure 27. HD-XBT deployment along AX8

B. The surface drifting buoy

Appreciable progress was made the past several years in the deployment of the surface drifting buoys in the tropical Atlantic basin, mainly under the responsibility of USA, France and Germany. These platforms supplement space-based retrievals of SST (and in rare instances SLP and wind), but their telemetered positions also make it possible to obtain an estimate of the surface currents in the basin. About 15,000 to 20,000 messages are transmitted in real time per month for the Atlantic tropical region 30°N-30°S.

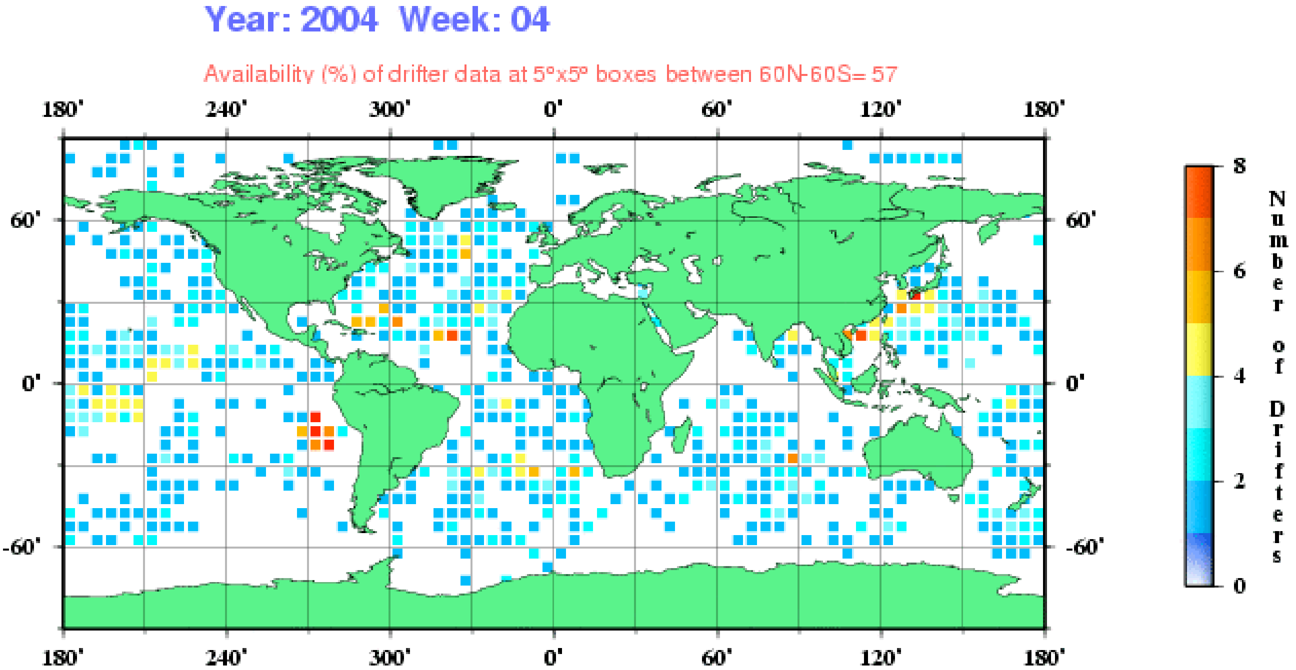


Figure 28. Availability of surface drifter data.

C. The PIRATA array

Both the TAO and PIRATA networks are made up of a set of buoys of the same type (ATLAS system) anchored to the seabed. The PIRATA network currently consists of 10 ATLAS systems: 4 along 38°W from 15°N to 4°N, 4 along the equator from 35°W to 0°E, and 3 along 10°W from 0°N to 10°S. Sensors (wind, temperature and humidity of the air, SST, solar radiation and precipitation) allow to estimate the energy transfer at the air-sea interface. The temperature and salinity profiles for the deeper oceanic layers (down to 500 m), that are of fundamental importance in longer-term climatic fluctuations, are also measured and transmitted in real time. As each ATLAS buoy has enough power for twelve months, electronic and mechanical maintenance for the network requires an investment in ship time which comes to a total of nearly 90 days per year for the entire network.

PIRATA, which started in September 1997, is recognized as being one of the observation components of the international CLIVAR programme. It is a multinational effort involving Brazil (Instituto de Pesquisas Espaciais, INPE; Directoria de Hydrografia e Navigação, DHN; University of São Paulo, USP; Fundação Cearense de Meteorologia e Recursos Hidricos, FUNCEME), France (mainly with the IRD, but also with Météo-France, Ifremer and CNRS/INSU) and the United States (National Oceanic and Atmospheric Administration, NOAA). While the buoy equipment is supplied by the USA (NOAA), Brazil and France provide all logistical support for the oceanographic vessels needed for deploying and maintaining the buoys. In 1999, it was suggested that the current set-up for PIRATA co-ordination between Brazil, France and the United States be continued beyond the original 1997-2001 pilot phase in the context of a "consolidation phase" lasting five more years from 2001 to 2005. This phase should allow for the preparations needed to continue the network after 2005. Temperature and salinity data returns for 2003 are provided in Figure 29. Time series from selected locations are provided in Figures 30 and 31.

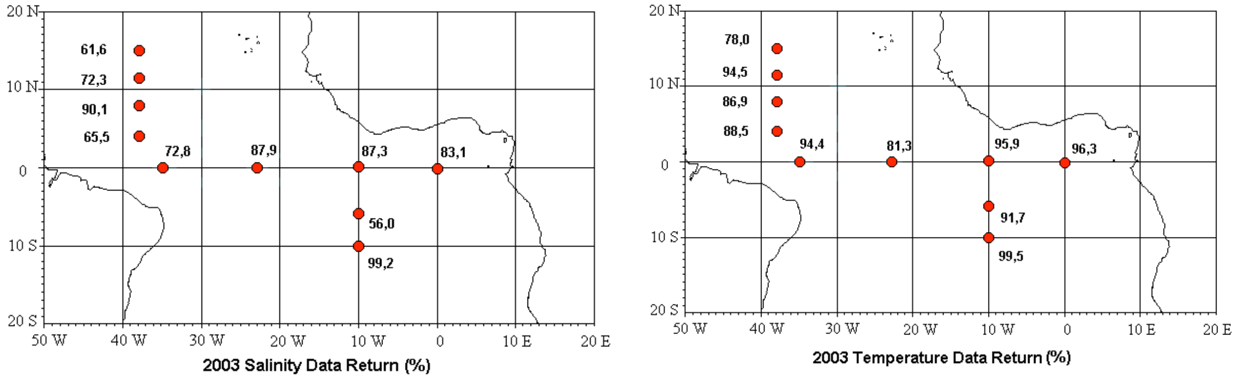


Figure 29. PIRATA temperature and salinity data returns for 2003.

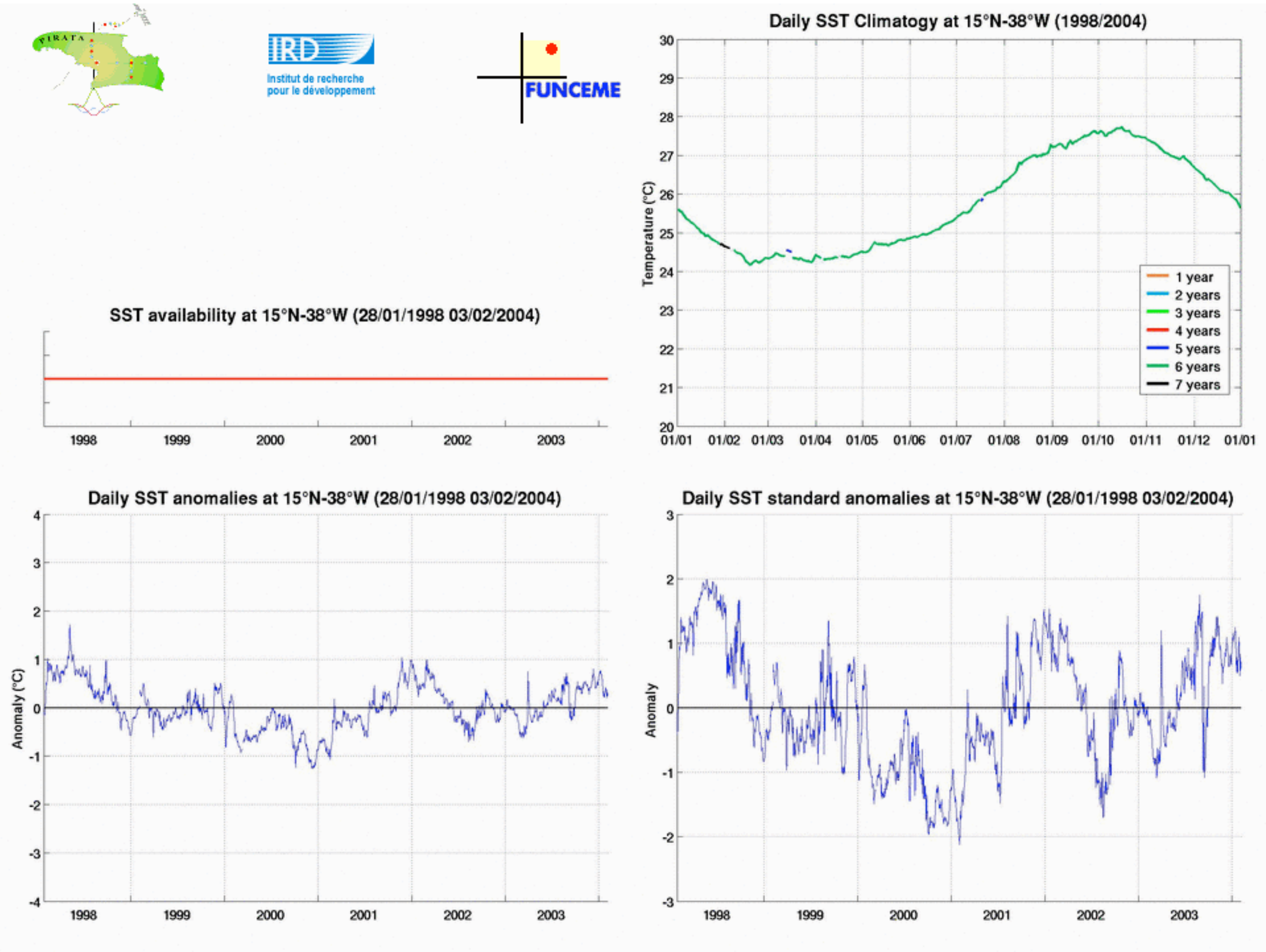


Figure 30. PIRATA observations at 15^{o}N- 35^{o}W.

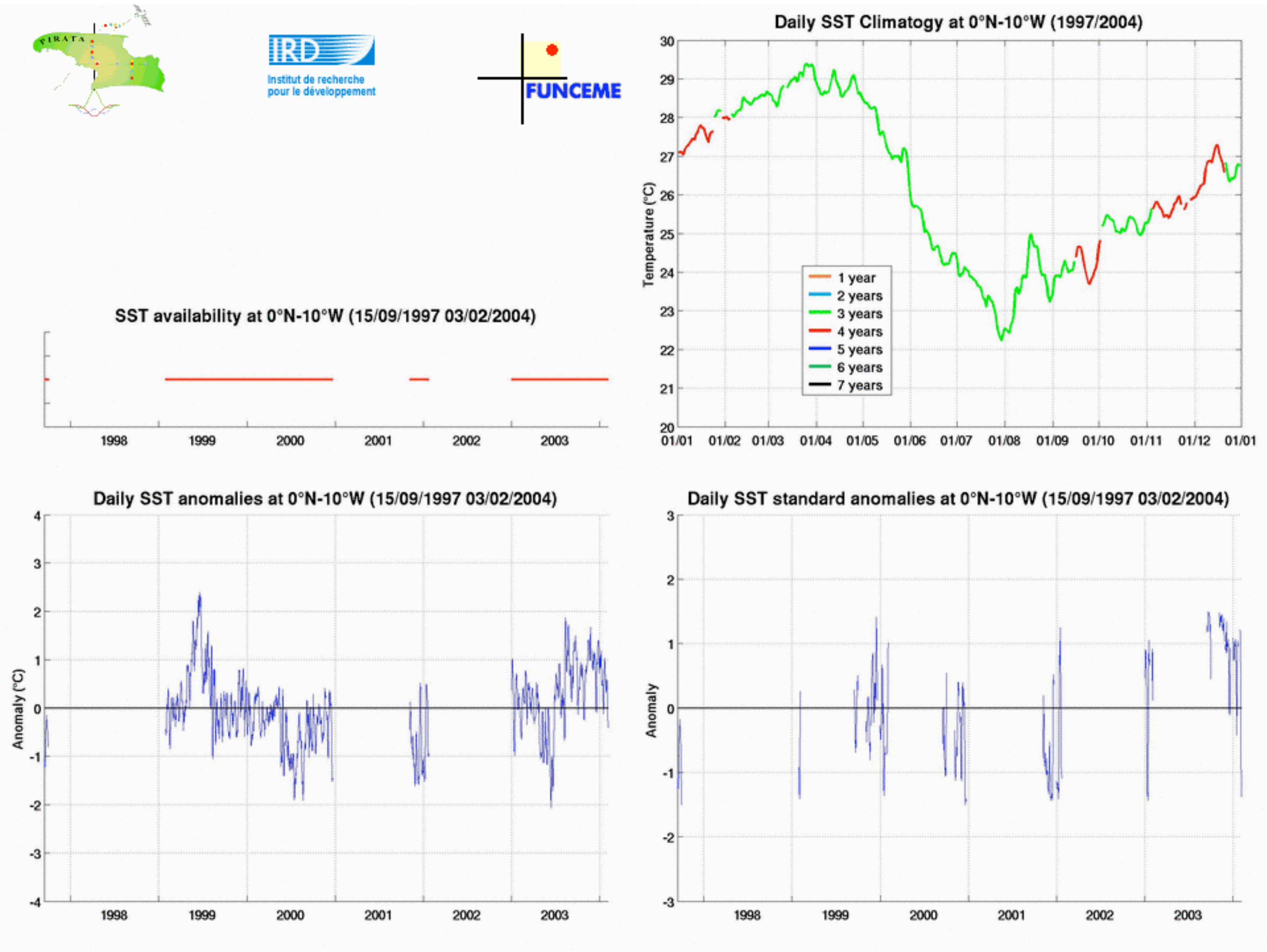


Figure 31. PIRATA observations at 0°N- 10°W.

Three gradual geographic extensions of the original network are being considered for experimental purposes. Two extensions concern the African edge of the Atlantic basin: a first one, the North-East Extension (PIRATA-NEE), off the coasts of Mauritania, Senegal and Guinea, and the other one, the South-East Extension (PIRATA-SEE) off the coasts of Gabon and Angola. These two eastern extensions, taken together with the original network within the Gulf of Guinea, are highly relevant to the goals of the international AMMA Programme (African Monsoon Multidisciplinary Analysis) and, for this reason, could benefit from additional support (logistical, financial, etc.). A third project for extending the South-West Extension (PIRATA-SWE), runs along the edge of Brazil's coastline to the south of the equator. Brazilian institutes (e.g., INPE, FUNCEME) are particularly interested in taking part in this extension project which could help in the knowledge and the forecasting of the Nordeste climate variability.

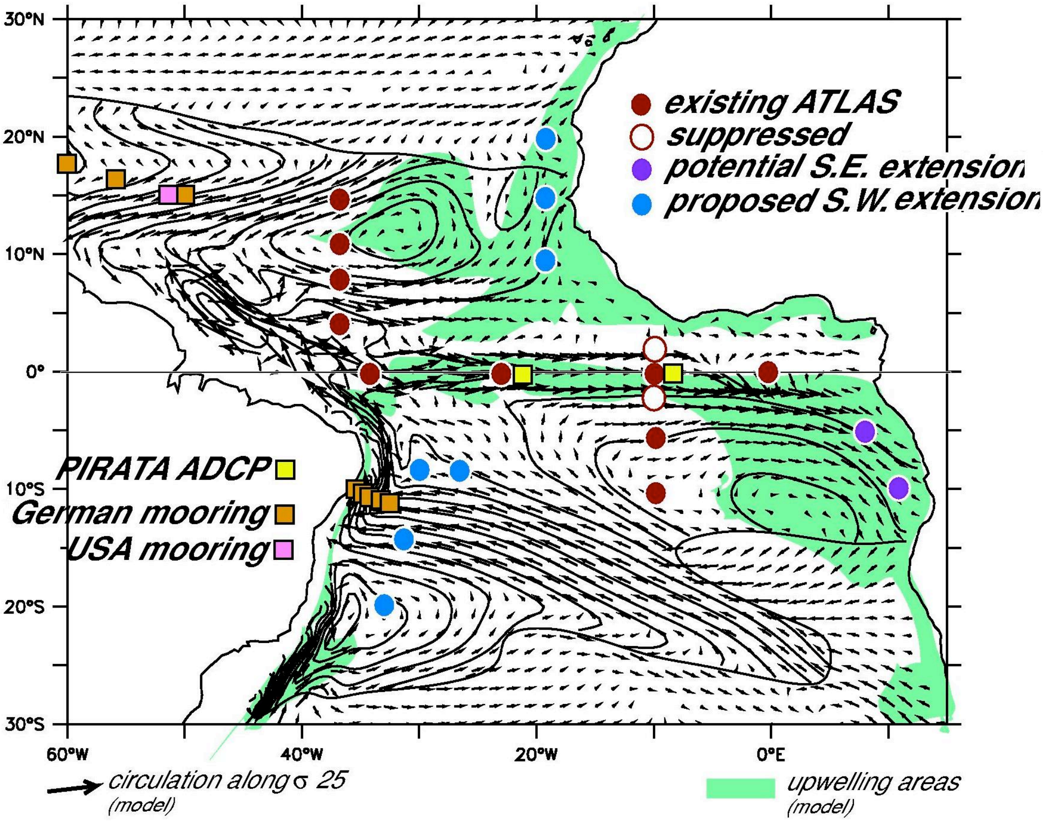


Figure 30. Proposed PIRATA extensions.

D. The Argo system in the tropical Atlantic

Argo floats cycle from 2000 m depth to the surface every 10 days, with a 4-5 year lifetime for individual instruments. The Argo target for 2005 is to provide 100,000 T/S profiles and reference velocity measurements per year from about 3,000 floats distributed over the global oceans at 3-degree spacing. By February 4, 2004, the status of Argo was 1041 active floats (34.7% of the target). An estimated 192 floats are needed for the tropical Atlantic 20°N-20°S. Figure 31 presents the present deployment plan and data density. All Argo data are publicly available in near real-time via the GTS, and in scientifically quality-controlled form with a few months delay. Global coverage should be achieved during the Global Ocean Data Assimilation Experiment, which together with CLIVAR and GCOS/GOOS, provide the major scientific and operational impetus for Argo. The design emphasizes the need to integrate Argo within the overall framework of the global ocean observing system. An example of the CORIOLIS temperature analysis of Argo observations in presented in Figure 32.

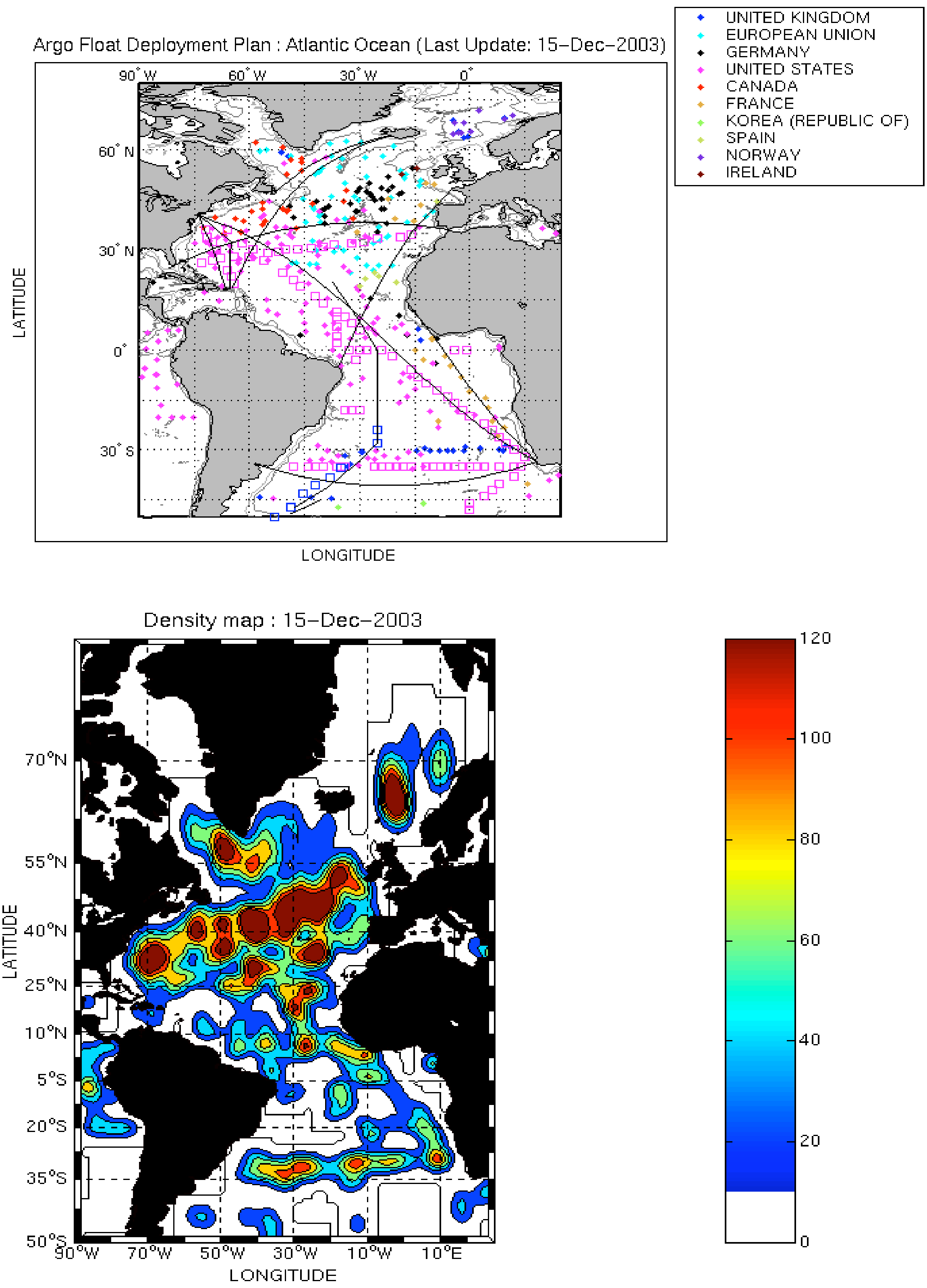


Figure 31. Argo deployment plan (top), Data density map: 100% =target 3°x3° (bottom).

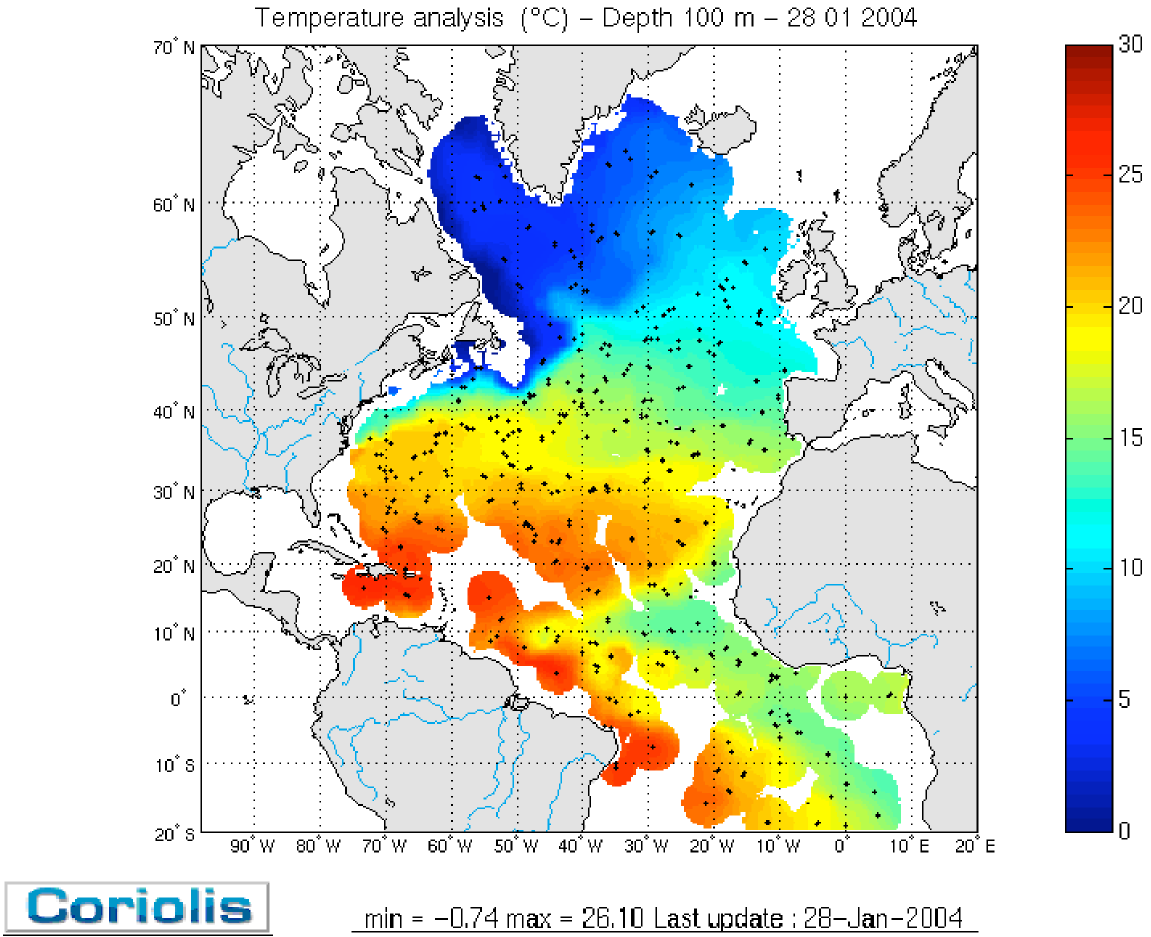


Figure 32. 100 m temperature analysis from Argo observations January 28, 2004.

The South Atlantic Climate Observing System

The South Atlantic (SA) is a relatively poorly sampled ocean. For instance, some studies concluded that the leading mode of SA SST variability is a monopole pattern with a maximum located along the South Equatorial Current (SEC), presumably associated with SEC shifts. However, other studies suggest that this pattern emerges only due to the poor data coverage, and that the variability at interannual time scales is dominated by a dipole structure. In the tropical Atlantic the intertropical convergence zone (ITCZ) and its associated atmosphere and ocean elements control rainfall and other climatic impacts over Africa and South America. The ITCZ is extremely sensitive to small changes in regional SST gradients and external atmospheric influences. Anomalies in the SA atmosphere and ocean can set off interactions that effectively modulate the ITCZ variability. Because the SA is the main source of upper layer waters at low latitudes, variations in the SA meridional heat transport in the upper ocean, can modulate ITCZ variations. In addition, through their influence on SST in subtropical upwelling areas, shallow subtropical cells can provide an oceanic modulation of the ITCZ at decadal time scales. However, studies of the tropical – subtropical SA linkages are just beginning.

Formation of North Atlantic Deep Water (NADW) and the associated sea-air heat flux are a major element of the climate system. Export of NADW through the SA to other ocean basins requires a compensating northward flow across the equator. Heat and mass exchange between the SA and the Indian and Pacific Oceans are of critical importance for the global thermohaline circulation and its variability. The SA is the gateway by which the Atlantic meridional overturning circulation (MOC) communicates with the global ocean, exchanging properties and mass with the Indian and Pacific via the Southern Ocean and around South Africa. These inter-ocean links make possible the unique global reach of NADW and of the compensating return flow within the ocean upper layers.

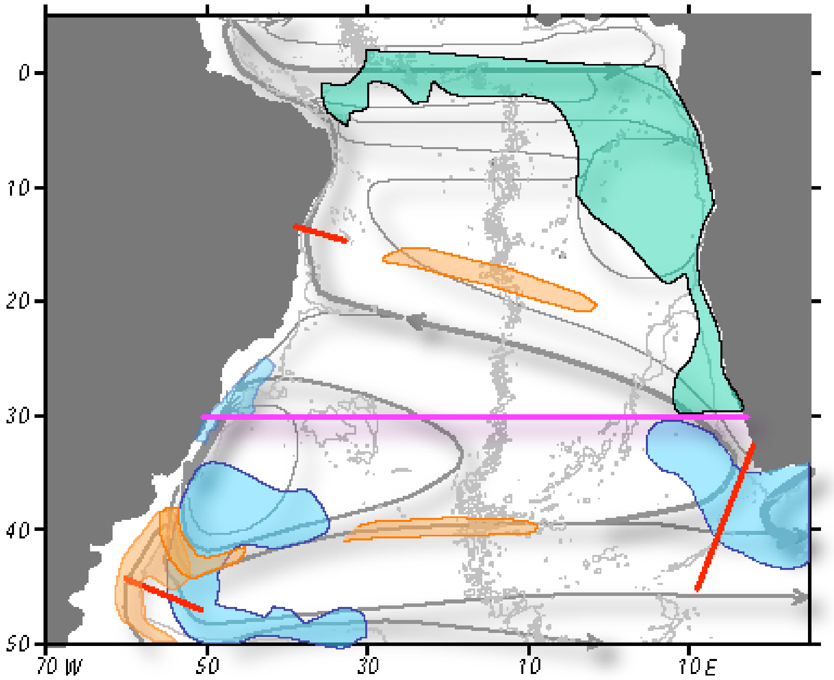


Figure 33: Regions identified as important for implementing a South Atlantic observing system for climate. The light blue shading indicates the high eddy kinetic energy regions in the Brazil/Malvinas Confluence and the Agulhas Retroflection. Light orange shading indicate the regions of convection and subduction. Light green shading areas of upwelling associated to the shallow tropical cells. Red lines depict areas of interest for monitoring the inter-ocean exchanges and the bifurcation of the South Equatorial Current. Purple line near 30°S region for monitoring the meridional mass and heat flux (adapted from SACOS WG reports).

Waters of Pacific, Indian, Atlantic and Southern Ocean origin collide and blend in the Argentine and Cape Basins where large sea-air buoyancy fluxes and mixing lead to intense vertical mixing, convection and subduction. Numerical simulations and observations indicate that the water mass characteristics of the upper limb of SA branch of the global thermohaline circulation (GTC) is largely determined at the highly energetic eastern and western boundary regions. These processes may be effective short-circuits of the MOC. Eventually, the transformed water masses feed the Benguela Current and subsequently the upper equatorward limb of the MOC of the Atlantic. Their temperature and salinity characteristics control the buoyancy budget and overturning of the Atlantic. The varying ratio between the input of cool and relatively fresh Pacific waters around South America and the warm and salty Indian Ocean waters around South Africa, and from the varying intensity of the water mass transformation processes in the southwest Atlantic and the Cape Basin. Since these regions are also choke points of the global thermohaline circulation, we postulate the need to improve our understanding of the linkages between these regions and the large-scale circulation. Because the characteristics of the northward upper-layer fluxes appear to depend on time and spatial scales set by the SA circulation, to determine the export of thermocline waters to the North Atlantic it is not sufficient to know the magnitude of the inflows from the Pacific and Indian Oceans. Indeed, it can be argued that since the SA circulation depends on the interocean fluxes and those, in turn, depend on the SA circulation, any attempt to determine one independently of the other will lead to an ill-posed problem.

Do the meridional mass, heat and freshwater fluxes through the subtropical SA matter to climate? Recent modeling experiments suggest that variations in these fluxes might modulate NADW formation and therefore the sea-air heat fluxes in the North Atlantic. These results show that Agulhas leakage stimulates and stabilizes the Atlantic MOC while northern fresh water fluxes oppose and destabilize it. In the present day situation the stabilizing southern ocean fluxes dominate, but with reduced Indian Ocean input the northern overturning is expected to be close to a switch to a different mode, with associated climate fluctuations. Other studies conclude that cold waters from Drake Passage dominate. Not surprisingly, estimates of the meridional heat flux through the SA are greatly uncertain

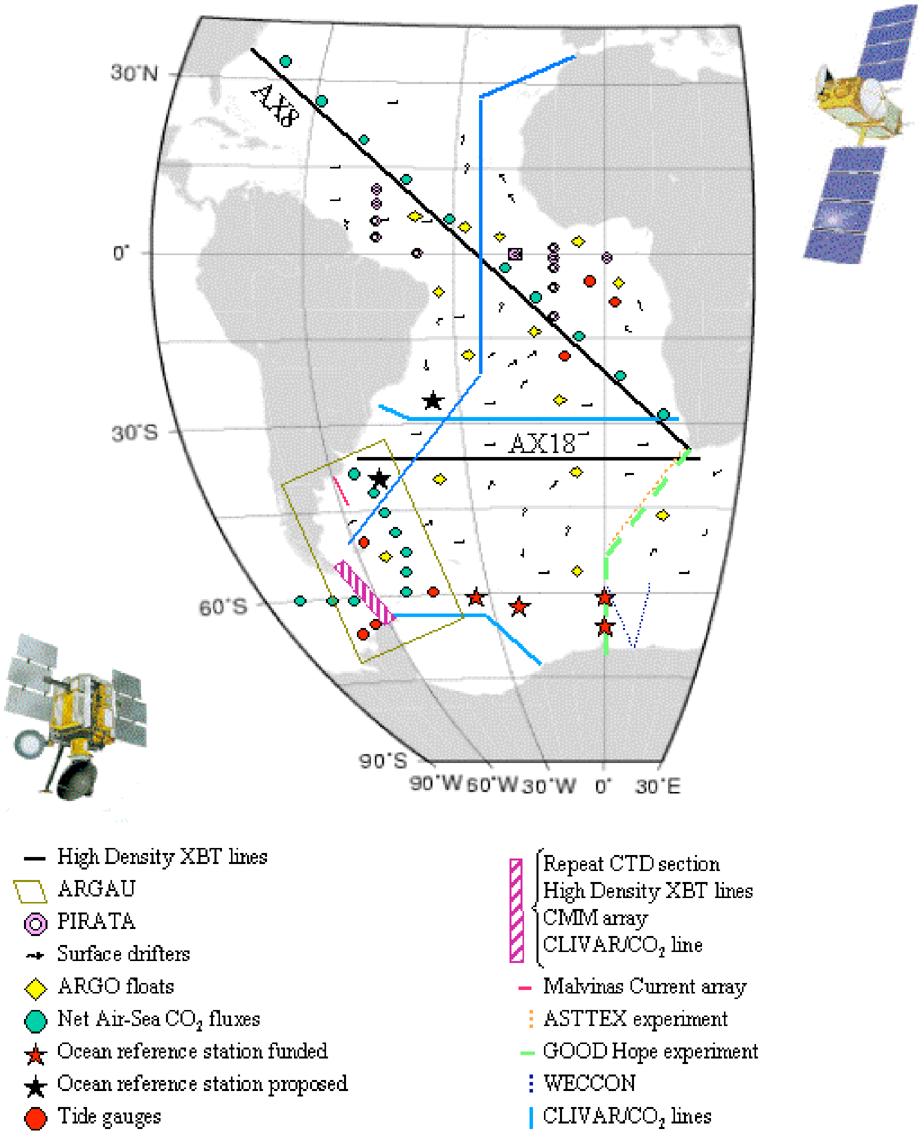


Figure 34: Funded and proposed observations in a South Atlantic Climate Observing System (from SACOS WG4 report and the white paper by Garzoli et al., 2003, presented at the SACOS meeting).

Long-term observations are needed to better quantify the role of the SA on climate. The role of the SA on the shallow tropical cells in the upwelling areas in the eastern basin and their influence on the SST gradients at low latitude. It is expected that the Argo float program and the repeat XBT lines will contribute to fill in the data gap, but it will take several years to obtain the observational base required to improve our understanding of the SA subsurface tropical – subtropical interactions and its long-term variability. Extension of the existing Pirata array both to the SW and SE should allow the monitoring and prediction of the Benguela Niño. A monitoring program for the SA should involve measurements of the varying ocean meridional fluxes and the air-sea fluxes and estimates of the modifications in the two major blending regions in the southwest and southeast Atlantic. To monitor the net effect of the varying interocean exchanges and subsequent mixing and water mass modifications on the buoyancy characteristics of the SA and the basin-scale overturning fluxes, a zonal section is proposed across the SA at about 25-30S. In addition, direct, long-term current and temperature measurements are needed in the eastern and western boundaries. Figure 33 summarizes the main areas of interest and schematically presents the location and type of recommended observations.

A summary of sustained, long-term, ongoing and funded observations in the South Atlantic is presented in Figure 34. Maintaining these observations is essential for the detection and understanding of large scale climate fluctuations in the South Atlantic. The observations include expendable bathythermograph sections and Argo profiling floats, designed to monitor the heat content of the upper ocean and its space – time variability. Two additional lines were initiated this austral summer between southern Brazil and Argentina and the Antarctic Peninsula. Multidisciplinary, long-term time series stations are planned in the central subtropical South Atlantic and in the Cape Basin. In addition two time series stations will be deployed in the western South Atlantic. Surface drifters provide information on the circulation in the Ekman layer and also sea-level pressure data in remote areas, where observations are dramatically sparse. Summer repeat surface CO2 lines are in place in the western South Atlantic since 2000. These measurements are to continue until 2010. Additional CTD and XBT sections will be occupied across Drake Passage in South of Africa.

Atlantic Region Land Observations

A. Scientific Background

It is generally agreed that seasonal to interannual variability is mostly influenced by ocean-atmosphere interaction, with land processes playing a secondary role. However, as our ultimate goal is to predict climate over continental regions where people live, the importance of land-surface processes is much elevated. Land processes become particularly important in semiarid regions located at the edge of seasonal migration of convective centers where a slight weakening or shift of monsoon rainfall can make large difference to the climate and ecosystem. The circum-Atlantic region includes some of the world's most climatically sensitive zones such as the West Africa Sahel and northeastern Brazil (Nordeste), where the impact of climate variability is far reaching and the sensitivity to land processes is highest. The American monsoon system has only recently been widely accepted as a coherent continental scale climate system that straddles the Pacific and the Atlantic Ocean basins. For example, the shear size of tropical South America, namely the Amazon basin, may enable it to play an important role in Atlantic climate variability.

The role of land processes in climate variability can be looked at from two related aspects: the feedback effect in modifying variabilities arising from ocean and atmosphere which is often manifested as enhancement of low frequency variabilities and damping of high frequencies; and also the direct impact on regional to global climate due to anthropogenic land disturbances such as deforestation, desertification and seasonal agricultural practices.

Some of the major land related issues have been recently emphasized:

- To quantify the importance of memories in soil moisture (1 month to 1 year) and vegetation (weeks to decades) as a function of location and timescale, and utilize these memories to improve climate prediction. Progress has been made for soil moisture in regions such as North America, while vegetation interaction has been identified in West Africa. Key mechanisms need to be identified and the degree to which they modify climate variability needs to be quantified.
- To understand the relative importance of the following processes to continental climate anomalies:
    - a. Remote SST; such as ENSO anomalies
    - b. Local SST: changes in the Atlantic SST patterns
    - c. Land feedbacks.

  Specific questions include:
    - What is the relationship between the marine ITCZ and land ITCZ or convection centers: competitive (east-west thermal contrast) or cooperative (north-south thermal contrast)?
    - Is a continental climate anomaly such as over the Sahel the result of a shift in the ITCZ or a change in its intensity?
    - What are the relative roles of various land features such as albedo, dust, evapotranspiration, surface roughness?

    - How do the African easterly waves interact with the monsoon circulation?

  These questions are critical for making SST forecasts useful for predicting continental climate.
- There is a critical need in improving the model simulation of key climatological features:
    - Diurnal cycle of convection
    - Seasonal cycle of the convection centers and ITCZ movement
    - Land-sea contrast, which might be closely related the current deficiencies in simulating tropical Atlantic SST by coupled atmosphere-ocean models.
- There is a strong need for better communication between observation and modeling, and between atmosphere-ocean and land-surface communities. Field experiments should focus more on climate related issues, rather than merely mesoscale structures. More effort is also needed in synthesizing existing data into frameworks easily accessible for modelers. Observationalists need to come up with coherent scenarios that can be tested by models, while modelers need to appreciate more what their model can not do. The land-surface community needs to identify the 1st order processes most relevant to climate variability and quantify their importance in a concerted way.

B. Land observations

There is no single program aimed at circum-Atlantic land observations. The Coordinated Enhanced Observing Period (CEOP) initiated by GEWEX, with its emphasis on global reference sites and satellite observation, collects consistently formatted land and atmosphere data from around the world for the period 2001-2004 (Fig. 35). Most of the reference sites coincide with sites used by CLIVAR programs such as VAMOS and AMMA. Thus there is an opportunity for CLIVAR-Atlantic program to provide the impetus and coordination for linking the land observations on both sides of the Atlantic.

Much of the CLIVAR research on the Americas can be described under the Variability of American Monsoon Systems (VAMOS), which includes the North American monsoon experiment (NAME) and the Monsoon Experiment South America (MESA) (Fig. 36).

GEWEX has focused on land and hydrological processes through programs such as GEWEX Continental-Scale International Project (GCIP) for the Mississippi basin, and the GEWEX Americas Prediction Project (GAPP). Recently great strides have been made to link the traditionally more separate ocean-atmosphere and land-atmosphere observations. For instance, The US NOAA has merged its CLIVAR Pan American Climate Studies (PACS) and GEWEX Americas Prediction Project (GAPP) into a single The Climate Prediction Program for the Americas (CPPA). Other programs such as DOE ARM have also extended beyond radiation measurement to include physical land properties as well as carbon measurements.

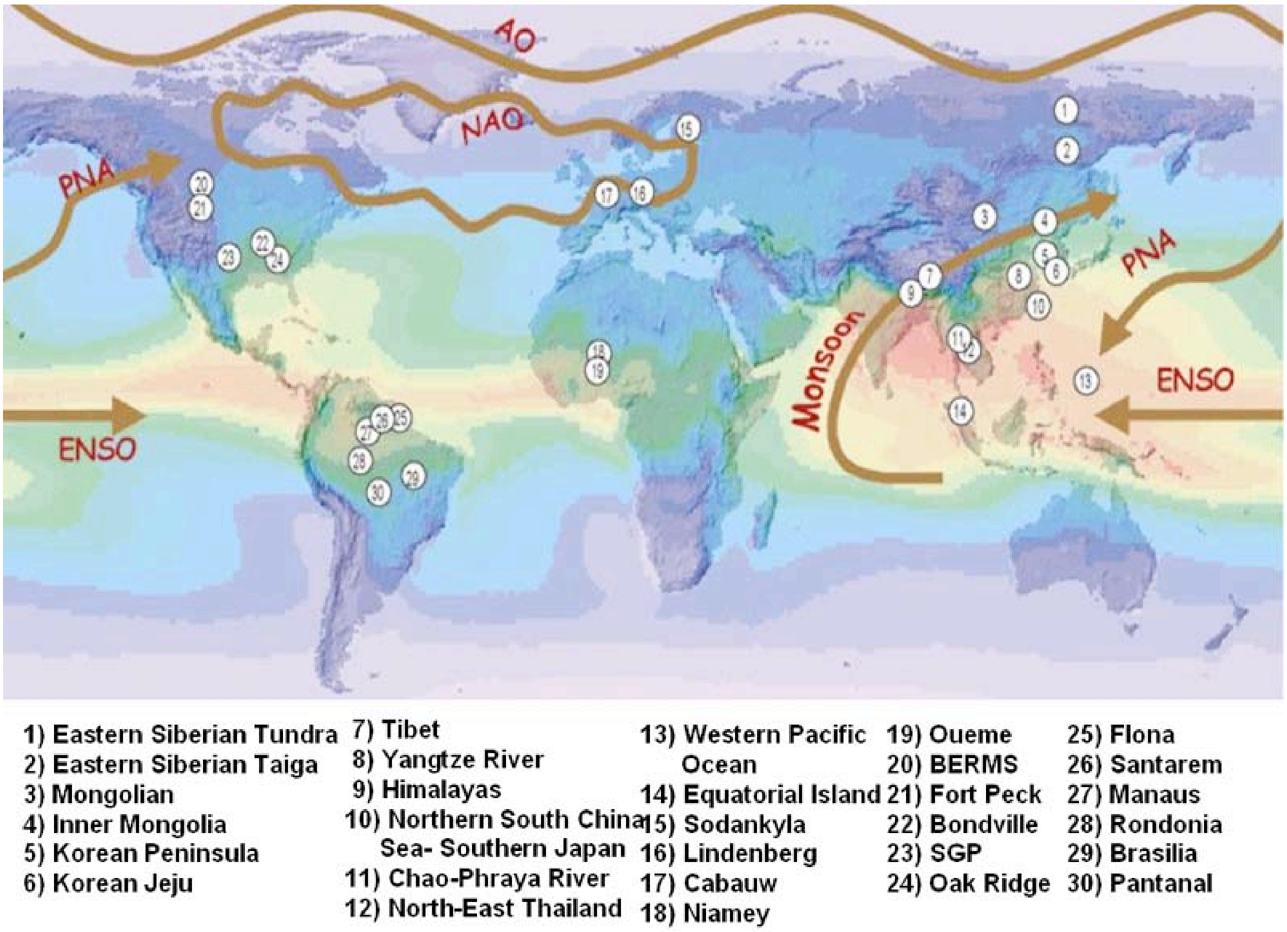


Figure 35. CEOP reference sites.

In South America, there is the long tradition of international research interest in the Amazon basin beyond climate concerns, such as the Amazon Boundary Layer Experiment (ABLE), Amazon Region Micrometeorological Experiment (ARME). A major ongoing project is the Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA), an international GEWEX research initiative led by Brazil, with major US participation sponsored by NASA. LBA emphasizes not only atmosphere and land processes but also ecological processes such as carbon cycle. CLIVAR-Atlantic can make better connection with LBA in support of both CLIVAR's main objective of climate prediction, and the understanding of climate impact on the world's richest ecosystem. Further south, VAMOS is playing a major role in coordinating the land observations through the South American Low Level Jet Experiment (SALLJEX) and at the La Plata Basin (PLATIN).

On the east side of the Atlantic, there are extensive observations over Europe through numerous national and European efforts such as GEWEX BALTEX. There is little coordinated land observation around the Mediterranean region and West and Central Asia despite the strong need for such data in this region of high climate sensitivity.

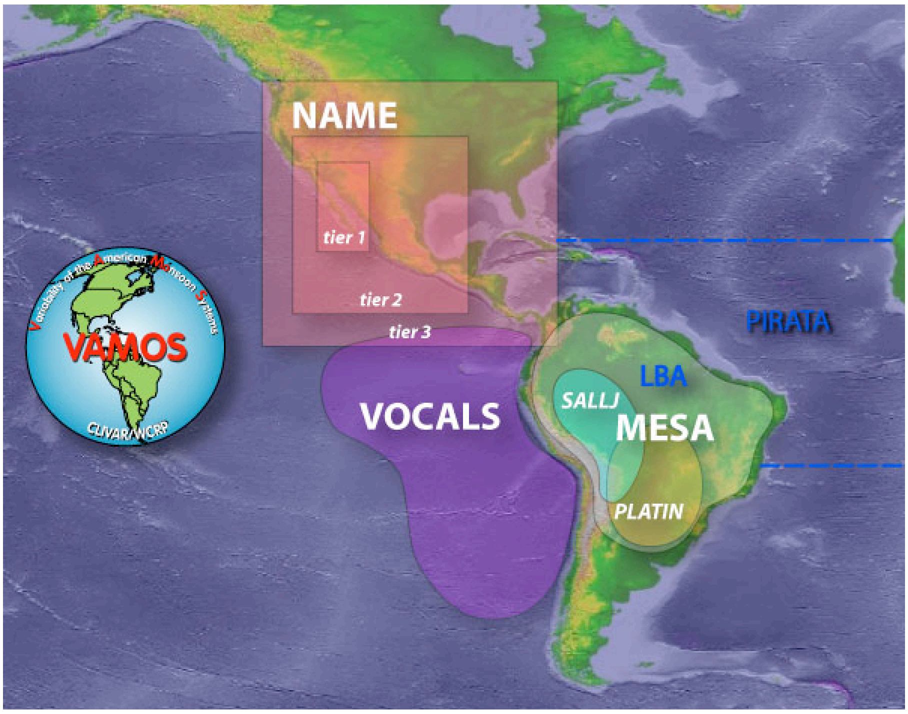


Figure 36. Elements of CLIVAR VAMOS.

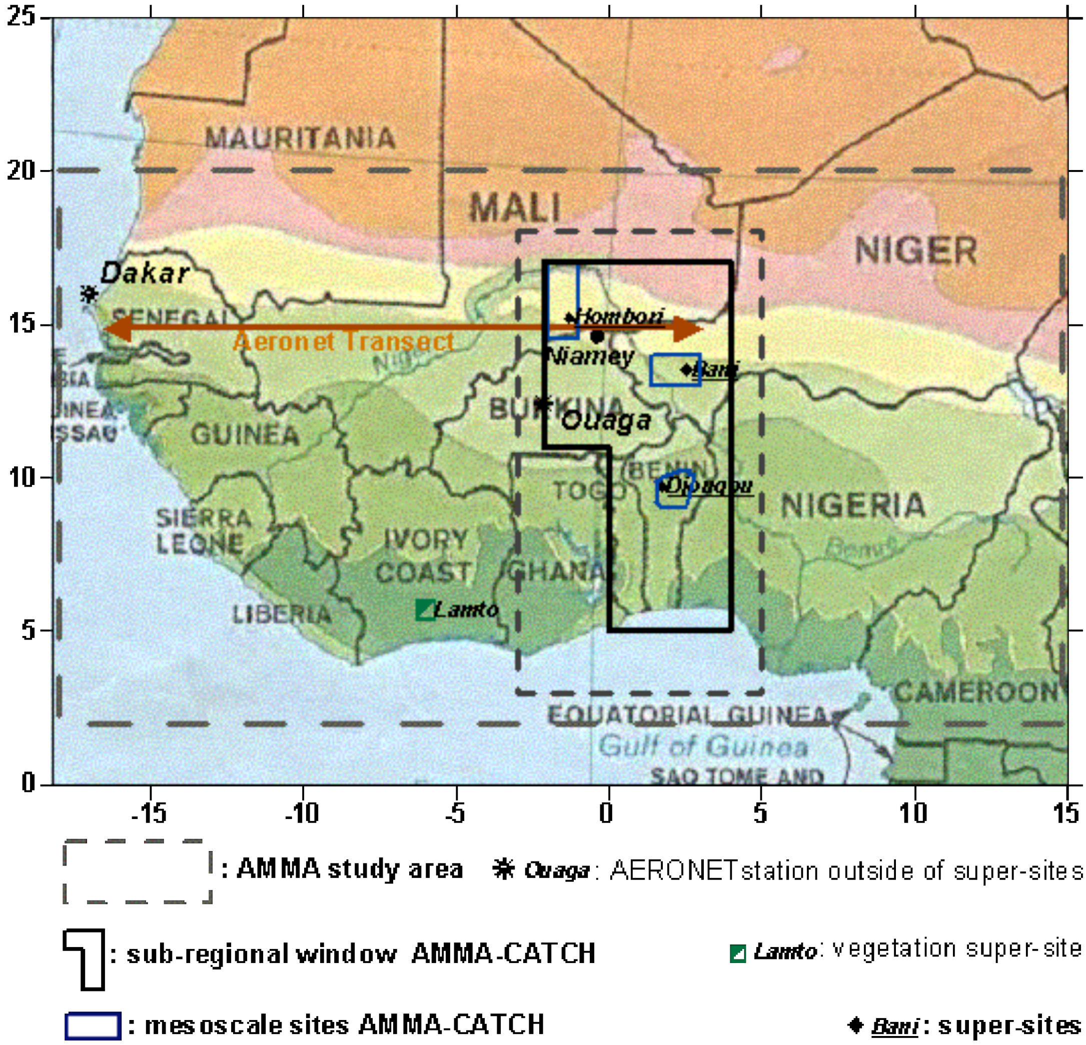


Figure 37: The African Monsoon Multidisciplinary Analyses experiment.

Over Africa, most observations have been over the Sahel, the most populated region in Africa. These observations include long term rainfall data that have shown the well known multi-decadal drought. Observations of atmospheric radiation, surface energy budget, land surface hydrology have been diverse through programs such as HAPEX-Sahel and CATCH. The African Monsoon Multidisciplinary Analyses (AMMA) will study the West African monsoon system through intensive and extended observations (Fig. 37). Within CLIVAR, AMMA is endorsed and supported by the Variability of the African Climate System (VACS) panel. AMMA is currently planned to start in year 2005. VACS and CLIVAR/Atlantic have entered into discussions on a Tropical Atlantic Climate Experiment as a means of supplementing the more land-based focus of AMMA. CLIVAR-Atlantic plans to coordinate their Atlantic observation with AMMA for the monsoon season. This will provide valuable information on the co-evolution of land and ocean convection centers.

Compared to ocean observations, a great challenge with land observation systems is how to extrapolate point observations to larger scales. Remote sensing provides one of the most useful scaling tools. For this reason, projects such as CEOP coordinate closely with the Committee on Earth Observation Satellites (CEOS). Success in TRMM, TERRA, AQUA, ESA ENVISAT missions have provided or will provide key information in integrating ground based land observations. For instance, the MODIS sensor on board TERRA, with its balanced resolution and coverage has already provided a suite of information from vegetation characteristics to land cover change of unprecedented quality since 1999.

Remotely-Sensed Observations

The present suite of remotely sensed observations that provide coverage of the Atlantic Ocean and adjacent continents is expected to continue into the foreseeable future. NASA, NOAA, ESA, CNES, and JAXA are all striving to continue the data continuity from the research and operational satellites that provide SST, scatterometry, altimetry, and chlorophyll concentration for the ocean, temperature profiles, humidity profiles, radiation, cloud properties, aerosols, and precipitation for the atmosphere, and surface temperature and vegetation cover for the land surface. This suite of Earth observations will continue via a series of discipline specific Earth Probe and Earth Explorer research missions and mulit-discpline/operational platforms such as ENVISAT, NPOESS, GOES, and EUMETSAT platforms. New sensors expected over the next decade will focus on the hydrological cycle. ESA's SMOS mission will provide information on Soil Moisture and Ocean Salinity (SMOS), NASA's Aquarius and HYDROS satellites will provide complementary information on salinity and soil moisture, respectively. NASA's Global Precipitation Mission will serve to extend in both space and time rainfall rate estimates that began with the Tropical Rainfall Measurement Mission (TRMM).

A particular difficulty to be confronted in the years to come is that most of the measurements mentioned above are either from research satellites or from operational platforms that serve the needs of Numerical Weather Prediction (NWP). The fundamental requirements (e.g., accuracy, calibration, continuity, reprocessing, data stewardship) for remotely-sensed observations in support of climate monitoring and prediction are not equivalent to those for NWP. Although many of the satellite agencies have taken on or support the mandate to understand climate variability and change, most have not yet marshaled the resources necessary to produce and maintain climate quality data records from remotely-sensed platforms. Moreover, the synthesis and integration of remotely-sensed observations together with in situ observations is only now beginning for the climate problem.

Challenges for the Future

For the most part, the vast majority of climate observations in the Atlantic sector are for general climate monitoring or are deployed to support specific process studies. In this regard there is no Climate Observing System for the Atlantic Sector per se, rather the "observing system" we have is really an amalgam of various, yet complementary, observational platforms serving a variety of needs and purposes. Nonetheless, climate observations in the Atlantic sector are among the most extensive across the world's oceans. The absence of any routine or operational climate prediction for the Atlantic sector has also meant that climate prediction has not been a major driver to the design and deployment of climate observations in the region. Except for a few examples, observing system simulation experiments for the Atlantic have been minimal at best. This stands in stark contrast to the Pacific where sustained climate observations have been predicated on the needs of seasonal to interannual climate forecasts based on ENSO. As part of GODAE, ocean data assimilation efforts have begun in the Atlantic basin, but the emphasis here is on ocean state estimation and nowcasting, not climate prediction. CLIVAR is just beginning its ocean climate synthesis and integration via the newly formed Global Synthesis and Observations Panel. A major challenge for the future and the topic of this workshop is the prospect for prediction in the Atlantic sector. As CLIVAR efforts within the Atlantic Panel, VAMOS, and VACS establish the level of prediction skill within the region, it is reasonable to expect this will lead to specific observational requirements. Some of the observational requirements are likely to be met by the existing suite of observations, others may be satisfied in the near term by process oriented or field experiments, and others may call for totally new observations required in direct support of advancing forecast skill. At the present time this interplay between the observation and prediction communities is in its formative stages for the Atlantic.

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Coupled prediction systems for Atlantic Sector climate

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1. Introduction/motivation

On a global scale, it is the ENSO related SST variability in the Pacific which is the biggest single driver of seasonally averaged climate anomalies. In comparison to ENSO, Atlantic SST variability is typically weaker, and is often given little attention in ‘global’ seasonal forecast systems. Yet Atlantic SST variability is by no means negligible, and can have a substantial impact on the atmosphere and on seasonal weather patterns. This impact is most visible on the regional scale (for example, the influence of Atlantic SST on Brazilian Nordeste rainfall), but there is much evidence that the influence of Atlantic SST anomalies can extend great distances - albeit that this influence is ‘mixed in’ with remote forcing from the Pacific and elsewhere.

In this paper we focus on our present capabilities to predict Atlantic SST anomalies, and the implications this has for seasonal and decadal prediction of climate anomalies in the Atlantic sector. Of course, an important part of what is predictable in Atlantic climate is driven from outside. Here we assume that these other factors are either already handled reasonably well (possibly true for some ENSO influences), or will be pursued elsewhere. There is a specific issue of teleconnections in coupled models, namely how accurately signals propagate from a correctly represented tropical source outside the Atlantic, given the errors that exist in the mean state of coupled models (and their atmospheric components even when uncoupled). This is particularly relevant for areas such as Europe, which are quite a long way downstream of important forcing regions in the Pacific, and where it is difficult to be confident that a GCM will accurately reproduce the structure and phase of teleconnections. Despite its importance, we will not examine the accuracy of modelled Atlantic sector teleconnection structures in this paper, partly because this is an area where little work has been published.

The predictability of SST varies across the Atlantic, due to the variety of mechanisms which are operating. Equally, the physical importance of the SST in influencing climate anomalies varies, depending on the region of SST concerned. Our knowledge of exactly which regions of SST are most important in a coupled prediction system is still incomplete, but certain areas and seasons of established importance are given prominence in this paper. In particular, the ‘dipole’ structure is important for MAM precipitation in NE Brazil, while the equatorial SSTs are important for JJA rainfall in West Africa.

2. Overview of existing coupled prediction systems for the Atlantic

There are relatively few coupled models that have been used to investigate predictability and prediction skill specifically in the Atlantic sector. On the seasonal timescale, much work with coupled models has used basin-wide models of the Pacific or Indo-Pacific, with Atlantic SSTs simply being specified. Indeed, many operational seasonal forecasting systems today are still using empirical methods to generate an SST forecast for the Atlantic basin. As will be clear by the end of this paper, such a strategy is not unreasonable, given the challenges involved in trying to get coupled model forecast systems to work.

In discussing existing work, we distinguish between predictability studies, and attempts to use models for prediction of past (or future) events. Predictability work is not the focus of this paper, but with regard to seasonal variability we want to mention the paper by Zebiak (1993), which used a simplified coupled model together with data analysis to establish that coupled interaction in the equatorial Atlantic is a source of interannual variability. Compared to the Pacific the variability is much weaker (and sub-critical with regard to self-sustaining oscillations, according to Zebiak's estimate), and SST variability is clearly driven by many other factors besides. As far as we are aware, this Atlantic model has not been used for further studies into predictability (and prediction!) of the component of SST variability which it claims to identify. One point to note is that SST data suggests that there is a fair degree of correlation between interannual variability on the equator in the Atlantic, and SST variability further south. This is seasonally varying, and is most evident in the boreal summer. What this tells us about mechanisms and thus prediction strategies is unclear to the authors at the time of writing. Do seasonal/interannual cold or warm events in the south and equatorial Atlantic typically originate with sub-surface anomalies in the western ocean propagating along the equator and then southwards along the coast, or are other mechanisms more important, many of which give predictability essentially from observations of the SST field? Previous ocean modelling studies such as that by Carton et al (1996) established that equatorial SST anomalies were dominated by equatorial wind variability, but for a coupled system this still leaves much unresolved. Off-equatorial SST anomalies are normally ascribed to latent heat anomalies driven by wind variations, and on decadal timescales this is argued to be a possible mechanism for variability (Chang et al, 1997), but the exact roles of heat-flux/SST feedbacks, cloud feedbacks and non-local impacts on the interannual variability remain to be established.

For decadal variability in the North Atlantic, more work has been done on predictability than prediction *per se*. For example, the predictability of the thermohaline circulation has been addressed in various studies (Griffies and Bryan, 1997; Groetzner at al, 1999; Collins and Sinha, 2003), which agree that there is some decadal predictability in the fluctuations of the strength of the North Atlantic thermohaline circulation, but give differing assessments as to the implications in terms of predictability of surface temperature over surrounding land areas. Attempts to initialize models with an observed decadally varying state, and test our ability to make actual decadal predictions, are as yet not very visible.

Thus, when it comes to discussing actual prediction systems this paper is inevitably going to focus more on the seasonal/interannual problem. There are operational coupled global seasonal forecasting systems at ECMWF, UKMO, NSIPP and elsewhere, many of them covered by other presentations at this meeting. One other useful set of integrations are those from the EU-funded DEMETER project, which has run seasonal forecasts with a set of 7 different global coupled models, for a period covering more than 40 years in some cases. This gives a fairly rich dataset for investigating Atlantic predictability, and particularly in understanding the model dependence of the results.

3. The ability of coupled GCMs to simulate the mean climate of the Atlantic sector

The first challenge for a coupled GCM prediction system is to produce a reasonable simulation of the mean state of the Atlantic sector. Moderate levels of error will not necessarily destroy all predictive skill - in the case of ENSO variability in the Pacific, for example, we know that coupled GCMs can give useful forecasts despite significant errors. The interplay between mean state error, the model failings that produce the mean state error, and forecast errors is likely to be relatively complex, and dependent on the physical mechanisms giving rise to predictability. Nonethless, a simple a priori starting point is that the bigger the errors in the model mean state, the more likely we are to have trouble with our forecasts; and that if the mean state starts to look qualitatively different to reality, then we should expect to be in difficulty.

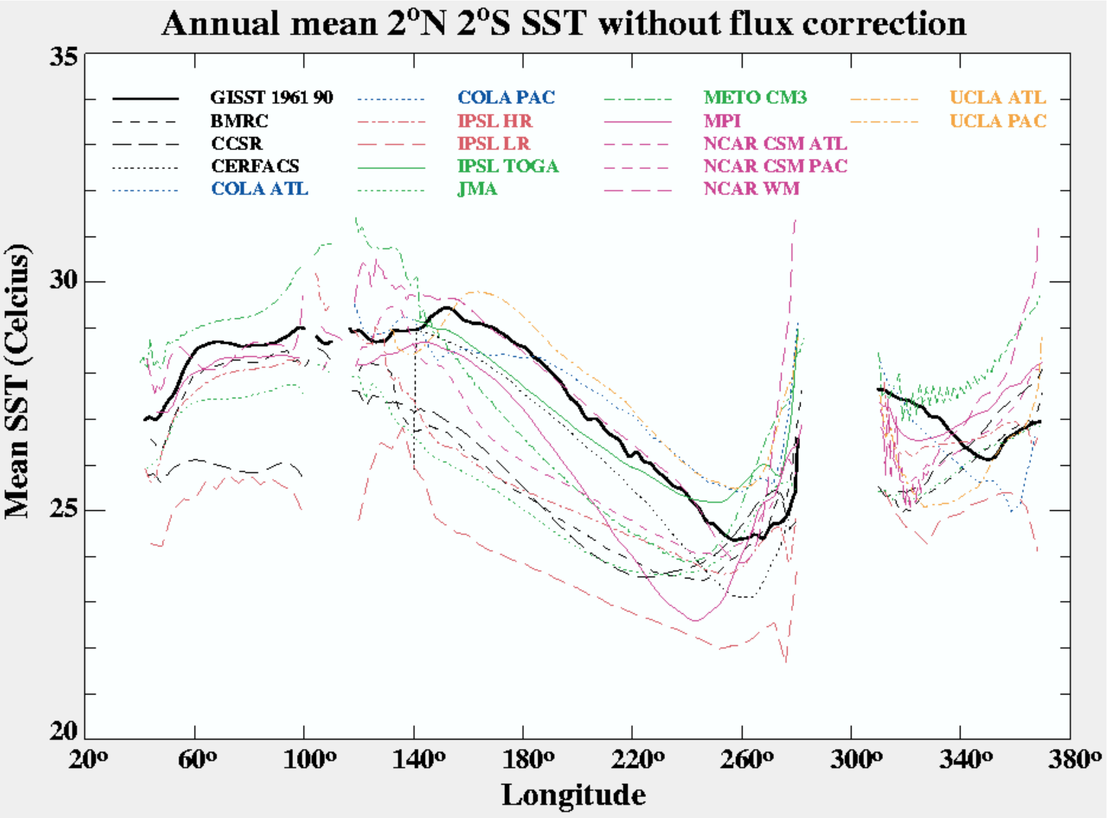

Figure 1: Annual mean SST in a set of coupled GCM simulations (Davey et al, 2002)

Past experience has shown that simulating the mean state in the tropical Atlantic is not easy. For example, Fig.1 shows the SST along the equator in a set of non-flux corrected coupled GCMs from the STOIC project (Davey et al, 2002). In the Pacific there is a considerable range of absolute values of equatorial SST, and the models clearly have problems near the eastern boundary, but at least the gradient in mid-ocean is reasonably represented. In the Atlantic, all of the models bar one have the mean gradient of SST the wrong way round!

However, the above figure is based on longer runs from coupled GCMs, and in the shorter runs typically used in seasonal forecasting systems (eg around 6 months), the model climate does not behave quite so badly in terms of SST. Nonetheless, the DEMETER runs show that models still have difficulty in reproducing the seasonal cooling in the eastern equatorial Atlantic in July, and that at least at this time of the year, the zonal SST gradients are poorly represented. It is also clear that the wind field over the equatorial ocean (in at least some models) has substantial errors right from the first month of a coupled integration, that is, the wind errors are not coming from the coupling but are in part inherent in the atmosphere model.

The analysis of errors in atmospheric GCMs is a substantial task that will not be discussed in any detail here. Nonetheless, one common difficulty is getting the right level of precipitation over land areas (the Amazon is one particular problem). Clearly in the Atlantic basin, a failure to position convection correctly with respect to land/ocean is a very serious problem, which is likely to cause a range of problems in simulating both the mean state and interannual variability. Unfortunately, recent experience at ECMWF suggests that it is not easy to remove problems of this sort. Another infamous problem in atmospheric modelling is the difficulty of simulating the low level stratus decks. Again, in the South Atlantic, if we get the stratus wrong, we have serious problems, given the size of the basin. And again, experience suggests that it is difficult to sort out the stratus problem at the same time as keeping everything else in reasonable working order. Nonetheless, in the case of stratus there is some optimism as regards progress. Improved boundary layer physics in the ECMWF model has led to a radical improvement in the stratus cloud decks, and Figure 2 shows that high amounts of cloud cover (>80%) are also maintained in the full coupled system.

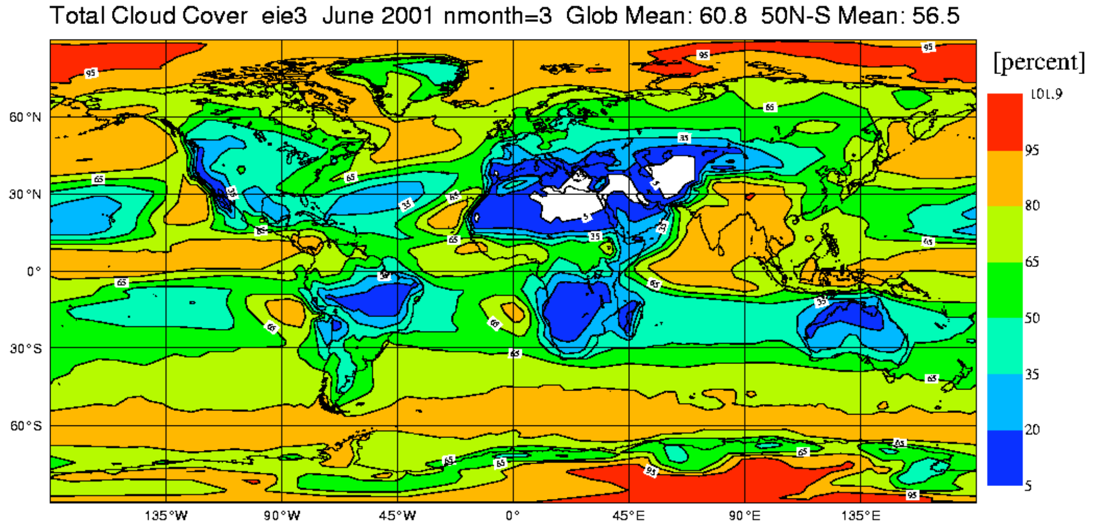

Figure 2: Total cloud cover in JJA, in coupled ocean-atmosphere integrations using the new boundary layer physics at ECWMF. Orange represents cloud cover above 80%, and the stratus decks are generally well represented.

One important diagnostic field is the 200hPa zonal wind. This both responds to deep tropical convection, and plays an important role in dynamical teleconnection of signals from the tropics into the mid-latitudes. How well do state-of-the-art coupled GCMs simulate this field? Figure 3 shows the climatological error from the ECMWF seasonal forecast system, for the JJA season. Errors are not negligible. Unfortunately, more recent versions of the model have errors which are larger, not smaller.

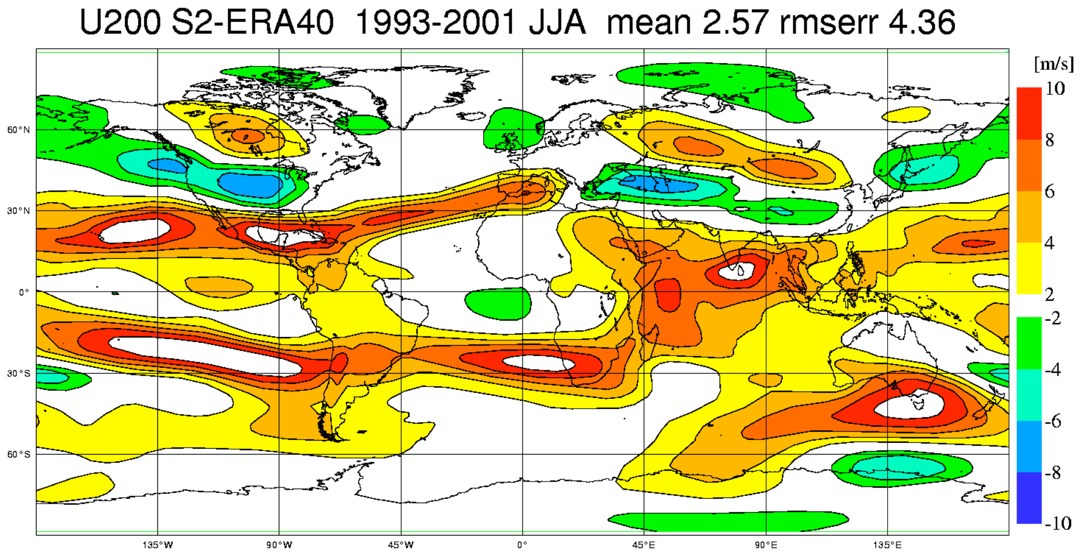

Figure 3: Mean error in the 200hPa zonal wind field from the ECMWF operational seasonal forecast model

In summary, the mean climate simulated by coupled GCMs in the Atlantic sector still has significant room for improvement. The models are not so bad as to preclude the possibility of obtaining something useful in forecast mode, but the problems are serious enough for us to expect a significant degradation of skill. It is easy to say that improvement of the models is an important priority. It may not be quite so easy for this community, or indeed anyone, to deliver the desired improvements.

4. The quality of ocean analyses in the tropical Atlantic

Knowledge of the state of the ocean is important for the understanding of the climate system, as well as being essential for initialization of seasonal forecasts. A way to obtain a global estimate of the ocean state is to use an ocean GCM forced by atmospheric fluxes. But uncertainty in time evolution of the wind stress often results in a large uncertainty in the interannual and decadal variability of the upper ocean, and model errors are likely to contaminate the results. Combining observations with models through data assimilation techniques is in principle the optimal solution for the estimation problem.

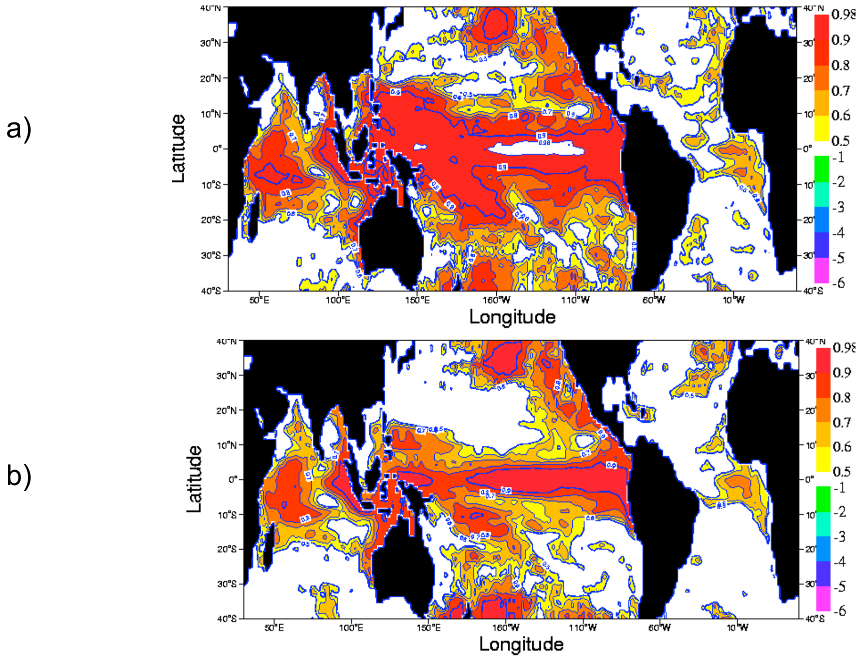

Figure 4: Correlation of sea level from altimeter data with sea level from the ECMWF operational ocean analysis, a) with in situ temperature assimilation, b) with no data assimilation. Correlations are for the period 1993-2001.

The impact of data assimilation can be evaluated by comparison with independent data. Figure 4(a) shows the correlation of the sea level from altimeter data with the sea level from the ECMWF operational ocean analysis (system 2), where only subsurface temperature is assimilated, during the period 1993-2001. For comparison, figure 4(b) shows the correlation for an experiment without data assimilation (i.e., forced run). In the tropical Pacific, data assimilation improves the representation of the ocean state: it increases the peak value of the correlation (above .98, saturated colour), as well as the area with correlations above 0.9, which now cover most the band of 10N-10S.

In the Atlantic, the correlation is lower than in the Pacific, with or without data assimilation. The forced run shows peak values above 0.7 in a small area around the east-central Equatorial Atlantic. In the assimilation run, the extension of the 0.7 contour is reduced. There may be several factors responsible for this degradation. Several studies have shown that ocean data assimilation is typically correcting systematic error, which can be caused by errors in the forcing, errors in the models or errors in the assimilation methods (Alves et al 2004, Vialard et al 2003, Balmaseda 2003, Bell et al 2004). The presence of systematic error can deteriorate the state estimation if the assimilation methods are not robust enough to cope with it. In fact, in several cases the assimilation method itself can be causing the error. The Equatorial Atlantic is a problematic area. To begin with, forced ocean models tend to produce a very diffuse thermocline with the wrong tilt. Additionally, the strong salinity stratification contributes significantly to the vertical stability, while in these experiments only temperature data are assimilated, since observations of salinity are scarce. This makes the Equatorial Atlantic a very demanding test for the multivariate temperature/salinity relationship. Further, the fresh-water fluxes (river discharge, precipitation/evaporation) are poorly known, which causes errors in the representation of the water-mass characteristics.

The presence of systematic error can also be damaging for the representation of interannual and decadal variability, since it can lead to aliasing of variability with changes in the observing system. In fact, one factor that contributes to the degradation of sea level in the assimilation run is the change in the observing system, namely the introduction of the PIRATA buoys after 1998. The impact of PIRATA manifests itself as a systematic decrease on the sea level over the Equatorial Altantic (Segschneider et al 2000). This does not imply that the effect of PIRATA is in itself damaging. In fact, if the correlation with the altimeter is computed only for the post-PIRATA era, the results are more optimistic. Figure 5 shows the correlation during the period 1998-2003. The correlation increases, with peak values of 0.8 located around the PIRATA array, which suggests that the data provided by the mooring are valuable. More accurate wind fields may be another factor in giving increased correlation.

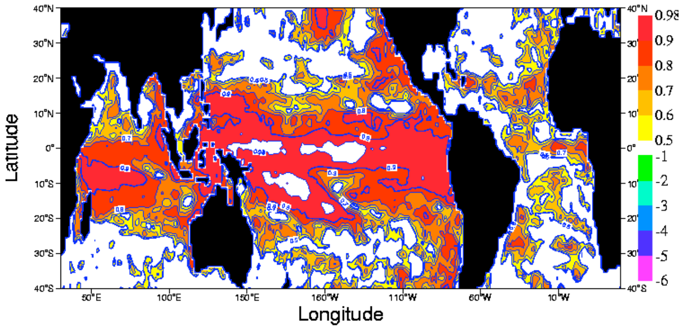

Figure 5: Correlation of sea level from altimeter data with sea level from the ECMWF operational ocean analysis with data assimilation for the post-PIRATA era (1998-2003). Values are higher in the equatorial Atlantic than those for the period 1993-2001.

These results suggest that appropriate methods to handle systematic error are needed in order to obtain consistent climate reanalyses that are not contaminated by the developments of the observing system. There is also a very clear need to continue to work to improve the multivariate constraints, as well as development to make direct use of the salinity data which is now becoming available from ARGO.

As well as further development of the assimilation methods it is desirable to reduce the error of the ocean simulations, either by improving the ocean models (mixing physics, resolution) or by improving the surface fluxes. The importance of surface fluxes can be illustrated by looking at the results produced by the same GCM forced by different wind stress. Figure 6(a) shows the time evolution (averaged over the Equatorial Atlantic 5N-5S) of two different wind stress products: the one used by the operational ocean analysis (referred as ERA15/OPS in what follows, represented by red) and the one provided by the ERA40 atmospheric reanalysis (blue curve). There are large differences during 1987, and during the decade of the 90’s. The largest difference by far occurs during 1996. The impact on the ocean can be measured by the evolution of upper ocean heat content (average T in the upper 300m), as shown in Figure 6(b). Uncertainty in the fluxes leads to uncertainties in the ocean state that are commensurate with the size of the interannual variability.

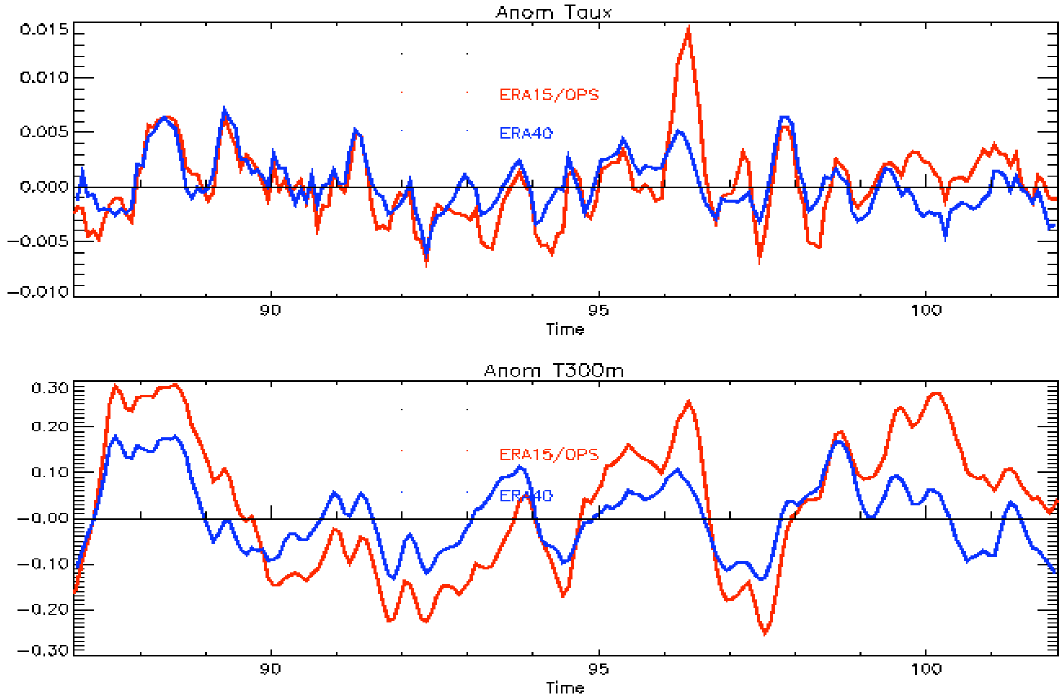

Figure 6: The upper panel shows the time evolution of the wind stress anomalies averaged over the equatorial Atlantic from ERA15/OPS and for ERA40. Note the large difference in 1996. Lower panel shows the evolution of the upper ocean heat content (average temperature in the upper 300m) when the different fluxes are used to drive the same ocean model.

It is legitimate to ask which of these two products is a better representation of reality. We use again sea level as a variable that can be compared with the altimeter data. Figure 7 shows the fit to altimetry of the model-derived sea level when using the winds from ERA40 and ERA15/OPS, but not subsurface data. The bars show the anomaly correlation statistics in different equatorial regions. ERA-40 fluxes improve the fit to the altimeter in all the equatorial regions. The correlation with the altimeter also gets consistently better everywhere around the globe (not shown), with the exception of the South Atlantic. The improvements of the forcing fluxes and the reduction of the ocean background error is the first step for to obtain reliable ocean reanalyis.

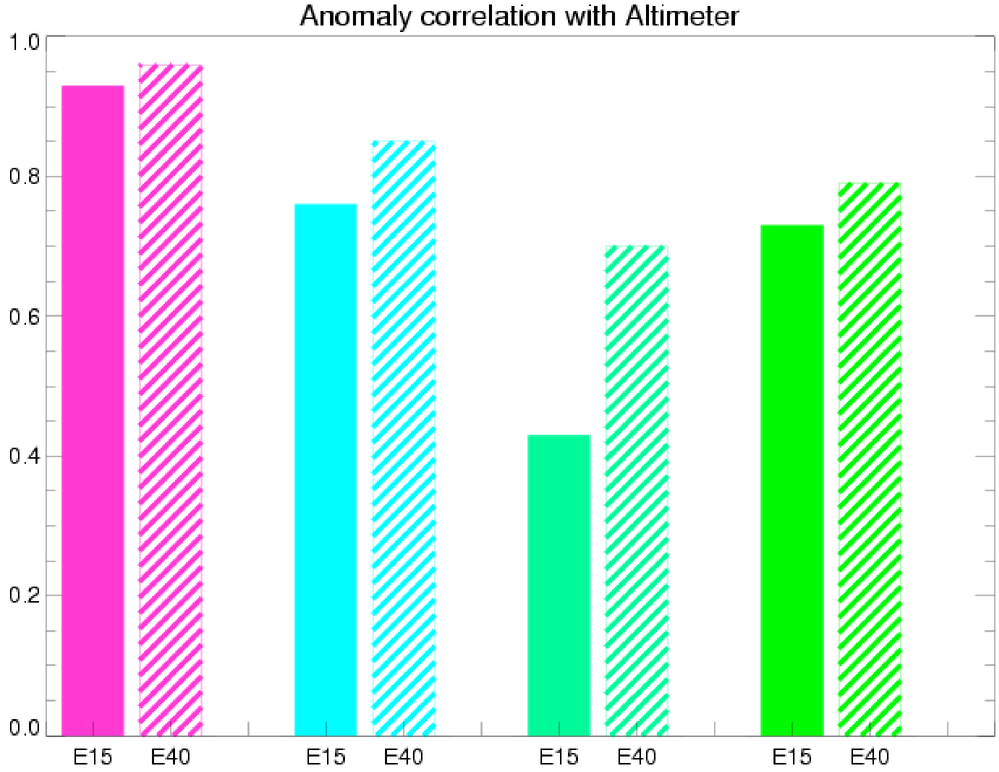

Figure 7: Correlation between ocean model derived sea level and altimetry in the West Pacific (purple), East Pacific (blue), Atlantic (pale green) and Indian (bright green) equatorial oceans. The model derived sea level has been produced using ERA15/OPS fluxes (solid bars) and ERA40 fluxes (dashed bars). ERA40 fluxes clearly improve the ocean estimate as measured by the correlation with the altimeter sea level

5. The skill of coupled GCM forecasts for the tropical Atlantic sector

We will look first at the predictability and prediction of SST on seasonal timescales, and we will focus on some commonly used indices of SST. Equatorial variability is well captured by the ATL3 index (3N-3S, 20W-0E), see Zebiak (1993). Variability in this region is thought to be partly due to an ENSO like mechanism (where ocean initial conditions should be important), partly forced by teleconnections from ENSO, and also appears to be somehow linked on interannual timescales to variability further south. Two other important indices of SST variability are NSTRATL (5-28N,80W-20E) and SSTRATL (20S-5N,60W-20E), introduced by Servain (1991), who used these indices to form the much discussed ‘dipole’ of Atlantic SST variability. Here we simply look at the two regions separately. Note that on interannual timescales there is quite a strong correlation between the SSTRATL and ATL3 indices. This is not simply due to SSTRATL including the equatorial region, but involves true covariability of SST in equatorial and off-equatorial regions. The ‘dipole’ indices are designed to look at decadal variability, and are not quite optimal for looking at interannual processes such as the SST variability best associated with Nordeste rainfall; nonetheless they offer a reasonable approximation and are used here to help give us a first understanding of the predictability of some of the key aspects of tropical Atlantic SST variability.

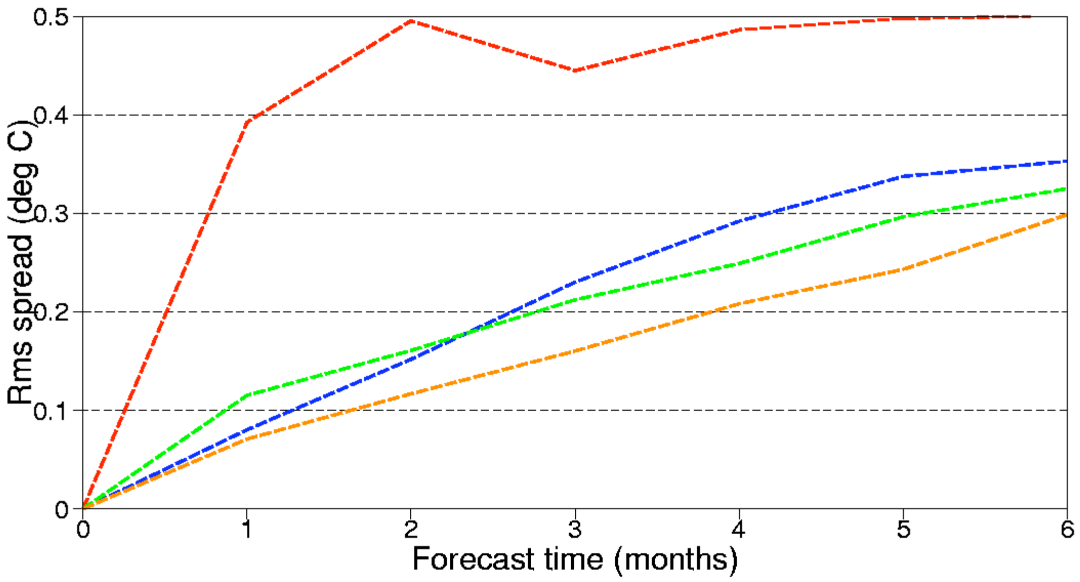

Figure 8(a): SST predictability in Nino3.4 region, derived from four experiments. Red and blue lines have ocean initial conditions prepared without data assimilation; red has wind perturbations applied and blue does not. Green and orange have data assimilation, green with wind perturbations, orange without. See text for details.

Figure 8 shows the estimated SST predictability (derived from the ensemble spread) from 4 experiments for each of several regions, covering the years 1987-2001. The red line shows the result when using wind perturbations to create an ensemble of initial conditions, when no data assimilation is used. The blue line shows the result when wind perturbations are not used, so that the ocean sub-surface is the same in the initial conditions of all ensemble members. In both cases, SST perturbations are applied in the surface layers at the start of the forecast. Figure 8(a) shows that in the Nino 3.4 region of the Pacific, the wind perturbations create a very large spread in the SST forecasts, additional to that which depends only on surface perturbations. This is a nice demonstration that the sub-surface state of the ocean is important for predicting SST. We next consider forecasts with wind perturbations (green) and without (orange), but this time in a system which uses ocean data assimilation to create the initial conditions. We now see that the data assimilation greatly reduces the spread produced by the wind perturbations (green versus red), although the spread is still larger than in the case of no wind perturbations (green versus orange), so that the data assimilation has not completely removed the effect of the specified uncertainty in the wind. Thus for ENSO forecasting we can demonstrate (i) that the sub-surface is important, and (ii) that for the period 1987-present, we are able to use in-situ data to constrain the system against any significant uncertainties in the wind field that may exist.

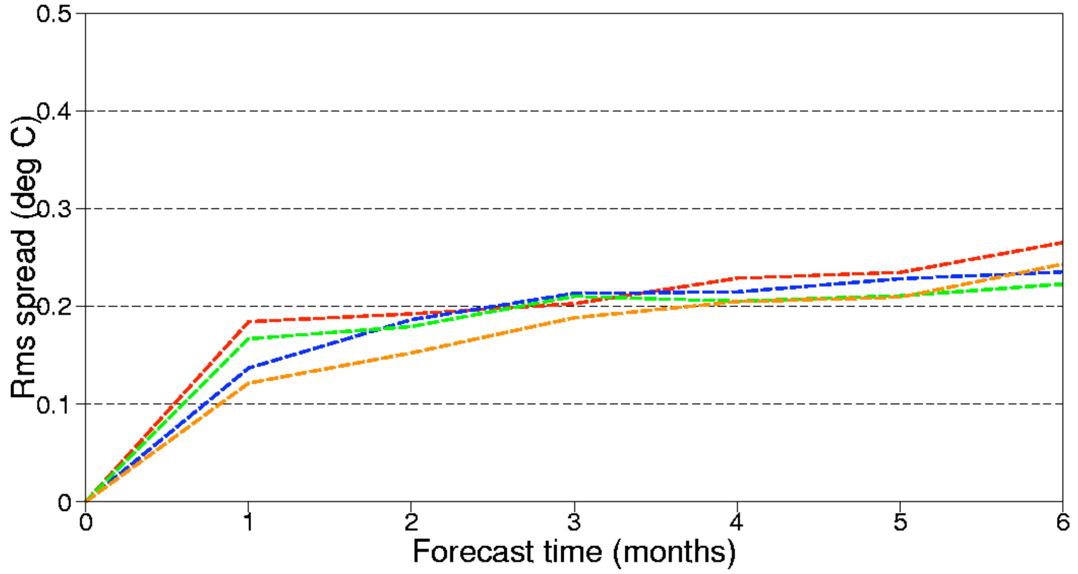

Figure 8(b): SST predictability in ATL3 region

We now turn to look at the tropical Atlantic. Figure 8(b) shows the same curves for the ATL3 region. Comparing the red and blue curves shows that the influence of the wind perturbations is much less than in the Pacific. Assuming that the wind perturbations are reasonably efficient at perturbing the ocean sub-surface (and the analysis results discussed earlier suggest they are), this shows that the sub-surface is of only modest importance in determining SST variability in ATL3. Comparing the green and orange curves shows that data assimilation does not reduce the impact of the wind perturbations on the forecast spread. This is again consistent with the analysis results above, and says that for this period (1987-2001) the in-situ data and our methods of using them are not sufficient to overcome errors in the wind forcing. This is in marked contrast to the situation in the Pacific. Note, though, that the coupled model has a mean bias which results in a deeper thermocline in this region, meaning that the real-world sensitivity of SST to sub-surface perturbations is likely to be higher than the value obtained from the model.

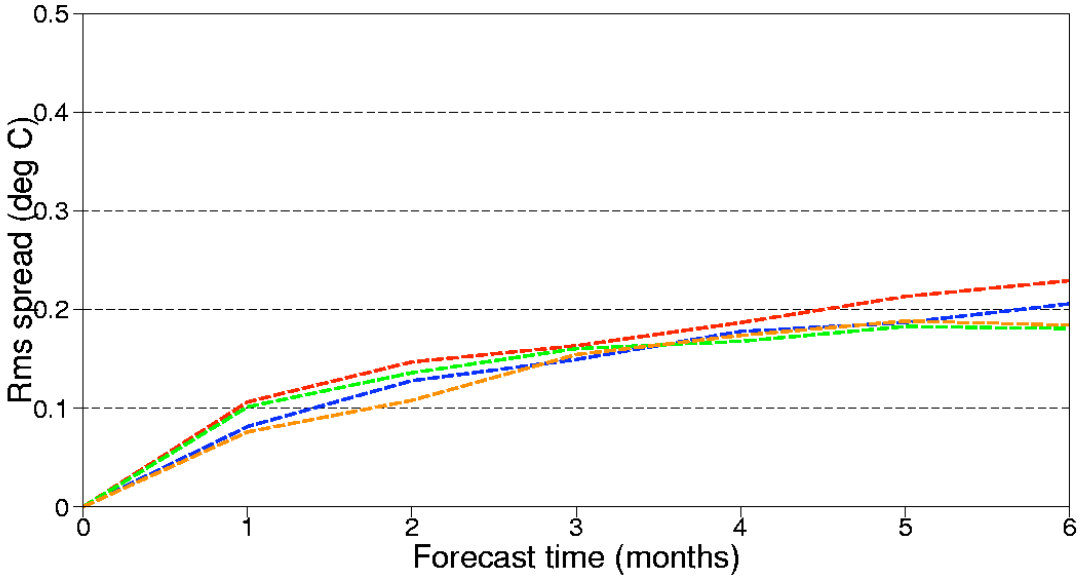

Figure 8(c): SST predictability in SSTRATL region

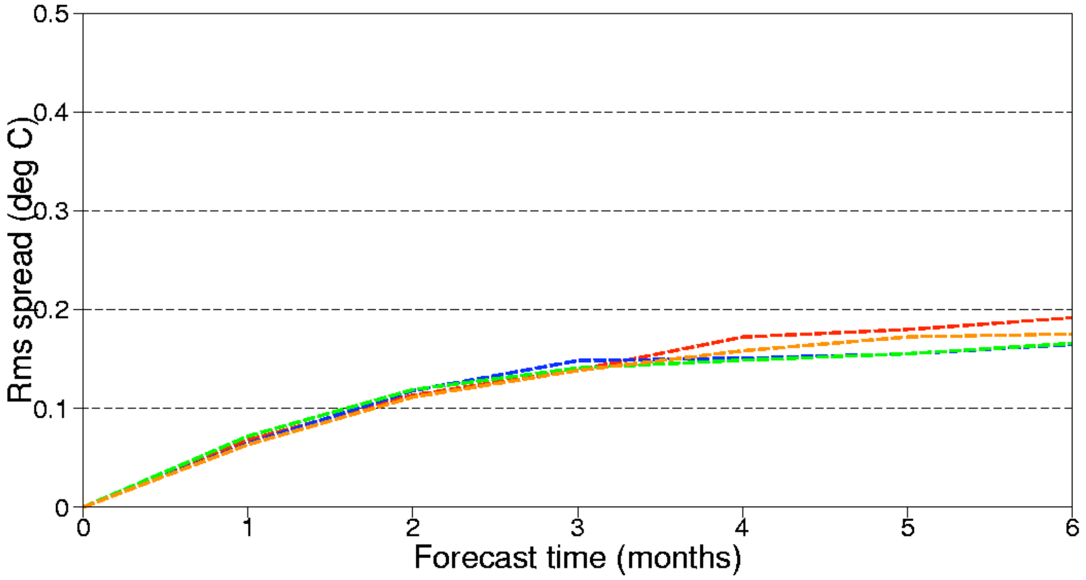

Figure 8(d): SST predictability in NSTRATL region

Results from SSTRATL are shown in Figure 8(c). The spread grows more slowly than in the equatorial Atlantic in all experiments, perhaps due to the larger area and slower physical processes being important for the SST evolution. In relative terms, the contribution of the wind perturbations is similarly modest, however, and again the assimilation of in-situ data does not usefully constrain the system. Figure 8(d) shows NSTRATL, where the spread in the early months is essentially unaffected by the subsurface ocean perturbations, and the data assimilation becomes irrelevant. Analysis of a longer period (1958-2001) shows that there is a small component to the spread that comes from the wind perturbations, but it is the smallest of the regions considered here.

These results graphically illustrate why coupled ocean-atmosphere SST forecasting systems for the Atlantic are little developed in comparison to the Pacific. The lack of influence of data assimilation on Atlantic SST forecasts can also be seen by looking at the individual forecasts, where the Atlantic forecasts are almost always very similar, but the Pacific forecasts often show significant differences between the ensemble mean forecasts from data assimilation and non-data assimilation forecasts (figure not shown).

We can also compare the predictability estimates with the actual forecast skill (figures not shown). If we do this for the ERA-40 wind forced runs for the period 1959-1999, we see that in the NSTRATL the actual rms errors are only modestly larger than the predictability estimate, and the forecasts beat persistence in both rms and anomaly correlation terms, ie the SST forecasts are doing better than damped persistence. A time series of ensemble mean forecast values shows that the model is fairly active, and often reproduces the growth of anomalies (eg positive in 1966, 1980, 1995 and 1998; negative in 1976 and 1989) as well as their decay. In general terms, it seems that the coupled model forecasts are doing a reasonable job of picking up a substantial portion of the 'remotely driven' SST variability in this part of the ocean, and although there are clearly more errors than would be expected in a perfect forecasting system, the overall performance is not too bad. This conclusion is consistent with the work by Huang et al (2002), who showed that in the north sub-tropical Atlantic, much of the SST variability is remotely driven, while in the south Atlantic local coupled processes seem to dominate.

Similar plots for ATL3 and SSTRATL show that forecast performance is not as good as for the north sub-tropical Atlantic - there is a noticeable gap between the rms errors which we actually obtain and the model estimates of the predictability limit. Anomaly correlation is worse than (damped) persistence in the case of SSTRATL. Plots of actual forecasts show that although there are times when the correct development of anomalies is predicted (notably in 1997/98), there are also times of forecast failure (eg the failure to create or even maintain the extended period of cooling in 1991/92; the cooling in late 1996/ early 1997 was also not particularly well handled). There are occasional 'false' developments, such as a non-occurring cooling in November 1995, but in general the model underestimates the amount of variability, particularly in the ATL3 region. The overall impression is that the model forecasts are correctly handling some forecast information, including teleconnections from the Pacific, but are failing to capture certain processes and/or information. Given the quality of the ocean analyses and the existence of at least some sensitivity of the forecasts to sub-surface perturbations, it is reasonable to conclude that some part of the forecast failure is due to inadequate initialization of the Atlantic Ocean initial conditions. It is not clear whether such inadequacies are sufficient to explain the majority of forecast error, though.

It is also of interest to compare the forecasts made with different models, for example those in the DEMETER project. Most DEMETER models were initialized in essentially the same way using ERA40 winds, although there are slight differences in the exact method used. In the Pacific, time-series of the scores for the different models show substantial differences between model performance in individual events, even though average model performance is broadly similar. That is, there is a relatively low correlation between the errors in different models, and averaging across models is a powerful technique for giving better forecasts. This is consistent with model error being important in Pacific SST forecasts, something which is also evident from the large mismatch between actual forecast errors and those estimated as being due to initial condition uncertainty. In the Atlantic, however, the forecast errors from the different models are typically much more correlated; this is notably true in the SSTRATL region. If the forecast errors were dominated by unpredictable behaviour in the observed system, then this would be fine. However, as discussed above, it seems that forecast errors are larger than can be accounted for by indeterminacy or (probably) initial condition error, at least in overall terms. We are thus left to ponder the question as to whether all of the models have some common error, and/or are missing some significant process which gives rise to variability.

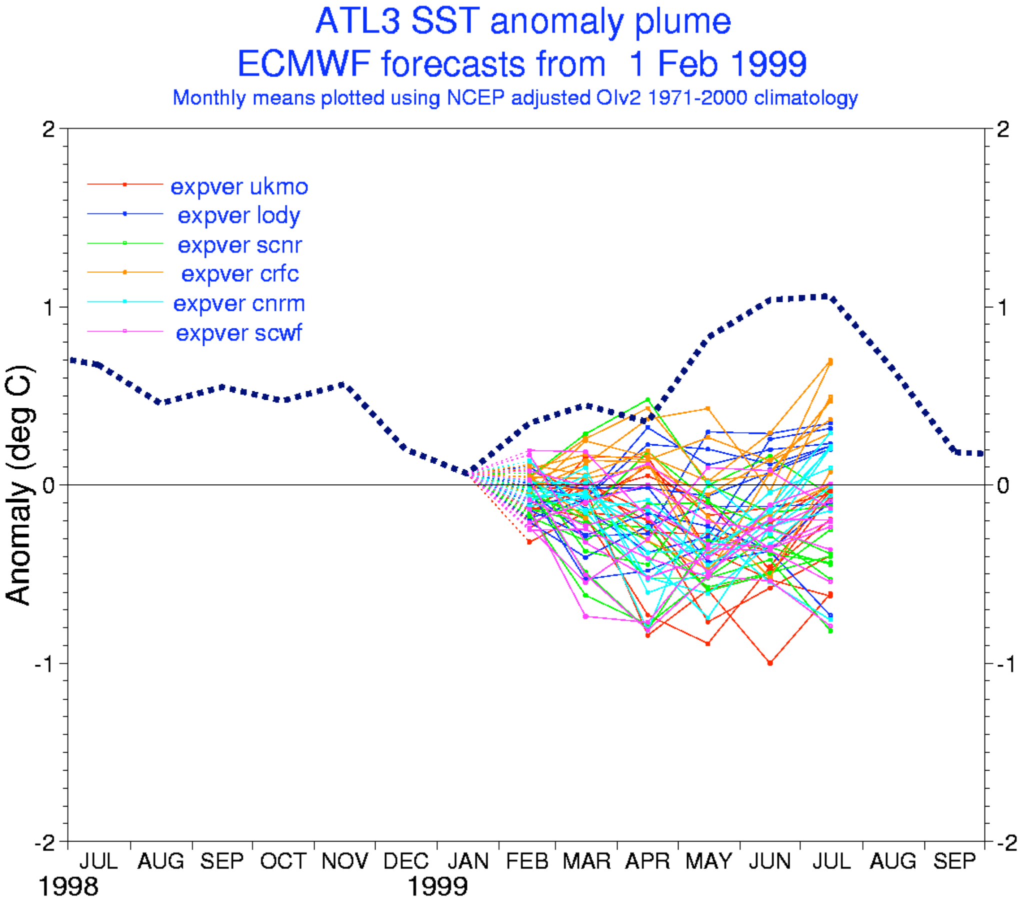

Figure 9: Forecasts from 6 different models for the ATL3 SST in 1999.

Figure 9 shows an example of a ‘failed’ multi-model forecast for ATL3 SST. The SSTRATL forecast failed in a similar way. It is possible that in this particular case, initial condition error beyond that sampled by the wind perturbations might be responsible for the forecast failure, but the statistics suggest that this will not work as a general explanation for the size of the forecast errors, and that the models may be suffering from some common failure. In the Pacific, use of a multi-model ensemble results in an ensemble spread which matches the rms forecast error; in the Atlantic this is not so. Note that in the ATL3 region, periods of large error often coincide with the July cooling of the mean state, which is a period when we know that all of the DEMETER models fail to adequately reproduce the seasonal cycle of SST, so the possibility of common model error affecting the forecasts at this time is not implausible.

One can also examine the atmospheric forcing fields acting on the ocean in these regions. There is some evidence that the coherent part of the heat-flux variability is partially reproduced by coupled forecast models, although the accuracy of ‘observed’ heat flux anomaly data (in this case from ERA40) is not certain. In terms of wind anomalies, there are clearly some problems. For example, in early 1996, 5 months of sustained positive zonal wind anomaly led to a warming in the ATL3 SST. The ECMWF coupled system is not able to sustain these wind anomalies even for the first month; and both it and all of the DEMETER models fail to capture the SST warming in short range forecasts. Examples could also be given of success in the models reproducing analyzed wind variability.

6. Conclusions

Our abilities to predict the future evolution of tropical SST anomalies in the Atlantic Ocean seem to be still rather limited. In the northern sub-tropical Atlantic, the main issue seems to be the fundamental predictability limit: our model forecasts are not too bad when measured against this. For the equatorial and southern Atlantic, there seem to be other problems as well. There are a number of reasons behind our overall performance:

1. The potentially predictable signal is relatively small. Stochastically forced damped persistence, with a bit of remote forcing from the Pacific, is not a bad approximation to what happens in much of the Atlantic, at least on seasonal timescales.

2. Partly because the signals are small, past observing systems give a rather inadequate basis for initialising and even verifying model forecasts. One complication in preparing this paper was the level of discrepancy between different ‘verification’ datasets, both for SST and altimetry. Some of these are easily explained by the known behaviour of EOF-based reconstructions, but other aspects of dataset differences are not straightforward, and seem to reflect real uncertainty in past SST. The uncertainties are not huge, but because the signal is weak, they are by no means negligible.

3. For recent periods, particularly when good quality scatterometer data is available, wind-forced ocean model runs appear to capture a moderate amount of the altimeter-estimated sea-level variability. See also the recent study by Florenchie at al (2004), where their success in simulating the south Tropical Atlantic is visibly improved by the better quality scatterometer winds. Assimilation of data to produce consistent ocean analyses remains difficult, and with present data sets and techniques it is hard to improve on the wind-forced results. Treatment of salinity and appropriate multivariate constraints remain important issues.

4. There is a predictability ‘gap’ in our results for the equatorial and South Atlantic, in that the errors in our forecasts appear substantially larger than can be explained by a combination of unpredictable ‘noise’ or the acknowledged errors in the ocean initial conditions. Part of this predictability gap may be directly due to model errors, eg an inability to produce the right atmospheric response to some specified SST anomaly. However, it is also likely that due to biases in the mean state, the sensitivity of model SST to the ocean sub-surface is underestimated. This is likely to be particularly important in JJA in the equatorial ocean, given that the observed strong upwelling is absent from the models. This is the season when the

equatorial SST anomalies have a significant impact on West African rainfall, and when our equatorial SSTs have the biggest errors. At least for the equatorial SSTs in this season, it looks as if we will need both better ocean initial conditions and better coupled models which can reproduce a good mean state.

5. When it comes to predicting atmospheric behaviour, whether forced from within the Atlantic sector or remotely, the limitations of the models are important.

So how can we take things forward? Several points seem worth making on this topic:

1. The observing system has recently improved, both in terms of in-situ data and data available to create forcing fields. Testing of our models and their forecast abilities might benefit from detailed work in this (very short) data rich period. For example, the present 2004 cooling of the tropical south Atlantic is an interesting forecast 'bust' for our present operational systems.

2. Serious work is needed on assimilation schemes to reconstruct the tropical Atlantic ocean state from limited data, in order to have reasonable estimates for some historical period.

3. Over the last few years, many global coupled GCM forecasting systems have been run. Typically, little attention has been given to the Atlantic sector, and the tropical Atlantic in particular. More analysis is needed of the Atlantic. Note that a lot of model output is available to outside researchers, for example data from the European DEMETER project can be freely downloaded from the internet.

4. We did not discuss in this paper the role of the surrounding land areas as a source of variability. Nonetheless, it can be argued that the possible role of soil moisture, vegetation and aerosol sources in both seasonal and longer timescale variability in the Atlantic sector should be investigated.

5. Although it is clear that the tropical Atlantic is not a dominant source of seasonal predictability on a global scale, it is important to visibly acknowledge that the Atlantic is of importance, does have impact especially regionally, and is presently inadequately treated in our forecast systems. We need to admit that until the Atlantic is better handled, our forecasting capabilities are incomplete; and thus we need to be willing to commit the resources and the effort to improve the situation.

This paper has said little about decadal prediction. Much work is being done to try to understand the mechanisms and degree of decadal predictability in coupled models. The situation is perhaps analogous to the early days of ENSO coupled modelling, where a variety of oscillating models were constructed, which turned out to involve different mechanisms and have different characteristics. Progress in understanding 'real-world' ENSO variability benefited when the models were confronted with reality, and put to use in trying to make forecasts and hindcasts of the real system. It must be admitted that in the case of ENSO the field was not quick to mature, and important issues are still being debated. Nonetheless, it can be argued that only when decadal prediction systems start to be applied to real world forecasting problems will we be able to understand how the world really works. Given the signal to noise/error ratios inherent in studying decadal variability, the task will be challenging. But given the actual and potential importance of decadal or longer climate variability, we should be willing to try.

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Seasonal-to-Decadal Predictability and Prediction of West African Climate

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Introduction

During boreal summer, the West African monsoon is a major feature of the global circulation. Thus, it is not surprising that many studies have identified aspects of the climate system that accompany fluctuations in the West African monsoon. Indeed, some of the first studies of tropical Atlantic variability were driven by an interest in climate variations over West Africa. This review article focuses on the teleconnections between global ocean-atmosphere features and the West African monsoon. These teleconnections are particularly relevant because they lead to a degree of predictability on seasonal timescales. Other factors also will contribute to the way in which the monsoon varies from one year to the next and over decades, including continental land surface characteristics and internal atmospheric processes, so the prediction skill from ocean-atmosphere coupling alone will never be perfect. Some, and conceivably most, of these other aspects of variability may be fundamentally unpredictable. Research into other potential sources of predictability, such as initial land surface conditions, is still emerging and discussion of some of the issues will be included in the concluding section. That final section also touches on predictability at smaller spatial scales and of weather statistics through the season, features which often strongly project on environmental aspects that most matter for society.

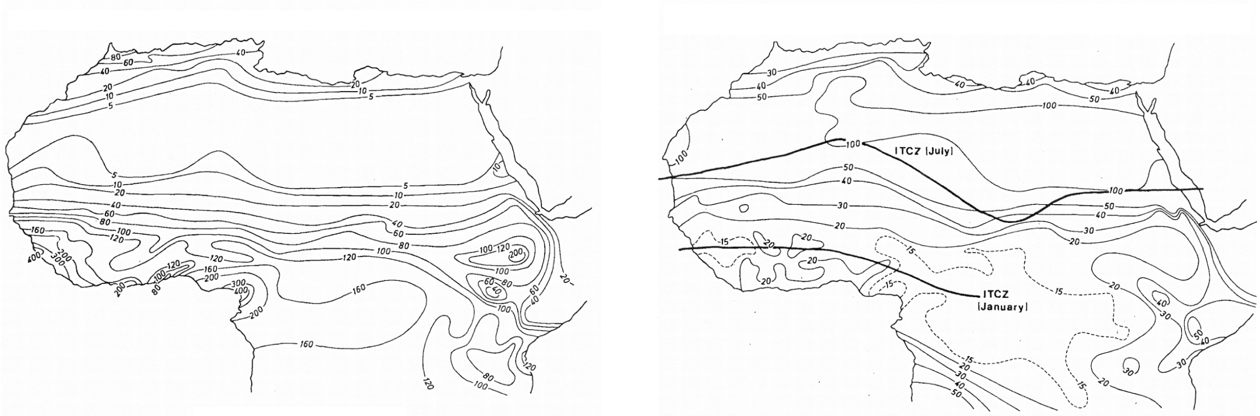


Fig 1.Climatology of Africa (North of the Equator). Left panel is mean annual rainfall (cm). Right panel is variability of annual rainfall total, expressed as the ratio of standard deviation to annual mean (multiplied by 100). From Nicholson, 1980.

For this review, the West African monsoon is mainly represented by indices of rainfall during the period of the historical record. This is far from ideal, but indices of rainfall have been widely researched and the input data subjected to quality control, so that rainfall indices are believed to provide a reliable record of the spatial pattern of climate (e.g. Fig. 1) and of climate variations in the region (Figs. 2 and 3).

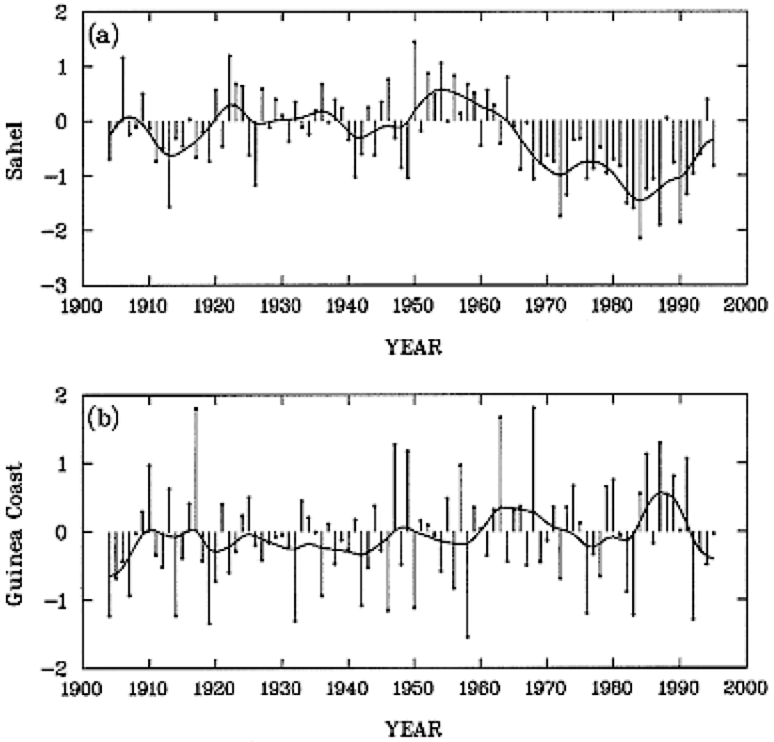


Fig 2. : Indices of July-September West African rainfall with low pass filter to emphasize nature of multi-decadal variations. (a) Sahel (here defined 12.5°N-17.5°N, 37.5°E to the west coast of Africa), (b) Guinea Coast (here defined 7.5°E-7.5°W, 10°N to the south coast of West Africa. From Ward, 1998. The choice of these domains is supported by the covariance of July-September rainfall totals within each region, as revealed in analyses of West African rainfall variability. Though other subdivisions are possible, this particular choice is well suited for summarizing large-scale seasonal predictability in the region.

The Sahel region, lying along the southern fringe of the Sahara desert, receives almost all its 100-400mm of annual precipitation during April-October, with the peak of the rainy season during June-September. Moving south from the Sahel, annual rainfall totals increase (Fig. 1), but in West Africa, during the Sahel rainy season, conditions to the south are relatively drier toward the Gulf of Guinea coast. Indeed, these regions have a bimodal annual cycle of rainfall, with August usually marking a reduction of rainfall in the annual cycle, defining a “Little Dry Season” at the time when the heaviest rains associated with the Inter-Tropical Front (ITF) are usually at their most northerly location. The July-September rainfall in this southern region (here referred to as the Guinea Coast Region) is climatically interesting because in some years, the ITF remains active further south than normal and rainfall is substantial in this region too, often at the expense of rainfall in the Sahel. The transition seasons of March-June and October-December are of interest in both the Sahel and the regions to the south. In the Sahel, they include the characteristics of the onset and recession of the rainy season. To the south across the Guinea Coast region and Central Africa, they form the two main rainy seasons. The Sahel dry season is also included in this review as there is increasing interest in interannual and decadal climate variability at this time of year as well, in particular the variations in atmospheric dust. This review builds upon an earlier one with an ocean-atmosphere focus (Lamb and Peppler 1991) and complements a more recent one with a more land-atmosphere perspective (Nicholson 2000).

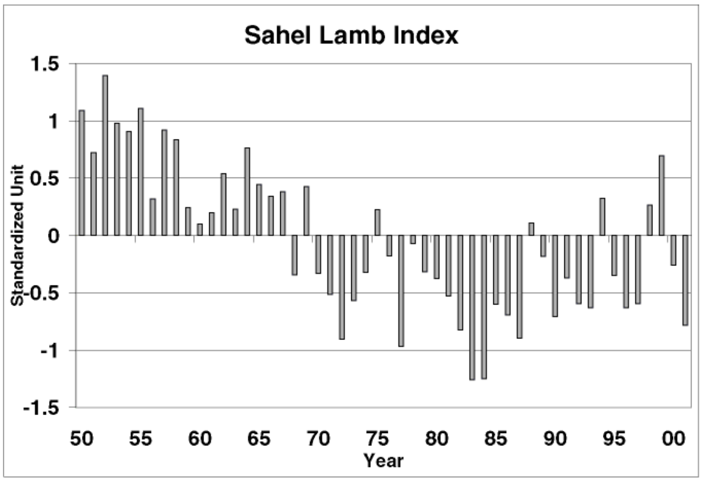


Fig 3 : Index of April-October Sahel rainfall, 1950-2001. Rainfall indices are found to be consistent and reliable records of climate variations in the region, provided sound analysis procedures are applied to the rainfall stations. (Lamb, personal communication)

Some Early Teleconnection Studies of the West African Monsoon

In a series of composite analyses and case studies, Lamb (1978a,b) identified relationships between West Sahel rainfall, tropical Atlantic sea-surface temperatures (SSTs) and tropical Atlantic near-surface atmospheric circulation. Wetter years appeared to be associated with a warmer tropical North Atlantic, cooler tropical South Atlantic and an associated northward displacement of the Intertropical Convergence Zone (ITCZ) over the tropical Atlantic. Drought years essentially exhibited opposite characteristics. These interpretations were reinforced by the results of Hastenrath (1984), Lough (1986), Lamb and Peppler (1991, 1992) and Janicot (1992).

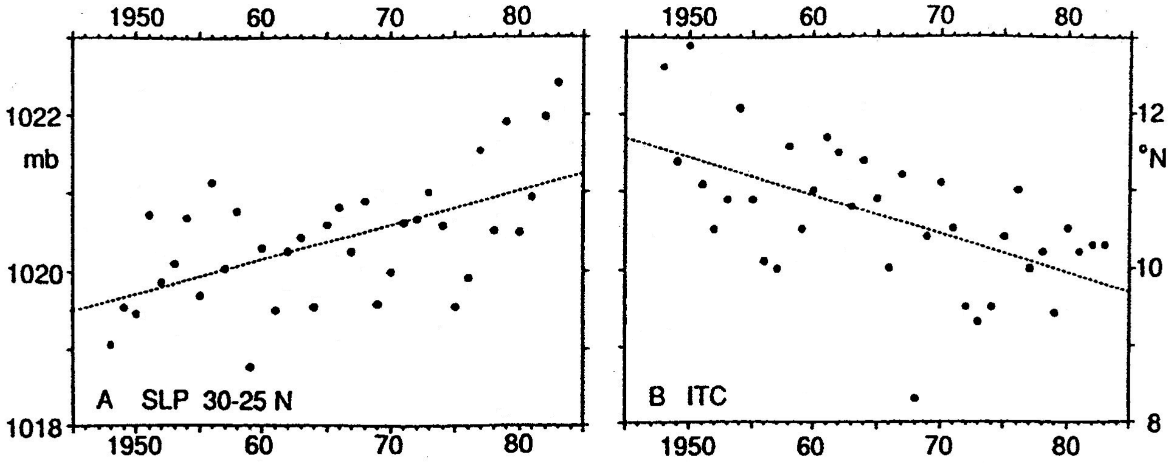


Fig 4: Time series of climate elements in the tropical North Atlantic for July-August 1948-83. (a) Sea-level pressure, (b) Latitude of wind confluence (zero meridional wind component). From Hastenrath, 1990.

The next development was to extend the teleconnections with SST beyond the tropical Atlantic. A series of papers (e.g. Folland et al. 1986, 1991, Wolter 1989, Adedoyin 1989, Fontaine and Bigot 1993, Shinoda and Kawamura 1994, Ward 1998) established that wetter years in the Sahel were associated with warmer SSTs throughout much of the Northern Hemisphere and cooler SSTs throughout much of the Southern Hemisphere, including the whole Indian Ocean. This North-South contrast in SST anomalies is often referred to as creating an "anomalous interhemispheric SST gradient". The potential influence of these large-scale SST anomalies on West African rainfall was confirmed in General Circulation Model (GCM) experiments forced with prescribed SST anomalies throughout the globe and/or in individual ocean basins (e.g.

Folland et al. 1986, Palmer 1986, Folland et al. 1991, Palmer et al 1992, Diedhiou and Mahfouf, 1996). It has nonetheless emerged that while some GCMs capture the variability of the West African monsoon very well and are excellent tools for its study, many other GCMs have a very poor representation of this aspect of the climate system (e.g. Sud and Lau, 1996).

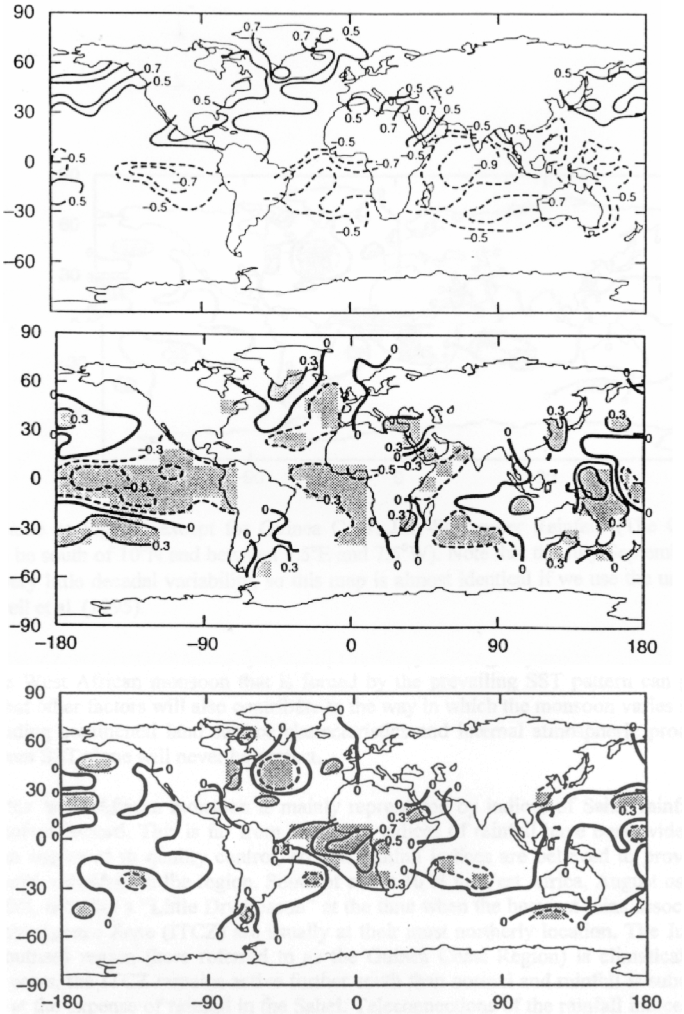


Fig 5: Correlation between West Africa July-September rainfall indices and July-September sea-surface temperature. (a) Correlation with low frequency component of Sahel rainfall (smooth line in Fig. 2a), (b) Same as (a) but with high frequency component (residuals from the smooth line in Fig. 2a), (c) Same as (b) but for Guinea Coast rainfall. In (b) and (c) shading indicates statistical significance at 5% level. From Rowell et al. 1995.

Subsequent work has further established the nature of the teleconnections, and the current status of understanding will be detailed in the remainder of this review. One problem posed to the diagnostic analyses is the strong multi-decadal variability that exists in time series of the West African monsoon (Nicholson 1980). Thus, it has proved useful to study the decadal and interannual variability separately (e.g. Hastenrath, 1990 on the decadal component (Fig. 4) and Rowell et al., 1995 and Janicot et al., 1996 on both the decadal and interannual components). This separation can be achieved by passing a smooth line (filter) through the climate time series and creating two new time series (see Fig. 2): (i) a series describing the decadal variability (the smooth line, Fig. 2) and (ii) a series describing the interannual variability (residuals from the smooth line in Fig. 2, sometimes referred to as the sub-decadal variability). Teleconnections with the decadal and sub-decadal time series can then be studied separately.

Teleconnections with the Decadal Sahel Rainfall Fluctuations

Diagnostic analysis of decadal teleconnections during the historical record is made very difficult by the small number of degrees of freedom that we have available to study. Put simply, there may be only two or three decadal fluctuations in the time series of interest, and this makes it difficult to draw conclusions about whether other decadal variations that occur at the same time have real causal connections, or whether they are coincident by chance without any causal relations. Thus, when we calculate the correlation between the decadal Sahel rainfall variation and the decadal SST variation (Fig. 5a) the result should be viewed as descriptive only, and we need to use physical arguments to assess which relations have causal basis. One way to gain supporting physical and dynamical evidence for the connections is to study the response of GCMs to prescribed SST forcing.

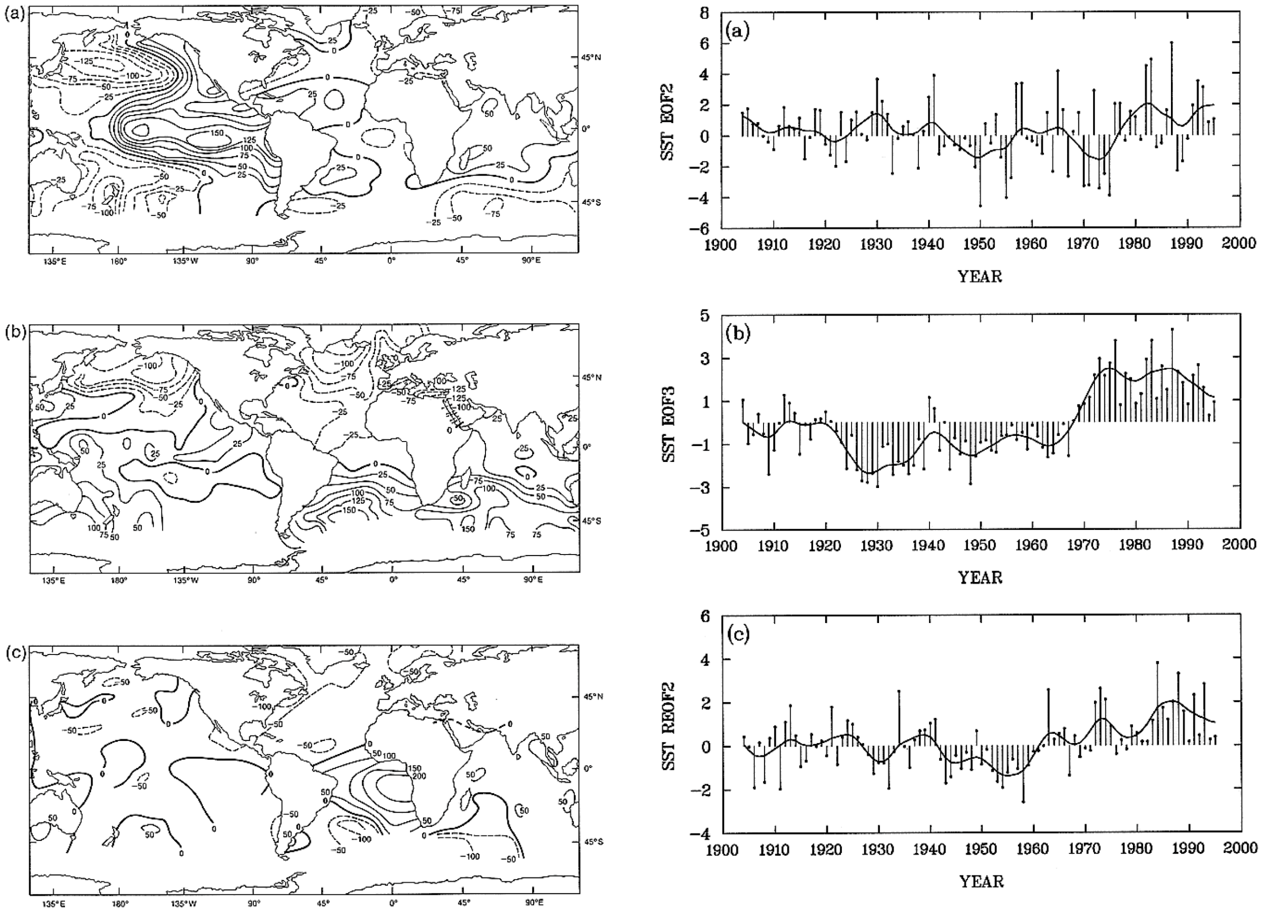


Fig 6: Leading components of sea-surface temperature (SST) that relate to West African July-September rainfall. Patterns are from a Principal Component (PC) analysis of global SST, 1901-80. (a) PC2, representing ENSO, (b) PC3, representing interhemispheric contrast of SST anomalies, (c) lower order rotated PC, representing Equatorial / tropical South Atlantic warming/cooling events, and aspects of tropical Atlantic SST meridional gradient changes. From Folland et al., 1991.

The results in Fig. 5a reflect strongly the Sahel wet MINUS Sahel Dry SST composite of Lamb (1978a,b) and Folland et al. (1986). Thus, a warmer North Atlantic, Mediterranean Sea and North Pacific, and a cooler South Atlantic, Indian Ocean and (in some parts) tropical Pacific accompanied the wetter epoch in the Sahel in the 1950s and 60s, while the opposite SST arrangement accompanied the drier epoch of the 1970s and 80s (many features, especially the Indian Ocean correlations, were also emphasized by Shinoda and Kawamura, 1994).

GCM experiments forced with components of this SST arrangement have responded over West Africa in a way that is consistent with a causal relation between this SST distribution and decadal Sahel rainfall variations (Palmer 1986, Folland et al. 1991, Rowell et al. 1995, Trzaska et al. 1996, Rowell 1996, Bader and Latif 2003, Giannini et al. 2003, see Fig. 7). There is evidence for a reinforcing role for land surface – atmosphere interaction (e.g. Zeng et al. 1999). The extent to which this reinforces the SST pattern and therefore plays an even more central role in the multidecadal variability in the climate system as a whole, is presently unclear and forms an intriguing question for future research.

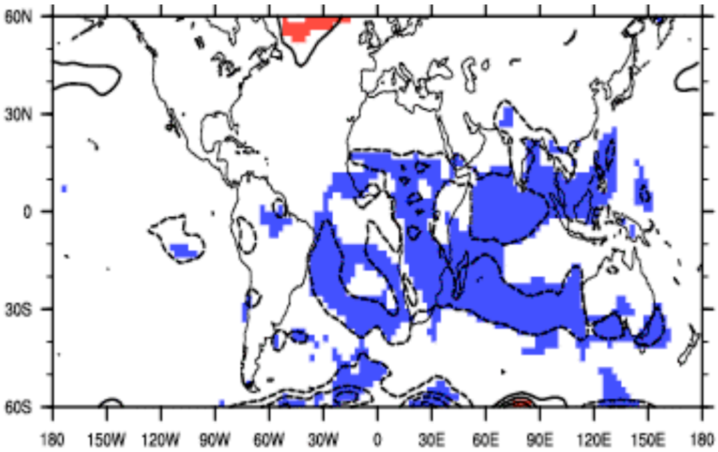


Fig 7 : Association of low frequency Sahel rainfall with low frequency surface temperatures, as simulated in NSIPP1 GCM driven with observed SST 1930-2000. From Giannini et al. 2003.

Many of the above SST aspects emerged in a single principal component mode of global SST (Fig. 6b), emphasizing the contrast between the Northern Hemisphere and Southern Hemisphere (a similar pattern is also discussed by Janicot et al. 1996). The decadal relationship of this pattern with Sahel rainfall is also repeated in the first half of the century as well (Ward 1998), with, for example, a warmer Southern Hemisphere and cooler Northern Hemisphere during the relatively dry epoch of the 1910s. Changes in the thermohaline overturning of the global ocean have been proposed as a mechanism to generate the SST anomalies (e.g. Gray et al. 1997), but the process is still under investigation, including whether the interhemispheric gradient changes in SST documented in the historical record could have been created by a number of unrelated climate processes. There is some evidence that the relatively wetter 1990s (compared to the 1980s) in the Sahel was accompanied by a more favourable interhemispheric SST gradient during boreal summer, but the evolving decadal signals require continued analysis and monitoring to confirm any substantial change in the decadal state.

In addition, changes in the meridional SST gradient throughout the tropical Atlantic have also been proposed as a key component of decadal-scale climate variation (e.g. see discussion in Servain et al. 1999), which can particularly impact the near-equatorial interhemispheric SST gradient in the tropical Atlantic. This may have also contributed to the decadal scale West African atmospheric variability.

Finally, recent work by Giannini et al (2003) and Bader and Latif (2003) has highlighted the connection between a warming trend in the Indian Ocean and the persistence of drought in the Sahel. Bader and Latif (2003) tested the sensitivity of ECHAM4.5's atmospheric circulation to the wet-minus-dry pattern of global and regional SSTs. The pattern they used is characterized by basin-wide cooling in the tropical Pacific, Indian and South Atlantic Oceans (see their Fig.2a). They found that the global pattern of wet-minus-dry SSTs induced above-average rainfall in the Western Sahel. An Indian Ocean only pattern also induced change in Western Sahelian rainfall, even more so if the cooling of the Indian Ocean is exaggerated by 1^{o}C.

It is possible that the warming of the Indian Ocean may have been amplified by the change in tropical Pacific climate around 1976 (Trenberth and Hurrell 1994, Graham 1994). The mechanisms linking Indian Ocean variability to the West African monsoon (also considered in Rowell 2001) will need to be investigated in greater detail in order to advance our understanding of variability and predictability of the West African monsoon.

Hastenrath (1990) documented the ocean-atmosphere changes in the tropical Atlantic that accompanied the decadal fluctuations in Sahel rainfall. The results showed a southward displacement of tropical Atlantic circulation features, especially the intertropical convergence zone (Fig. 4b) during the extended drought period. The sea-level pressure (SLP) results for the tropical North Atlantic (Fig. 4a) are consistent with the correlation pattern between decadal SLP and decadal Sahel rainfall (Ward 1998) which shows, for the wetter Sahel period, enhanced cross-equatorial pressure gradient from the southwestern tropical Atlantic to the tropical North Atlantic. However, the rainfall changes over West Africa suggest that there is more than a simple southward shift of the climate zones, since there is no significant increase in rainfall south of the Sahel during July-September.

Other aspects of the low frequency SLP anomalies associated with Sahel rainfall fluctuations in Ward (1998) are consistent with other decadal teleconnections proposed elsewhere in the literature. These include, for wetter Sahel epochs, increased hurricane frequency (Landsea and Gray 1992, Gray et al. 1997, Goldenberg et al. 2001) and associated large-scale atmospheric variations (Chelliah and Bell, 2004) and some increase in Indian monsoon rainfall (Kraus 1958).

Interannual Teleconnections with the Tropical Atlantic

On the interannual (sub-decadal) timescale, there is now good evidence for a coupled ocean-atmosphere Equatorial Atlantic mode (sometimes referred to as the Atlantic El Niño) (Zebiak 1993, Huang et al. 1995, Servain et al. 1999). It results in relatively short term (season to a few seasons) warming and cooling events in the Equatorial Atlantic. The SST in this Atlantic region correlates positively with West African July-September rainfall south of about 10ºN, and negatively with rainfall north of about 12ºN. These relationships show up well with the correlation maps of sub-decadal rainfall in the Sahel and Guinea Coast. This coupled teleconnection mode accounts for at least some of the out-of-phase tendency between the Sahel and Guinea Coast July-September rainfall totals, often referred to as a “dipole” in rainfall anomalies (Nicholson 1980, Janowiak 1988). When the Gulf of Guinea is anomalously warm in spring and summer, one line of argument would suggest that the West African monsoon should be weakened since the surface temperature contrast between the land and sea is reduced (Eltahir and Gong, 1996). However, Vizy and Cook’s (2001) analysis of GCM simulations and the NCEP/NCAR reanalysis showed that another mechanism dominates. When the Gulf of Guinea is warm, evaporation is enhanced and the southerly flow across the Guinean coast that, in part, feeds moisture into the West African monsoon system carries more moisture, consistent with the results of Lamb (1983). This leads to increases in precipitation south from the usual maximum of precipitation. GCMs have found it more difficult to represent the concomitant drying over the Sahel. However, Vizy and Cook (2002) were able to clearly simulate and analyze the Sahel part of the dipole anomaly using a regional climate model (a modification of MM5) with only slightly finer horizontal resolution (120 km) than is typical in GCMs. Thus it remains to be proven whether GCMs have difficulty due to resolution, or whether particular formulations and parametrizations are needed to represent the dipole.

In addition to the near-equatorial “Atlantic El Niño”, other interannual variability in the tropical Atlantic is also found. For example, some independent variability was found connecting enhanced western Sahel rainfall (but not eastern Sahel) with warming in the tropical North Atlantic (Ward 1998), which would be consistent with the original findings of Lamb (1978a,b). The finding was also demonstrated for the westernmost part of the Sahel by Ndiaye et al (1999) using indices of rainfall for Senegal. However, as noted in the next section, the sub-decadal timescale statistical association over all years of the tropical North Atlantic to West Africa may be influenced by other co-varying forcing factors.

Interannual Teleconnections with ENSO

The El Niño / Southern Oscillation (ENSO) has now been identified with rainfall fluctuations in West Africa (e.g. Semazzi et al. 1988, Folland et al. 1991, Rowell et al. 1995, Janicot et al. 1996, Nicholson and Kim 1997, Barnston et al. 1998, Ward 1998): warm events (El Niño) are associated with reduced rainfall north of about 10ºN, while cold events (La Niña) are associated with enhanced rainfall north of about 10ºN. The negative correlations in the central and eastern tropical Pacific with Sahel rainfall in Fig. 5b describe the teleconnection.

The ENSO teleconnection with Sahel rainfall in boreal summer is associated with a large-scale change in the global tropical circulation including, for a wetter Sahel, increased Atlantic hurricane frequencies, modified western Pacific and Indian Ocean circulation patterns, and enhanced near-surface cross equatorial flow in the tropical Atlantic associated with enhanced pressure gradient from the southwestern tropical Atlantic to the tropical North Atlantic (e.g. Goldenberg and Shapiro 1996, Camberlin 1995, Ward 1998). The circulation features have some similarities with those associated with the multi-decadal fluctuations of Sahel rainfall. Thus, it is possible that both ENSO and the decadal interhemispheric contrast in SST can excite similar fluctuations in the West African monsoon and other regional circulation features. In contrast, the Atlantic Equatorial mode discussed above seems to excite a smaller-scale regional circulation anomaly from the Equatorial Atlantic into West Africa, leading to (for warm Equatorial Atlantic SST) more rain south of about 10ºN in West Africa and less rain in the Sahel. Note that for the ENSO mode and the decadal rainfall fluctuation in the Sahel, rainfall anomalies south of about 10ºN in West Africa are on average relatively small during July-September – that is, these modes do not have a strong expression during July-September in Guinea Coast rainfall anomalies.

Two teleconnection features found with Sahel rainfall at interannual and decadal timescales but which have not yet been fully studied are: (i) the connection between Sahel rainfall anomalies and European summers, with wetter Sahel years associated with anomalous cyclonic circulation Northern Europe (Folland et al 1988), and (ii) the connection between Sahel rainfall and Eastern Mediterranean circulation and SST, with higher SST and lower SLP in wetter Sahel years (e.g Raicich et al., 2003).

Stability of the Interannual Teleconnections and Relative Roles for Tropical Atlantic and Tropical Pacific SST

When studying teleconnections in the climate system, an important question concerns the temporal stability of the relationships – that is, do the teleconnection relationships go through periods of being strong, and then periods of being weak, or even reverse sign? A regression model between a Sahel rainfall index and two key SST indices for sub-decadal timescale (one index for ENSO and another for the tropical Atlantic) showed similar SST-Sahel relationships in the periods 1904-48 and 1949-90 (Ward 1998), which is an encouraging result and gives confidence that the ENSO and tropical Atlantic influences are repeating features of the climate system. The relative strengths of the Sahelian variance explained by the two predictors was very similar, suggesting that on the interannual timescale, in a linear statistical sense, ENSO and the tropical Atlantic are explaining similar fractions of Sahel rainfall variance. However, Janicot et al (1996) noticed that the connection between Sahel rainfall and ENSO has been particularly strong since the early/mid 1970s (i.e. during the dry epoch), and was much weaker in the 1950s and 1960s (i.e. during the wet epoch). At the same time, the influence of the tropical Atlantic appears to have been stronger in the 1950s and 60s, and weaker after 1970 (Fig. 8). Therefore, one of the current key questions is to assess reasons for the teleconnection fluctuations. It is important to recognize that the statistical strength of a relationship will vary over time simply due to sampling. Thus, it is valuable if time-variation of relationships can be simulated in models with a physical basis for the variations. One hypothesis suggests that the interhemispheric SST anomaly gradient might modify the impact of ENSO forcing on West Africa (Janicot et al. 1996, Trzaska et al. 1996), with the state of the Indian Ocean proposed as a particularly significant factor. A further consideration is that ENSO may have been more active in the in the more recent drought epoch.

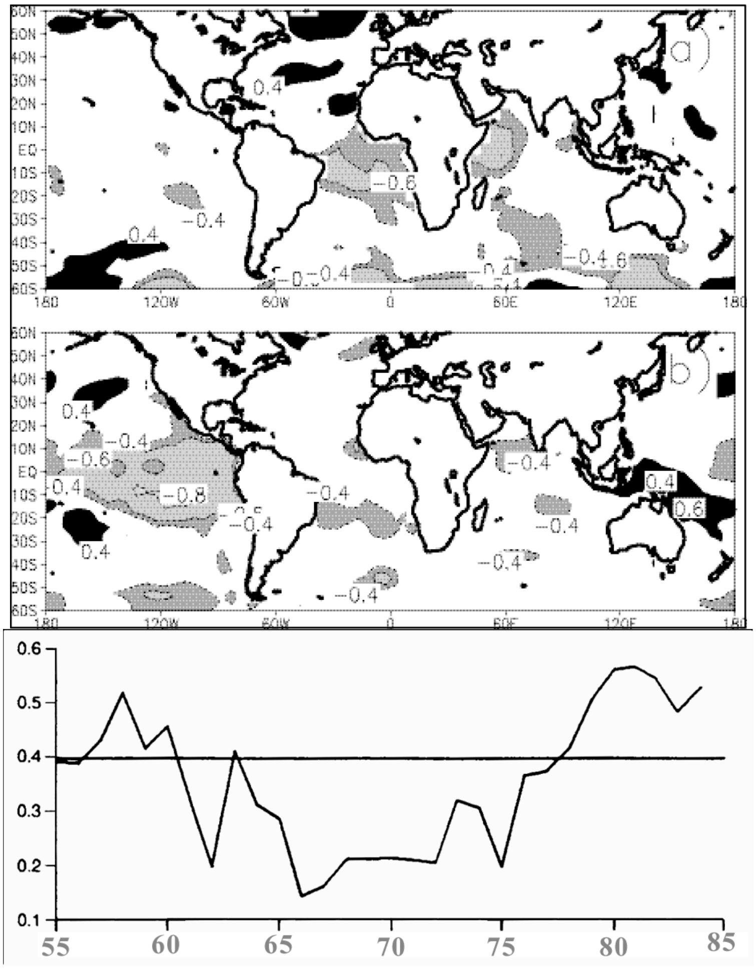


Fig 8 : On the temporal variation of the relationship between Sahel rainfall and SST. (a) Correlation 1950-69, (b) Correlation 1970-90, (c) 20-year running window correlation with SOI. From Janicot et al., 1996, 2001.

Summary of Atmospheric General Circulation Model Simulation Skill for Boreal Summer over West Africa

While GCM evidence has been important in arriving at the above understanding, it is also important to reflect that many GCMs continue to have difficulty with representing variability of the West African monsoon when given observed SST patterns. This was pointed out by Sud and Lau (1996) based on AMIP simulations, and is evident from verifying the performance of many of the current state-of-the-science GCMs (e.g. http://iri.columbia.edu/forecast/climate/skill/SkillMap.html). These skill maps, generated at IRI, show that most GCMs have good skill in simulating the variability of the Guinea Coast July-September rainfall anomalies associated with Equatorial and tropical S. Atlantic SSTAs, but skill for West African July-September rainfall north of about 10N is often near zero. Nonetheless, there also continue to be examples of models that represent well the variability of Sahel rainfall, such as the NSIPP1 model (Fig. 9a) reported in Giannini et al (2003).

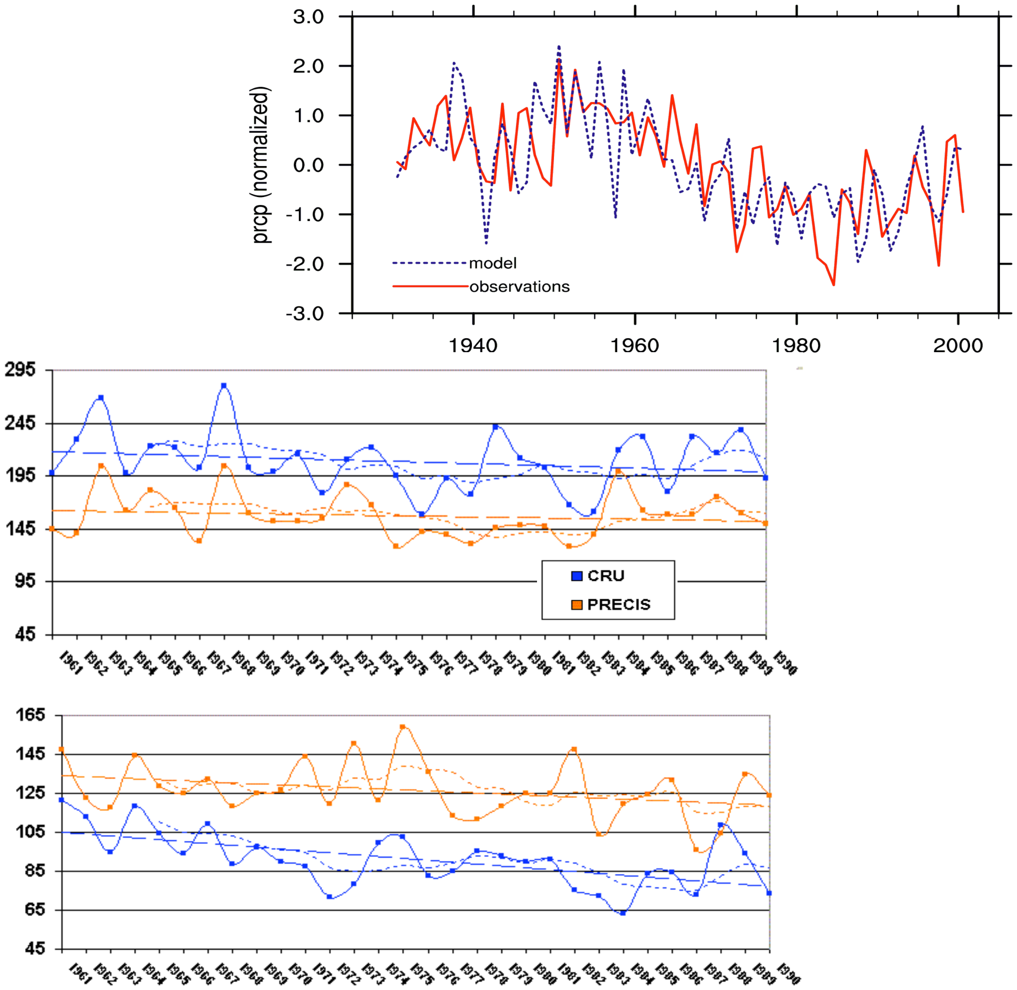
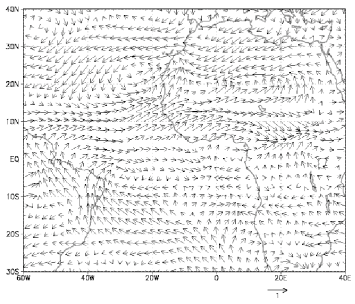
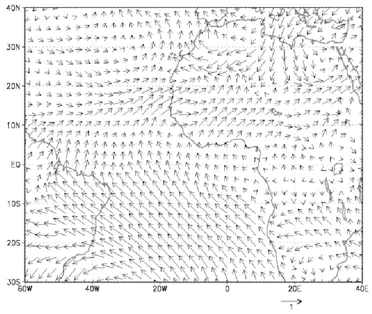


Fig 9 : Examples of models simulating West African rainfall when forced with observed SST. (a) Sahel rainfall in NSIPP1 model 1930-2000 (r=0.60). From Giannini et al., 2003. (b) Sahel rainfall in a high resolution regional model (HADRM3) driven with output from global atmospheric model HADAM3H, 1961-90 (unfiltered, r=0.27, interannual poorly captured, but low frequency component is partly captured), (c) Same as (b) but for Guinea Coast rainfall (r-0.66). Runs for (b) and (c) are preliminary estimates based on one ensemble run. From Kamga and Buscarlet, 2004.

The reasons why some models succeed and some models fail requires further investigation. Recent work by Kamga and Buscarlet (2004) reinforces the suggestion made in Section 4 that increasing resolution need not necessarily lead to better representation of the tropical Atlantic forcing of the Sahel-Guinea Coast dipole. The high resolution regional model represents very well the interannual variability of Guinea Coast rainfall (Fig. 9c), but is only able to capture some of the multi-decadal component of the Sahel rainfall (Fig. 9b).





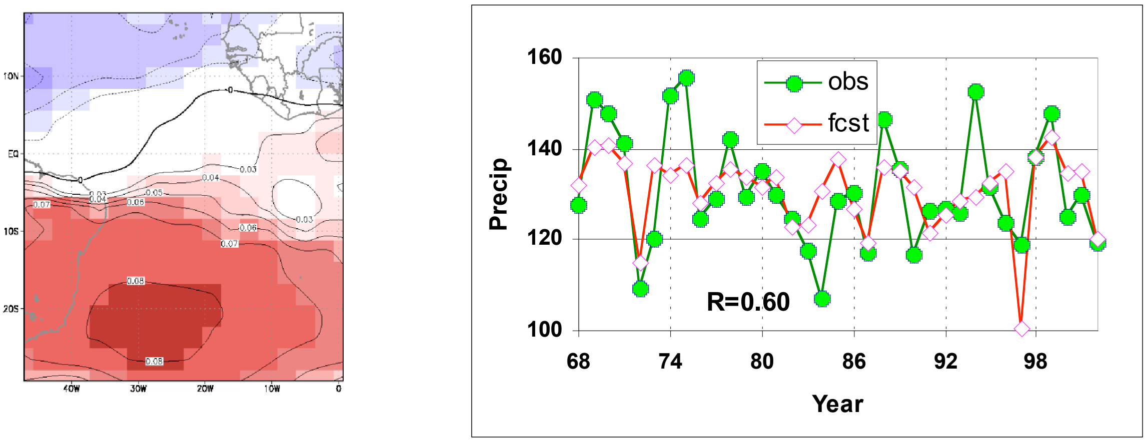


Fig 10 : Using atmospheric circulation over the tropical Atlantic to specify Sahel rainfall anomalies. (a) Correlation (1968-2002) between observed July-September Sahel rainfall anomalies and July-September 925mb wind in NCEP/NCAR reanalysis. Vectors are formed from the correlation with the u and v wind separately, so the vectors plotted can be viewed as a standardized composite wind field associated with a one standard deviation positive rainfall anomaly in the Sahel rainfall index. (b) Same as (a) but for the wind field predicted by the ECHAM4 GCM forced with observed SST, 1968-2002. (c) First principle component pattern of GCM 925mb wind field 1968-2002. (d) Using time coefficients of the PC1 in (c) to predict observed Sahel rainfall (result is created using simple univariate regression tested in cross-validation mode). From Ndiaye et al, in preparation.

It is possible that models will capture aspects of the West African monsoon and associated circulation over the tropical Atlantic, but fail to transform that into good simulations of West African rainfall. For example, Figs. 10a,b shows the correlation between an observed Sahelian rainfall index and the near-surface circulation in the NCEP/NCAR reanalysis and for a simulation by the ECHAM4 GCM driven with observed SST (Ndiaye et al., in preparation). The model quite accurately simulates the regional circulation teleconnection pattern extending across the tropical Atlantic, reflecting an ability to capture the variability in regional circulation associated with Sahel wet and dry years. Use of the first principal component of predicted zonal 925mb wind over the tropical Atlantic (Fig. 10c) permits a good specification of the Sahelian rainfall index using a simple linear regression between the Sahel index and the first PC of the GCM's zonal wind (Fig. 10d). This model output statistics (MOS) approach can be valuable for diagnostic understanding of the behavior of the model, as well as in a practical prediction setting. The result in Fig. 10 illustrates the need to improve the simulation of the West African monsoon's SST-forced variability in GCMs, as a basis for studies that will lead to better understanding of the range of factors controlling its dynamics and associated rainfall over Wet Africa.

Transition Seasons and West/Central Africa Rainfall

The above teleconnection results all referred to July-September rainfall totals, which for the Sahel, accounts for about 80% of the annual total. Teleconnections with June and October West African rainfall are different, compared to July-September. In June and October, Guinea Coast rainfall appears to have little association with Equatorial Atlantic SST, nor is there a tendency for a negative correlation between Sahel and Guinea Coast rainfall. Furthermore, for the Sahel, the early season rains have a positive correlation with ENSO warm events (i.e. June rainfall tends to be above normal in El Niño years) (Nicholson and Kim 1997, Ward 1998). This latter relationship is also true of late season October rainfall in the Sahel. While there is potential for more detailed analyses focusing on extreme years, these early results suggest that over all years, variance explained is small, indicating predictability of the early and late season rainfall in the Sahel appears to be low. More work is needed to establish the evolution of the teleconnections during the early and late season rains for sub-regions of West Africa and to establish the physical basis for why the teleconnections transform. The transformation is likely related to the background annual cycle evolution around the tropics.

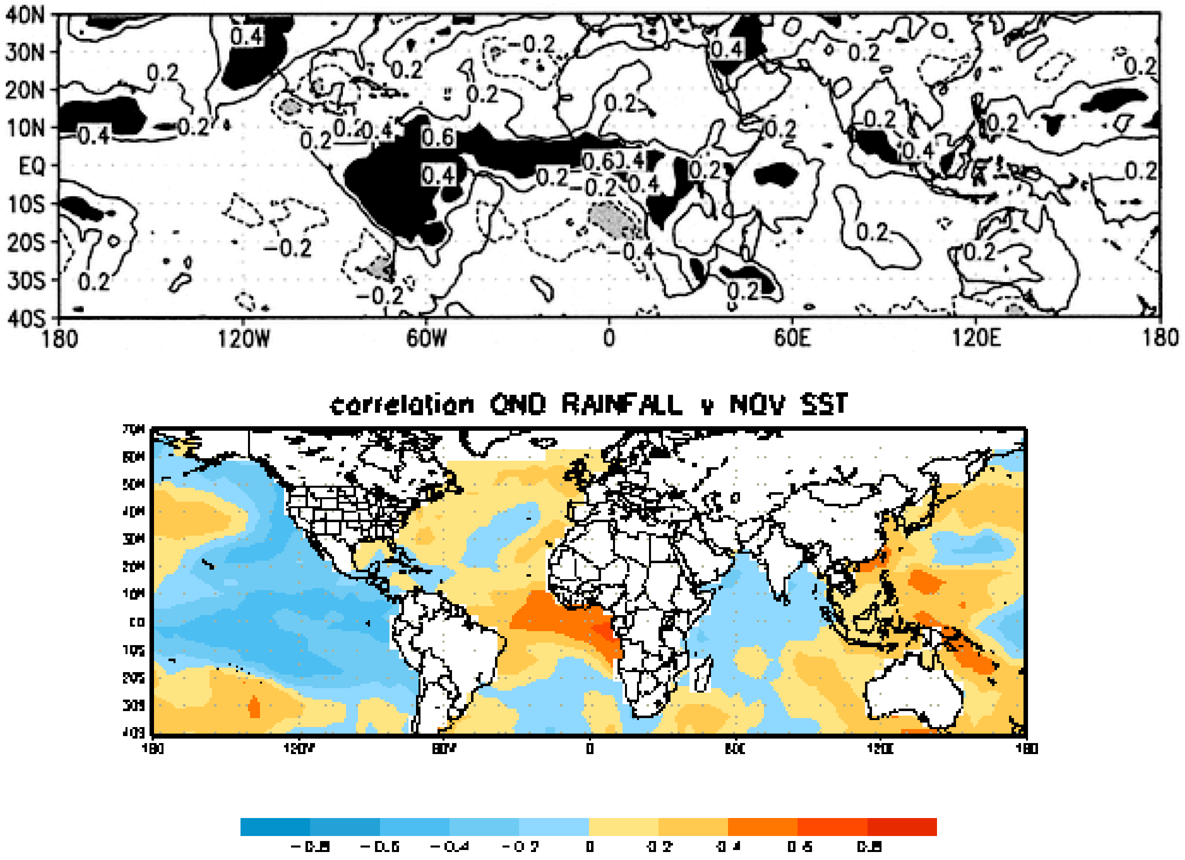
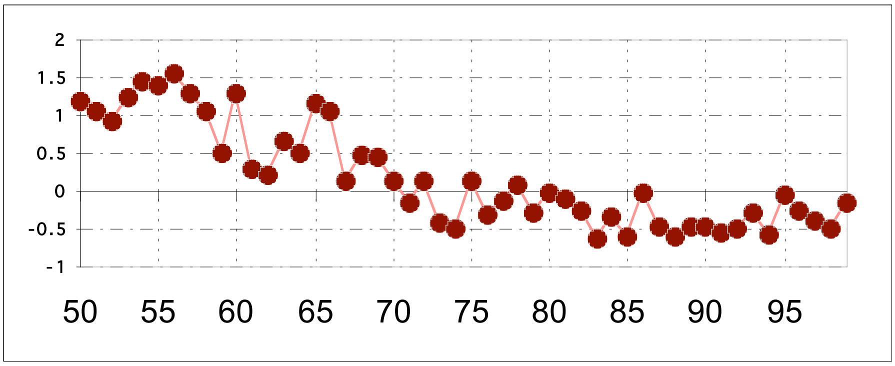


Fig 11: (a) Correlation between September values of SST REOF2 (Fig. 6c) and Oct-Dec outgoing long-wave radiation. This result suggests a degree of predictability in Oct-Dec season through Central Africa from tropical Atlantic SST. (Mutai and Ward, 2000). (b) Correlation of Oct-Dec rainfall index for southwestern Congo with Nov SST. (Alphonse Kanga, Direction de la Météorologie, Congo, personal communication).

For Central Africa in October-December, work has identified a role for Equatorial/South tropical Atlantic SST (Alphonse Kanga, PRESAC, personal communication, and Fig. 11). For example, Fig. 11a shows that September values of the tropical Atlantic EOF in Fig. 6c correlate strongly with outgoing long-wave radiation through the Equatorial Atlantic and extending into Central Africa, suggesting warm phase of the SST mode is associated with enhanced rainfall in these regions. This is supported by detailed analysis with rainfall indices for the region, such as in Fig. 11b. For March-May, linear relationships have proved weaker, thus potential predictability appears to be higher for the October-December season in the region, although these transition seasons have been less studied than the JAS season, and further analysis may yield evidence of a stronger coupling with the ocean than previously found. Indeed, new suites of forecast experiments such as DEMETER are becoming available to analyse for predictability and the MOS approach may provide further useful information.



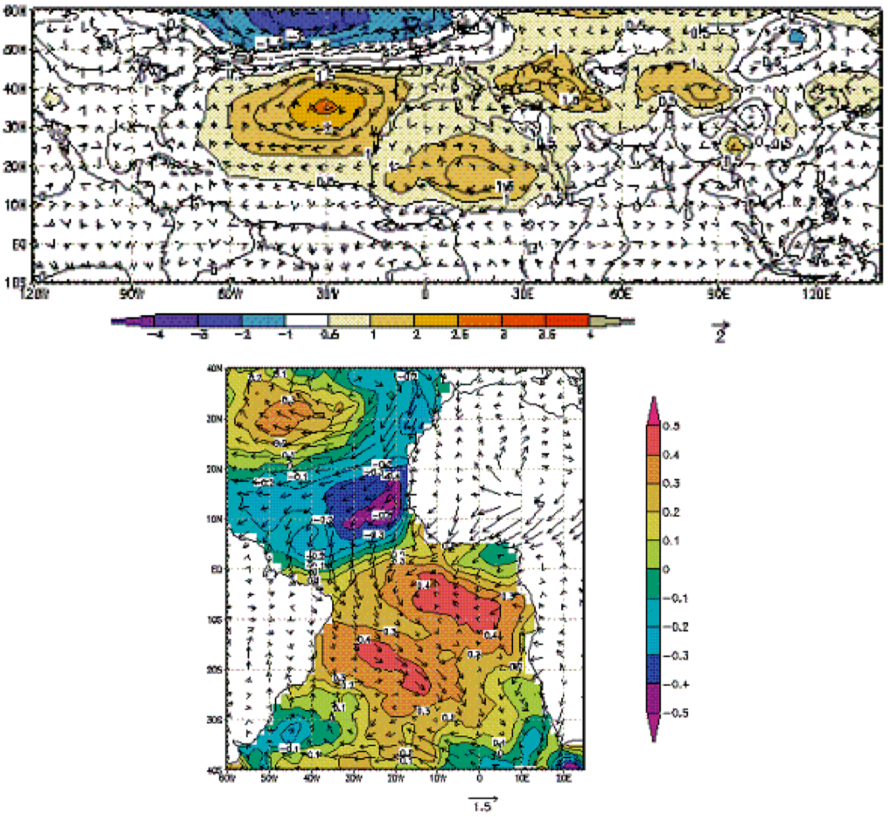
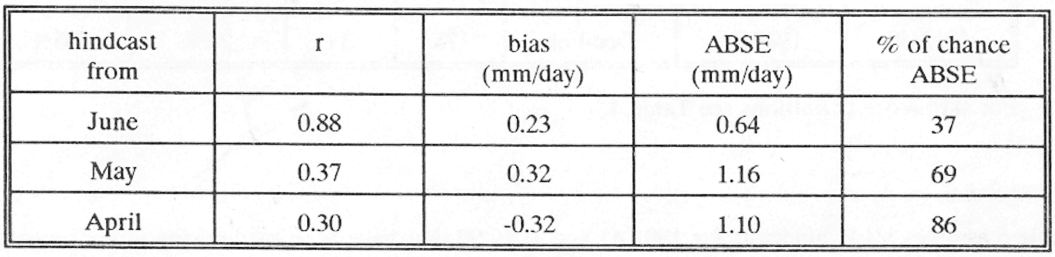


Fig 12 : Large-scale climate teleconnections associated with variations in Jan-Mar dustiness in the Sahel zone of Niger. (a) Normalized index of Jan-Mar visibility, used as a proxy for atmospheric dust. (b) Jan-Mar sea-level pressure and 850mb wind anomalies (from NCEP/NCAR reanalysis) in the six dustiest years. (c) Jan-Mar sea-surface temperature and 850mb wind anomalies in the six dustiest years. Ben Mohamed et al., in preparation.

Sahel Dry Season

There is growing interest in the climate variability associated with the Sahel dry season. There is strong variability in atmospheric dust that can have implications both climatic and societal (Prospero, 1999). An index of January-March visibility for Niger (Fig. 12a) can be used as a proxy for dustiness, and is found to display strong variations.

The seasonal climate characteristics associated with the dustiest years (Fig. 12b,c) show large-scale teleconnection structures (Ben Mohamed, et al. in preparation), including to tropical SST patterns, suggesting potential predictability, and some to extratropical atmospheric variability, which while of climatic interest, will not provide a contribution to predictability until phenomena like the North Atlantic Oscillation are able to reliably forecast. The factors giving rise to variability of the dust index require careful consideration. Trans-Atlantic dust transport in summer is strongly related to Sahelian rainfall of the previous year (Propero and Lamb, 2003). Thus, memory of the land surface could play a role. However, the results in Fig. 12b,c suggest that at least to some extent, the dust variations in the Sahel dry season are attributable to simultaneous wind circulation anomalies, which may in part be driven by large scale tropical SST anomalies. A further dimension to consider is whether the atmospheric and dust anomalies over West Africa are extending across the tropical Atlantic to influence ocean conditions.



hindcast from	r	bias (mm/day)	ABSE (mm/day)	% of chance ABSE
June	0.88	0.23	0.64	37
May	0.37	0.32	1.16	69
April	0.30	-0.32	1.10	86

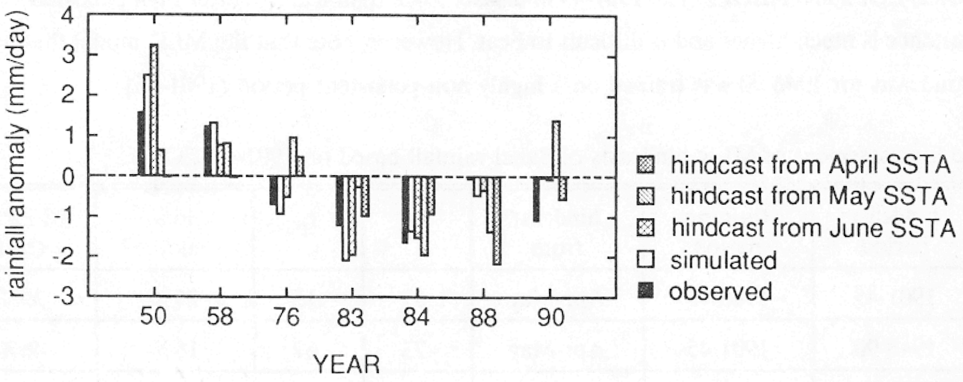
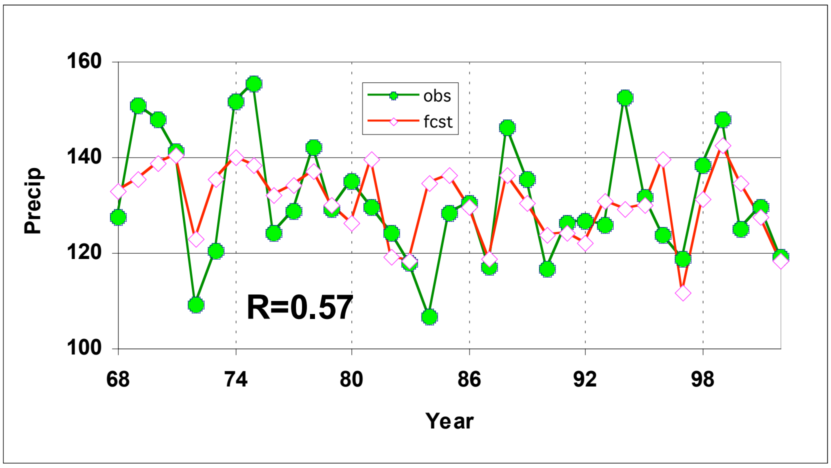


Fig 13: Early results using a 2-tier approach to evaluate predictability of Sahel rainfall using an atmospheric GCM (UKMO). Comparison of model skill when using persisted sea-surface temperature anomalies to drive the model and make predictions for the July-September Sahel rainfall anomaly in selected case study years. The table shows summary statistics for the model's predicted rainfall. From Ward et al., 1993.

Seasonal Prediction

The early work on Atlantic and global SST relationships with West African July-September rainfall was translated into experimental seasonal forecast methods using both statistical and dynamical methods (Folland et al., 1991). Early work with a UKMO GCM suggested substantial sensitivity to persisting SSTs even a couple of months ahead (Fig. 13). This sensitivity is reproduced when the MOS results from Fig. 10 are repeated with ECHAM4 experiments with persisted SSTs (Fig. 14., Ndiaye et al, in preparation). Linear statistical methods with observed SST predictors are less sensitive to SST changes, and provide moderate skill from April and May SSTs (Folland et al 1991).



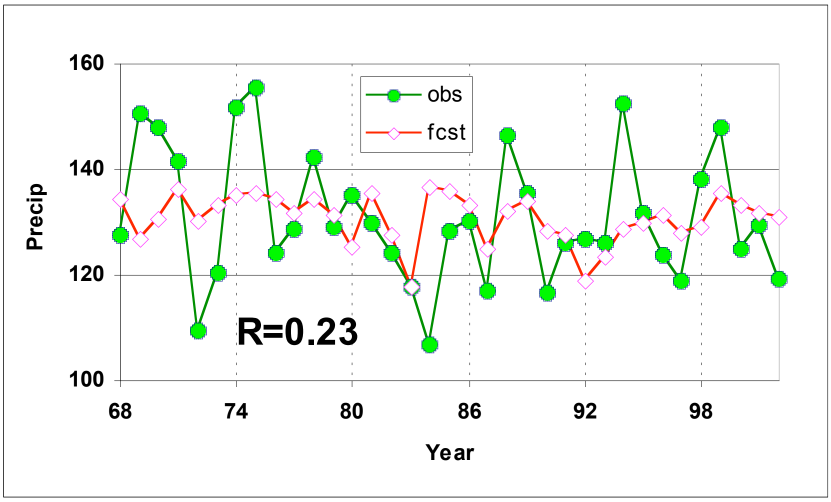


Fig. 14 : Same as Fig 10d, but using GCM forecast experiments with (a) persisted Jun sea-surface temperature anomalies used to forecast July-September, (b) persisted May sea-surface temperature anomalies. The suggestion is that the evolution of SST from May to June is critical for accurate prediction of the tropical Atlantic wind pattern that is associated with Sahel rainfall. (Ndiaye et al., in preparation).

National Meteorological and Hydrological Services (NMHSs) have been using such statistical models, including as part of the West Africa Climate Outlook Forum, PRESAO (examples of results for the NMHS models are in WMO (1998)). These models typically use up to four predictors: three regional SST indices and the SST EOF coefficient in Fig. 6b representing the multi-decadal North-South SST contrast. The other three SST indices cover ENSO, Equatorial / tropical South Atlantic SST and tropical/subtropical northwestern Atlantic SST. An addition that requires consideration is stimulated by the proposed importance of meridional moist static energy gradients for the West African monsoon (e.g. Eltahir and Gong 1996; Cook 1999). In addition to SST, this gradient is modified by land surface conditions in West Africa. The potential of initial land surface conditions to add to predictability is reviewed in Section 11 and evidence for a possible enhancement of predictability (e.g. Fontaine et al. 1999) is likely to be clearer through the enhanced observations planned for the African Monsoon Multidisciplinary Analysis (AMMA) experiment 2005-2007 and associated process and modeling research.

Particularly for the two Atlantic and one Pacific SST indices that are used, the regression models are most skilful when using the observed July-September values of the predictor indices. For some models, attempts are made to use available forecast evidence and current SSTA tendencies to estimate the expected JAS values of the SST indices, based on available information at the time of PRESAO in May/June. Thus, predictability of the tropical Atlantic SST is a key issue for the statistical models as well as numerical approaches to prediction. For the SST EOF (Fig. 6b), implicitly this is representing an estimate of the multi-decadal climate state and its role in the rainfall to expect in the upcoming season. Implications beyond a single season have not been widely discussed, but clearly there is potential for multi-decadal nowcasting from the multi-decadal mode (e.g. Fig. 6b), in addition to the information about the upcoming season. Since 1998, The West Africa Climate Outlook Forum (PRESAO) has convened around May-June each year to combine results from these models with other sources of prediction information, including GCMs, to create a consensus outlook for July-September in West Africa (e.g. Fig. 15). Additional factors considered are current state of the global climate and other issues such as awareness of the potentially transient nature of the teleconnection relationships. An important current question is to evaluate whether the current state-of-the-science coupled ocean-atmosphere models have the same sensitivity to initialization time ahead of the rainy season, or if the current generation provide an advance in skill and lead-time ahead of the West Africa monsoon (the DEMETER results represent an opportunity to explore this question, (http://www.ecmwf.int/research/demeter/d/charts/verification).

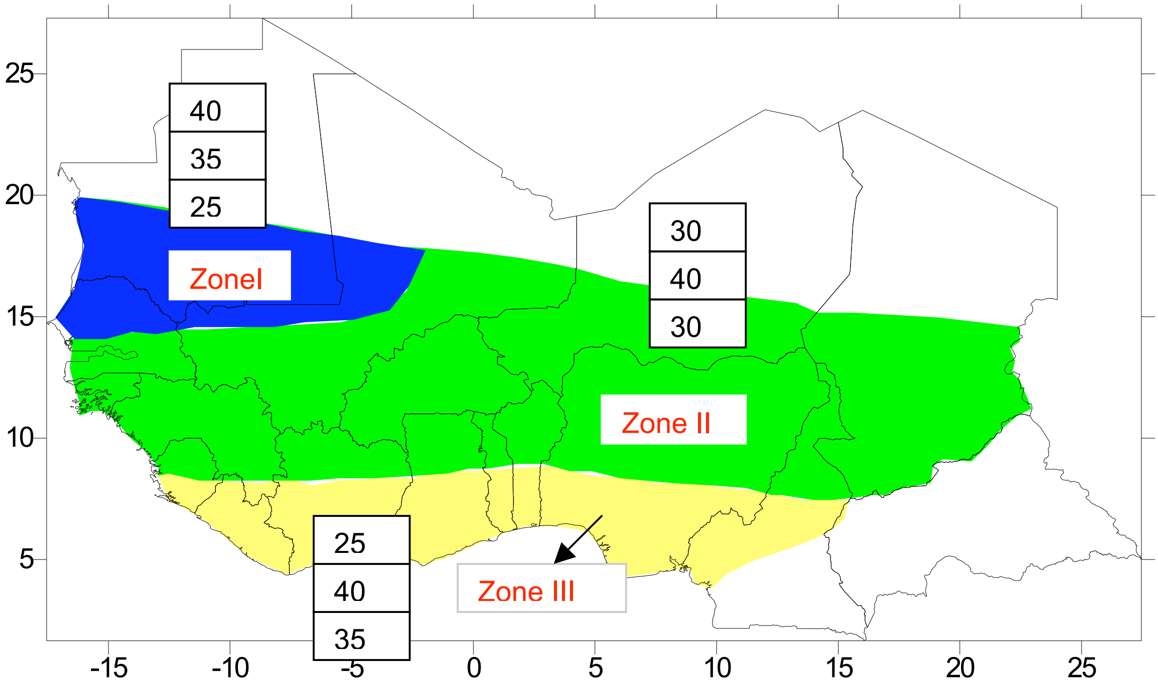


Fig 15 : Consensus seasonal precipitation forecast over West Africa made in late May 2004 and valid for July-August-September 2004. The consensus product is a combination of available dynamical and statistical model outputs. For each of the three zones, the boxes shown indicate the estimated likelihood of 2004 rainfall totals being in the above normal tercile, the near-normal tercile and the below normal tercile. For example, the above normal tercile is estimated to have a 40% likelihood of occurrence in zone I, a 30% likelihood in Zone II and a 25% likelihood in Zone III. Outlooks in the same format have been produced as part of the PRESAO process through a consortium of partners since 1998. (based on material provided by ACMAD).

Since 2002, a similar approach to PRESAO has been initiated to anticipate the Oct-Dec rainfall for the Guinea Coast region and Central Africa (PRESAC), using SST indices in the tropical Atlantic and other ocean basins. As noted in section 8, there are opportunities to explore predictability in these seasons using suites of model experiments, that may reveal a stronger coupling with ocean and potential predictability than previously apparent from statistical analysis alone.

Conclusions and Future Directions

The existing knowledge on ocean-atmosphere teleconnections with West African rainfall variability have been reviewed. At the sub-decadal timescale for the West African monsoon, two key rainfall controls are ENSO and the Equatorial Atlantic SST mode, supplemented with additional components of tropical Atlantic variation, including tropical North Atlantic. At zero lag, the ENSO and Equatorial Atlantic mode appear to have little linear correlation in boreal summer. However, one of the key areas for current research is to evaluate possible lead-lag teleconnections between ENSO and the tropical Atlantic (e.g. Delecluse et al. 1994). Also critical is how forcing from the tropical Pacific and tropical Atlantic interact over West Africa (e.g. Trzaska et al. 1996). At multi-decadal timescales, the paper has reviewed the teleconnections between Sahel drought epochs and anomalies in the interhemispheric SST gradient, both within the Atlantic, and more globally, especially involving the Indian Ocean. The atmospheric circulation anomalies are large scale, connecting the South Atlantic and West Africa with other regional circulation systems in the Indian and Pacific Oceans. Some of these large-scale decadal atmospheric features resemble those associated at the interannual timescale ENSO. In contrast, the circulation anomalies associated with the Equatorial Atlantic mode appear more local from the tropical Atlantic into West Africa.

A key area for future research is to understand and predict better the evolution of the coupled ocean-atmosphere system from early in the year into the July-September season, especially in the tropical Atlantic. Available evidence suggests the performance of GCMs forced with May SSTAs deteriorate quite dramatically from those driven with June SSTAs, suggesting there are key aspects of evolution around this period. Great improvements are needed in fully coupled ocean-atmosphere models for predictability and prediction in this region. Lebel et al. (2003) suggest that the average regime of the West African monsoon is in fact composed of two sub-regimes. One is an oceanic regime characterized as soon as April-May by a progressive increase of the moist air flow from the ocean into the continent, associated with the seasonal migration of the ITCZ from its southern position in the boreal winter to its northern position in the boreal summer. The second regime is a continental regime in which rain is mostly produced by large convective systems embedded in the easterly circulation. This continental regime sets in abruptly during the second half of June and 90% of the Sahelian rainfall is then produced by a small number (12 % of the total number) of large and organized Mesoscale Convective Systems (Mathon et al., 2002). Thus, understanding ocean-atmosphere coupling and land-atmosphere relationships as well as their comparative influence on the West African rainfall is important to improve prediction on the seasonal timescale.

In addition to the West Africa monsoon, work is now also emerging for the other seasons in West and Central Africa. Predictability already has been demonstrated and is being applied operationally for the October-December season in the Guinea Coast region and Central Africa. For the variability of dry season dustiness in West Africa, demonstrations have been made that it too is part of large-scale teleconnection modes reaching into tropical ocean-atmosphere variability as well as into mid-latitude variability related to the North Atlantic Oscillation. Deducing causality is complex, as research is led into the fully coupled nature of ocean-atmosphere-land system.

When evaluating the boreal summer West African teleconnections for the historical period, it is important to appreciate that the links with SST anomalies appear to account for up to about 50% of the total large-scale seasonal rainfall anomaly variance, and less than that once the decadal rainfall variance is removed. Thus, there is a large fraction of the rainfall variability that so far is unaccounted for by teleconnections with the ocean-atmosphere system. In addition, there is a need to assess teleconnections with finer spatial resolution in the rainfall fields and how the teleconnections are expressed in terms of changes in extreme weather events, rainfall disturbances and dry spells within the season. For this, better understanding of the interannual variability of synoptic disturbances in the region will be needed, building on such work as Burpee (1974), Thorncroft (1995), Lamb et al. (1998), Thorncroft and Hodges (2001), Diedhiou et al. (1999, 2001), Sultan et al. (2003), Mathews (2004), applying tools such as high resolution regional modeling (Jenkins 1997). The predictability of some features important to society, such as crop production and water resource availability, also will benefit from intensification of work on the relation of high resolution spatial variations and weather statistics to the now well-established large-scale predictability.

There are also a number of themes for ongoing research into land surface interaction (Nicholson 2000). For predictability, a key question concerns the extent to which initial land surface conditions have a role. Studies are hampered by uncertainties in long historical records of land surface properties. Interannual variations in pre-rainfall season land surface features is quite small in the Sahel, due to the severity and length of the dry season, but conditions to the south of the Sahel may conceivably have a role (Koster and Suarez 2003, Douville and Chauvin 2000, Philippon and Fontaine 2002, Gray and Landsea, 1992). For understanding decadal scale variability, the land surface has long been posed as a possible initiator of variability, as well as a possible contributor through feedback (e.g. Charney 1975, Charney et al 1977, Xue and Shukla 1993, Polcher 1995). Recent modeling studies have supported the role of the land surface as an amplifier of variability in the region (e.g. Zeng et al 1999, Wang and Eltahir 2000). The land-surface also can potentially play a role in amplifying the chaotic (unpredictable) component of seasonal variability. For example, if unusually wet conditions develop early in the season as a result of chaotic internal atmospheric variability, are there land-atmosphere feedback mechanisms to amplify this Sahel-wide? Strong evidence already has been presented that land-atmosphere feedbacks can act to amplify local rainfall anomalies through a season (Taylor et al, 1997, Taylor and Lebel 1998). Wherever the land surface is seen to have a role in contributing to the large-scale circulation variability, then that land surface influence can be expected to extend beyond the West African continent itself, and into the surrounding oceans. Such influence may be through the long-proposed land-atmosphere interaction mechanisms modifying circulation, or through the increasing awareness of the magnitude of dust that enters the Sahelian atmosphere and can influence atmospheric characteristics both over the continent and, through export of the dust, into the surrounding tropical Atlantic region and beyond. Many of the issues for further investigation mentioned in this section will benefit from the intensification of observations and research expected through the African Monsoon Multidisciplinary Analysis (AMMA). The intensification of observations of the land-ocean-atmosphere system and associated research can also be expected to provide opportunity to better understand the reasons for the inability of many GCMs to capture the variability of the West African monsoon, and to advance prediction efforts on the seasonal to decadal timescales. These insights, combined with the application of high resolution GCMs and/or regional climate models, offer the prospect for some enhancement of skill levels and lead-time for seasonal predictions in the region. While the scientific basis for the enhancements will be rooted in the physical process, empirical diagnostic and modeling studies, advances may well be incorporated in statistical forecast methods as well, so that the resulting forecast systems continue to be a mix of numerical models and statistical methods rooted in the understanding of the climate system.

Acknowledgments.

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Seasonal to decadal predictability and prediction of southern African climate

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Introduction

Southern Africa, broadly defined here as Africa south of the equator, is a region prone to pronounced flood and drought events and significant climate variability on a range of time scales. Some of this variability is thought to be forced remotely via ENSO (e.g., Nicholson and Entekhabi, 1986; Lindesay *et al.*, 1988; Mason and Jury, 1997; Nicholson and Kim, 1997; Reason *et al.,* 2000; Allan *et al.*, 2003) while some is related to variability in the neighbouring Indian and Atlantic Oceans (e.g., Hirst and Hasternrath, 1983; Lough, 1986; Ogallo *et al.*, 1988; Walker, 1990; Mason, 1995; Reason and Mulenga, 1999; Reason, 1999; Behera and Yamagata, 2001; Rouault *et al.*, 2003) or to local land surface processes (Zheng and Eltahir, 1998; Douville *et al.*, 2001). It should be stated at the outset that climate variability over southern Africa is complex with a multitude of forcing factors that interact with each other and wax and wane in their importance through the record. Landman and Mason (1997), Richard *et al.* (2000), Allan *et al.* (1996, 2003) amongst others all provide evidence of how the ENSO influence on southern Africa has varied while Mulenga *et al.* (2003) show that some dry seasons over northern South Africa may be directly related to ENSO whereas others show an influence from the subtropical and midlatitude Atlantic. In this paper, the focus is on possible relationships between the Atlantic Ocean and southern African climate and we begin by considering the annual cycle of SST, winds and moisture fluxes over this region.

Annual cycle

The potential influence of the Atlantic on southern African climate is mainly related to the variability in the Inter-tropical Convergence Zone (ITCZ) over the region, the South Atlantic anticyclone and, to lesser extent, the midlatitude westerlies. Compared to the eastern side of Africa and the neighbouring Indian Ocean, the annual cycle in ITCZ location over the Atlantic and neighbouring western Africa is far less pronounced. Throughout the year, the coherent structure of the Atlantic ITCZ migrates north and south, staying largely parallel to the equator across the basin with a slight inclination to the north in the eastern part of the basin (larger in some months than others). In austral autumn (April-May), the Atlantic ITCZ attains its southernmost position with its core reaching 5°S in the west, over the northeast coast of Brazil, but staying slightly north of the equator in the Gulf of Guinea region in the east. In austral winter (July-August), the Atlantic ITCZ moves furthest away from the equator to 8-10°N. Over neighbouring southern Africa, the ITCZ reaches its southernmost position in February when it lies across Madagascar, central Mozambique, and southeastern Zambia in eastern Africa. Over the latter region, there is a confluence with the Congo Air Boundary that separates moist tropical air over Angola / Congo from drier air over Namibia and Botswana. To the north of this confluence, the ITCZ stretches meridionally through Zambia and Congo before exiting out over the equatorial eastern Atlantic. Between February and April, the ITCZ moves northward over southern Africa while slowly reaching its southernmost position over the Atlantic near 5^{o}S as SST there reaches its maximum. In austral winter, the ITCZ over Africa is located well north of the equator.

Since Africa terminates at relatively low latitudes (near 34^{o}S), the annual cycle in the location and intensity of the subtropical anticyclone and midlatitude westerly belt over the South Atlantic is far smaller than in the North Atlantic or Pacific. On average, the South Atlantic anticyclone shifts only 6° of latitude between the seasons and a significant semi-annual oscillation in this position is observed. The zonal shift in the anticyclone is about 13°, again with a semi-annual signal superimposed, and it tends to lie closer to southern Africa in spring. These seasonal fluctuations in the anticyclone drive changes in surface wind which then impact on SST, particularly in the upwelling zones along the southern Angolan, Namibian and South African coasts and, further north, in the Gulf of Guinea and the Atlantic cold tongue.

Over the tropical Atlantic, the underlying surface conditions in the two extreme seasons are quite different. In austral autumn, a relatively weak and broad region of marine convection, strongest in the western equatorial region, is located over a wide strip of warm SSTs with weak latitudinal gradients. In the winter, the band of ITCZ associated precipitation is sharp and stretches across the entire ocean basin with largest values in the east. The band of warm SST is relatively narrow surrounded by strong latitudinal gradients, particularly to the southeast, where the Atlantic cold tongue resides.

The relationship between tropical SST, convection, and surface winds was studied by Mitchell and Wallace (1992). They emphasized the dominance of the first harmonic of the annual cycle in the pattern of ITCZ seasonal variability and proposed that the reasons for this behaviour lies in the response of the tropical atmosphere-ocean system to the variations of insolation in the presence of a north-south asymmetry of the distribution of land masses around the equator (particularly in the eastern boundary from which the trade winds are blowing). In particular, they note that it is the development of the massive convection centers over land (in the Atlantic case, the west African monsoon) during late boreal spring, early summer, that leads to the development of the cross equatorial flow in the east, which in turn forces equatorial upwelling and advection of cold water from the Southern Hemisphere and the development of the cold tongue. The development of the cold water leads to rise in sea level pressure over the equator, which further enhances the northward flow, which assists in the development of the monsoon. Over the ocean, the presence of warm water at ~7°N and the airflow from the south, contribute to the creation of a strong, and well-defined region of ITCZ convection. This positive feedback interaction between ocean and atmosphere is what keeps the marine ITCZ well to the north of the equator until well into austral spring, when the convection over land begins to move south of the equator.

A pronounced seasonal difference in rainfall patterns exists over southern Africa which is related to the annual cycle in the subtropical high pressure belt and the ITCZ. The annual cycle of rainfall based on the CAMS-OPI dataset (Janowiak and Xie, 1999) is presented as the percentage contribution of each season to the annual rainfall (Fig. 1.1). The southwestern Cape (SWC) region of South Africa is a mainly austral winter rainfall region, the south coast an all season rain region, whereas rainfall over most of the rest of subtropical southern Africa occurs mainly in the summer and is generated largely from convective thunderstorms (Harrison, 1984), driven for the most part by tropical-extratropical interaction and associated cloudbands. Over tropical southern Africa, the main rainy seasons shift towards bimodal in the east and late summer / autumn in the west. The Atlantic seaboard of southern Africa and the neighbouring hinterland contains the Namib, western Karoo and Kalahari deserts and is much drier than the eastern half of southern Africa.

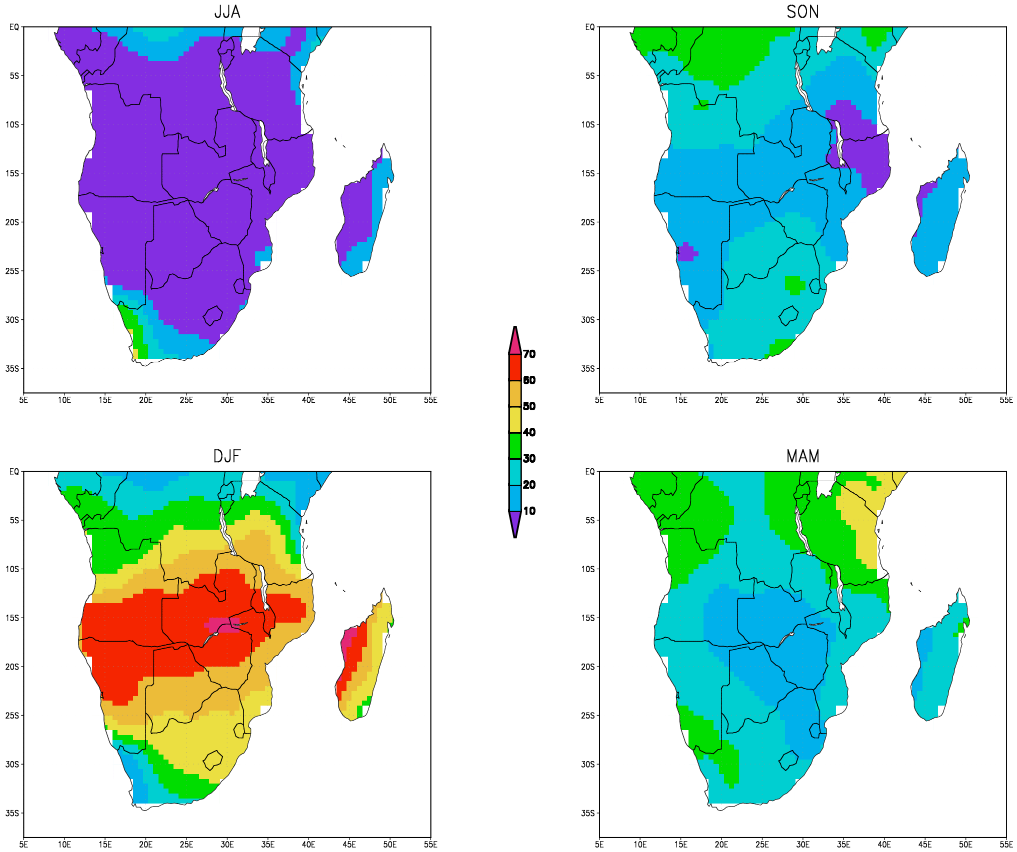


Figure 1.1: Seasonal rainfall as a percentage of the annual rainfall based on CAMS-OPI data for the period 1979-2003.

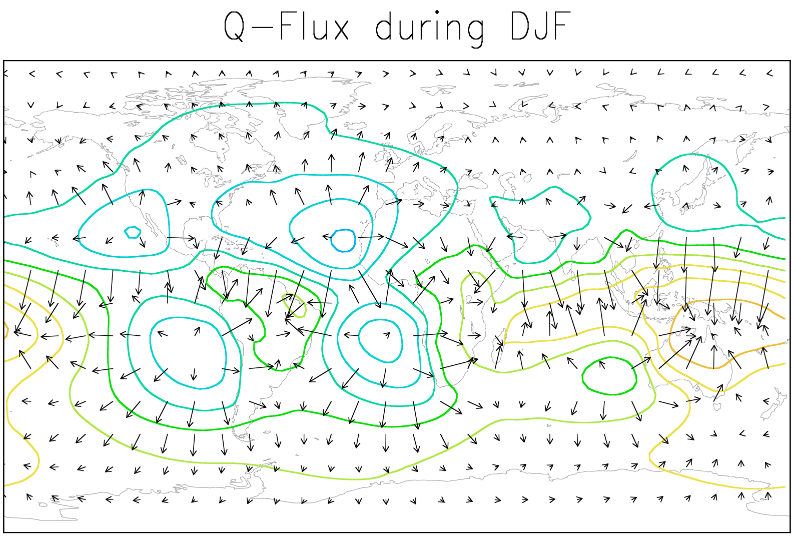
Winter rainfall over the SWC is frontal and is facilitated by the northward shift of the anticyclone over the South Atlantic and the development of a region of relative low pressure between it and the South Indian anticyclone that lies just to the south of the SWC. Substantial interannual variability exists and evidence exists that this may be related to South Atlantic SST gradients (Reason *et al.*, 2002 - Section 4). North of about 15°S, the influence of the tropical South Atlantic may be important via westerly moisture flux associated with the Angola low. This region receives most of its rainfall in late summer (February-April).

The Angola low is a shallow heat low that develops from about October over southern Angola and northern Namibia and strengthens considerably from January onwards. A confluence zone stretches northeast towards the meridionally oriented ITCZ across central southern Africa. North of the low, there is a relatively weak low level moisture flux from the tropical southeast Atlantic over Angola. To the south, low level easterly moisture fluxes originating from the Indian Ocean, dominate most of subtropical southern Africa in summer. In addition, the Angola low acts as the tropical source region for the tropical-extratropical cloudbands that bring most of the summer rainfall across southern Africa south of about 15°S. On occasion, easterly disturbances track west across subtropical southern Africa from the South Indian Ocean and merge with the low, typically leading to enhanced rainfall. Evidence exists (Rouault *et al.*, 2002) that modulations of the Angola low, related to tropical South East Atlantic SST, may significantly influence summer rainfall over large areas of southern Africa, particularly Angola and northern Namibia (Section 3) but also South Africa (Cook *et al.*, 2004).

Early studies of moisture flux and rainfall variability over South Africa (D'Abreton and Tyson, 1995) suggested that the Indian Ocean source of moisture for the summer rainfall area shifts between wet and dry years. NCEP reanalyses (Kalnay et al 1996) that have subsequently become available suggest that moisture sourced from the Indian Ocean feeds primarily into the ITCZ over Mozambique and the western Indian Ocean and that the South East Atlantic Ocean is also an important source of moisture for the southern Africa region (Fig. 1.2). The moisture sources and sinks in this figure are calculated from the divergent flow produced by the NCEP reanalysis model. This field, however, is classified as having second-order accuracy, suggesting that some level of error is possible in the moisture source/sink values. However, the importance of the South East Atlantic Ocean as a moisture source remains clearly evident for both DJF and JJA seasons.

Moisture flux is determined by atmospheric circulation. This is associated with the lower branch of the Hadley Cells in the tropics and with mid-latitude cyclones in the westerlies. The convergence of moisture in the ITCZ is clearly shown at about 10°S over the Indian Ocean and about 5°N over the Atlantic Ocean during DJF. In the austral winter the ITCZ shifts to the northern hemisphere and the South Atlantic Ocean remains a strong source of moisture. The southward flux of moisture over the South Atlantic Ocean is relatively strong compared to the other oceans in the Southern Hemisphere during both DJF and JJA (Fig. 1.2).

Further evidence of the relationship between rainfall variability in southern Africa and the large-scale circulation is shown with vertically integrated barotropic and baroclinic kinetic energy. Distinct contrasts between the characteristics of the daily archetype frequencies are found between wet and dry years (Tennant and Hewitson 2002). Typically barotropic kinetic energy is reduced and shifted polewards during wet summers and baroclinic kinetic energy breaks into two branches, with the northern branch over southern Africa. Similar associations have been found for the winter rainfall areas of the SWC. These are shown here as composites of the rate of conversion of eddy potential energy into eddy kinetic energy between wet and dry years (as defined in Tennant and Reason, 2004) (Fig. 1.3). During dry South African summers, this energy conversion is enhanced around 45°S over the South Atlantic Ocean. During dry winters in the SWC, a northward displacement of activity is shown in the western sector of the South Atlantic Ocean. Wiin-Nielsen (1962) described the energy cycle as eddy potential energy converting into eddy kinetic energy and then into zonal-mean kinetic energy. Northward displaced energy conversion in the South Atlantic Ocean would then contribute to enhanced zonal-mean kinetic energy downstream, i.e. in the African region, that would suppress rain-bearing systems over that region. It is of particular interest that these associations are located predominantly over the South Atlantic Ocean indicating the importance of the circulation in this region to rainfall in South Africa, and potentially, southern Africa.



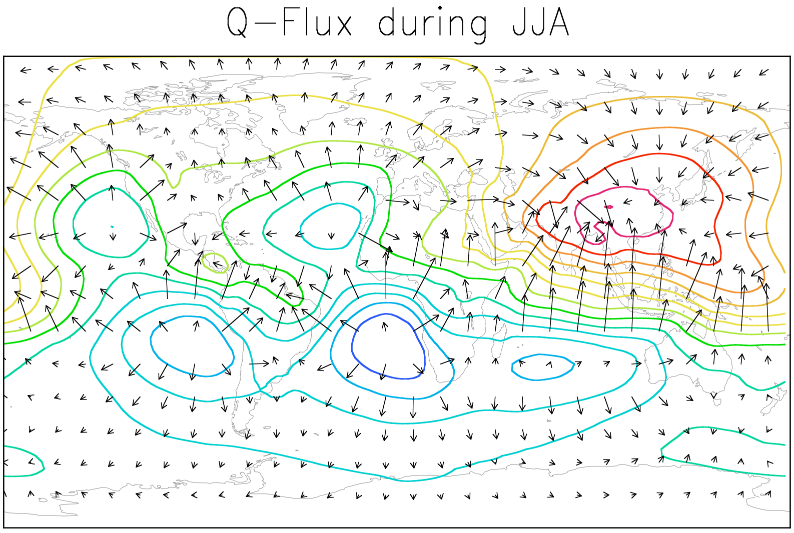


Figure 1.2: Average vertically integrated moisture flux and velocity potential for the austral summer (top) and winter (bottom) based on 6-hourly NCEP reanalysis data for the period 1979-2003.

Interannual and interdecadal variability

ENSO is the dominant mode of interannual variability over the tropical Southern Hemisphere whereas the Antarctic Oscillation or Southern Annular Mode (SAM) is the leading mode in the mid- to high latitude atmospheric circulation. Trends towards high-index polarity in the SAM have been noted (Thompson et al. 2000), but the effects of such trends on southern African climate are unclear. It is worth noting however that Fyfe (2003) and Simmonds and Keay (2003) show that such trends are likely accompanied by a decrease in mid-latitude cyclones over the hemisphere as a whole.

ENSO is known to project strongly over southern Africa and the South Atlantic (e.g., Lindesay *et al.*, 1988; Venegas *et al.*, 1996; Reason *et al.,* 2000) and has significant rainfall impacts, particularly during the mature phase. Anomalously wet winters in the SWC region of South Africa have been linked to the SAM (Reason *et al.*, 2002). In addition, the tropical Atlantic develops both its own zonal SST variability on interannual timescales, the so-called Atlantic ENSO (Houghton, 1991; Zebiak, 1993). On longer time scales, a meridional SST gradient mode exists in the tropical Atlantic that appears to be related to changes in the tradewinds either side of the ITCZ.

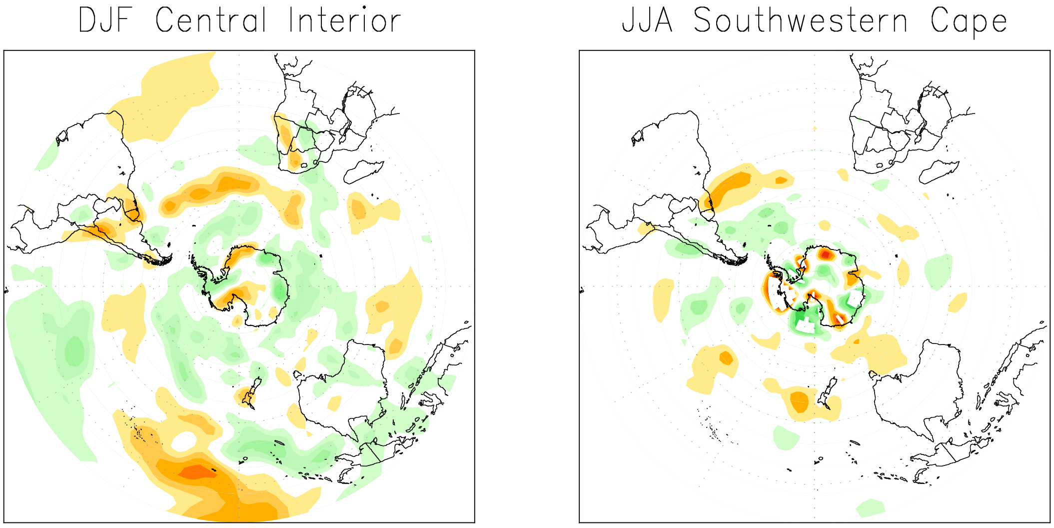


Figure 1.3: Dry-wet composites of the conversion rate (W.m^2) of eddy potential energy to eddy kinetic energy for central South Africa (DJF) and the southwestern Cape (JJA) over the period 1979 to 2002.

In terms of climate impacts on southern Africa, in addition to ENSO, various South Indian Ocean SST patterns (Walker, 1990; Mason, 1995; Reason and Mulenga, 1999; Behera and Yamagata, 2001; Reason, 2002), the so-called Benguela warm and cold events (Hirst and Hastenrath, 1983; Shannon *et al.*, 1986; Rouault *et al.*, 2002) and modulations of SST in the subtropics and midlatitudes of the South Atlantic (Reason *et al.*, 2002) are thought to be significant for various regions in the subcontinent. It should be emphasized that SST variability in the South Indian Ocean is generally believed to exert more influence over southern Africa than that over the South Atlantic (e.g., Nicholson and Entekhabi, 1986; Walker, 1990; Mason, 1995; Mason and Jury, 1997) since the airmasses originating over the former tend to be relatively warm and moist whereas those from the eastern Atlantic are relatively cool and dry. However, it is also true to say that the climate impacts of the Atlantic on southern Africa are less well understood.

Most of southern Africa experiences substantial climate variability on interannual and interdecadal scales. One of the strongest interdecadal signals in the Southern Hemisphere concerns the roughly 18 year cycle in summer rainfall over South Africa and neighbouring countries (Tyson *et al.*¸1975). Various mechanisms have been proposed including regional SST forcing and modulations of the Southern Hemisphere circulation (Mason and Jury, 1997), and the projection of ENSO-like decadal modes onto the region (Fig.2.1) which could also explain interdecadal variability observed in SWC winter rainfall (Reason and Rouault, 2002). These modes have a significant expression in SST over the South Atlantic (Allan, 2000); however, their rainfall impact over southern Africa arises via changes to the atmospheric circulation (Fig. 2.2) rather than from South Atlantic SST. For the summer rainfall region, there are changes in the local Indian Ocean Walker cell and the easterly advection of moist marine air over the land whereas for the winter rainfall region, large scale shifts in the jet and westerly storm tracks over the midlatitude South Atlantic are important (Reason and Rouault, 2002). Another significant interdecadal scale signal concerns the hemispheric modulation of the subtropical high pressure belt (Jones and Allan, 1998; Reason, 2000) including the South Atlantic. Given the importance of the South Indian and South Atlantic anticyclones for southern African climate, one might expect significant impacts on southern African rainfall variability; however, this is unclear.

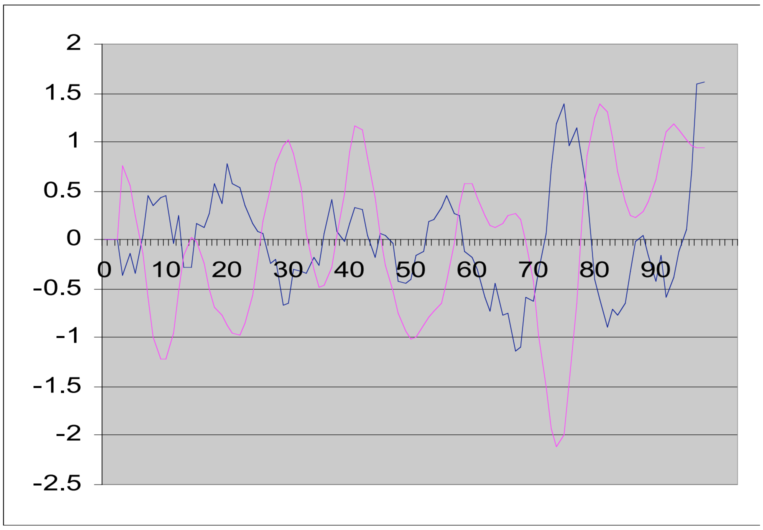


Fig. 2.1 South African smoothed summer rainfall (blue) for 1903-98 and average of ENSO-like EOFs on 9-13 year and 18-39 year filtered bands(pink). After Reason and Rouault (2002)

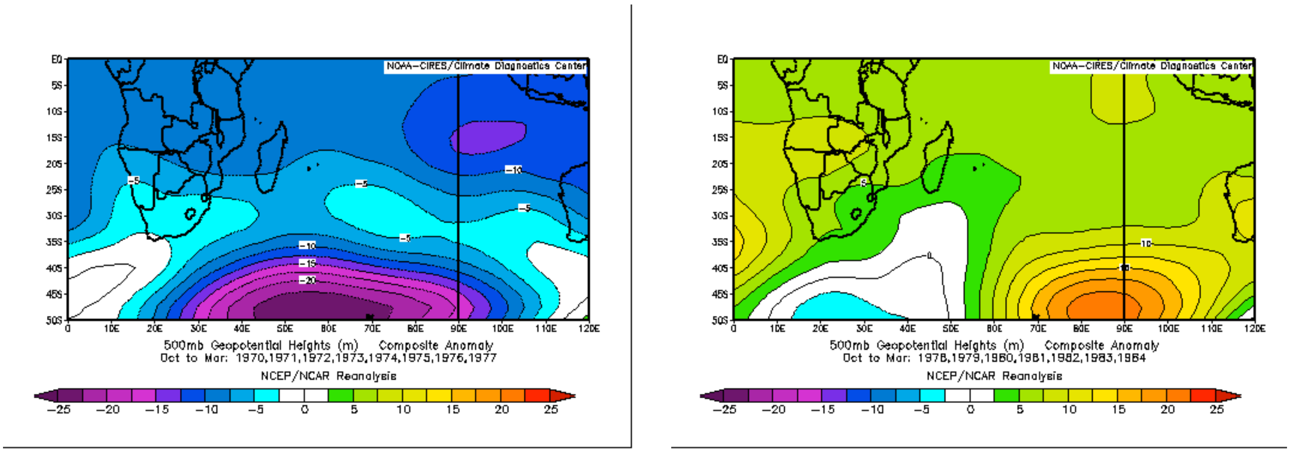


Fig. 2.2. 500hPa height anomalies (m) for a) the wet 1970-1977 period, b) the dry period 1978-1984. After Reason and Rouault (2002).

On interannual scales, variability around 2-3 years and 5-6 years is prominent (Nicholson and Entekhabi, 1986; Tyson, 1986). ENSO is a major contributor to interannual variability over southern Africa but by no means the only forcing. In addition to modulating the SST of the neighbouring Indian and South Atlantic Oceans, ENSO leads to changes in the regional atmospheric circulation, primarily via the local Walker circulation (e.g., Lindesay, 1988; Reason *et al.*, 2000) and the South Indian Convergence Zone (Cook, 2000, 2001) which tend to suppress (enhance) rainfall during the mature phase of El Niño (La Niña) events. Over the South Atlantic, Colberg *et al.* (2004) used a global ocean model forced by 50 years of NCEP fluxes to find that the SST and upper ocean circulation of the basin mainly responds passively to ENSO-induced changes in surface fluxes, the latter largely wind-driven via circulation anomalies associated with the Pacific South America (PSA) pattern (Mo and White, 1985; Karoly, 1989). In addition, to its influence on mid- and high latitude atmospheric circulation over the South Atlantic via the PSA pattern, ENSO also influences the South American Convergence Zone (SACZ), a feature that is most prominent in the austral summer. Local South Atlantic SST anomalies also influence the strength and location of this feature (Robertson *et al.*, 2003). Since the SACZ acts to export moisture and energy to higher latitudes, it influences the jet stream and generation of mid-latitude cyclones upstream of southern Africa which may then impact on the development of tropical-extratropical cloudbands over the subcontinent.

From the foregoing, it should be evident that southern African climate variability is sensitive to a range of factors and this poses great challenges for predictability. One simple way to try and isolate factors is to separate those clearly associated with ENSO events. Such a separation was attempted by Walker (1990) in an assessment of the influence of South Atlantic and South Indian SST anomalies on South African summer rainfall. More recently, Mulenga *et al.* (2003) separated interannual JFM droughts over northeastern South Africa into ENSO and non-ENSO droughts. The latter all appeared to show an atypically strong influence of relatively cool, dry South Atlantic air being advected over South Africa as a result of a cyclonic anomaly being located over the southeast Atlantic, either west of South Africa or just to the southwest. These droughts were classified by Mulenga *et al.* (2003) as ones where the atmospheric circulation over the subtropical to midlatitude South Atlantic had an anomalously strong role to play whereas most other droughts where tropical in origin, via ENSO. In addition to the very recent 2003/4 severe summer drought, previous strong examples include 1981/2, 1967/8 and 1951/2. The importance of the midlatitude circulation for these droughts suggests that their predictability is not high; however, some success in forecasting the current 2003/4 drought has been achieved using GCMs forced with forecast global SSTs from a coupled model. For example, the November-January seasonal forecast using HadAM3 forced with CSIRO COCA coupled model forecast SSTs suggested that the summer rainfall region would receive 80-100 % of average rainfall during this period whereas the COLA GCM run at the SA Weather Service indicated that northern South Africa would receive 50-75 % of average rainfall. Observed rainfall was considerably less than this in parts of South Africa but this model forecast was at least consistent in sign with the general drought conditions over most of South Africa.

As previously mentioned, warm and cool events in the tropical South East Atlantic (the so-called Benguela Niños and Niñas) have significant impacts on late summer rainfall, particularly over Angola and northern Namibia (Hirst and Hastenrath, 1983; Rouault *et al.*, 2002). These events involve modulations of the tradewinds over the South Atlantic which then generate equatorial Kelvin waves in the western Atlantic that propagate across and lead to coastal wave signals along the Angolan and northern Namibian coast (Florenchie *et al.*, 2004). Where the thermocline shoals towards the surface, typically off southern Angola, a large SST anomaly expresses itself. Given the approximately two month lag between the wind stress modulations and the manifestation of SST anomalies along the Angolan coast, some predictability of the SST anomalies may be achieved. Current statistical forecasting schemes (CCA, neural nets) in use in South Africa (Landman and Mason, 2001) do not capture these events, or indeed perform satisfactorily over the South Atlantic as a whole; this may be because of the importance of coastal trapped waves and other dynamics for their evolution which are not well represented by statistical models of this type.

Tropical South East Atlantic variability - Benguela warm and cool events

Benguela Niños are intermittent, acute, extreme warm events near the border between the southward flowing Angola Current and the Benguela upwelling system off southwestern Africa (Shannon et al. 1986). These anomalously warm events have dramatic effects on the fisheries and the climate of the region. They tend to induce significant rainfall anomalies (Rouault et al. 2003) and can drastically modify fish distribution and abundance (Boyer et al. 2001). Benguela Niños occurred in 1934, 1949, 1963, 1984 (Shannon et al. 1986) and more recently in 1995 (Gammelsrød et al. 1998). Such episodes are less frequent and less intense than their Pacific counterparts, and they tend to develop south of equator.

In essence, Benguela Niños express themselves as abnormally and persistent high sea surface temperatures (SST) along the coast of Angola and Namibia. Conversely, Benguela Niñas may be regarded as similar, except that the SST anomalies along the coast are cool (Florenchie *et al.*, 2004). Smaller warm and cool events along the Angola / Namibian coast occur frequently and may be generated in a similar way to Benguela Niños and Niñas; however, their surface expression is weak due to other factors.

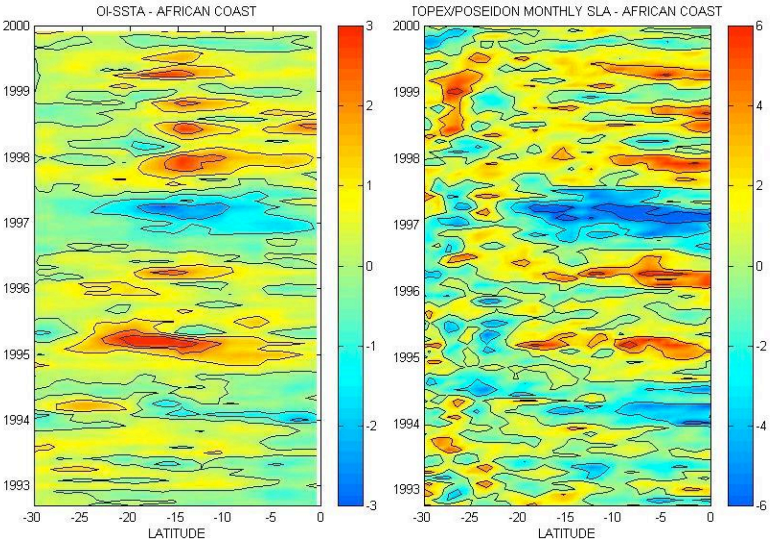


Fig. 3.1 Sea surface temperature (right) and sea level (left) anomalies along the African coast from the equator to 30°S versus time (after Florenchie *et al.,* 2003).

A combination of various observational and model analyses at different depths suggests that, despite their limited surface expression, warm and cold episodes along the coast of Angola and Namibia are in fact large-scale events spreading from the equator at different depths with a duration of several months. Analysis of altimeter, SST and OPA OGCM output (Florenchie *et al.*, 2003, 2004) indicates that all warm (cold) episodes in the tropical SE Atlantic over the 1992-2000 period tend to be associated with positive (negative) sea level anomalies spreading along the African coast from the equator to as far south as about 20°S **(Fig. 3.1).**

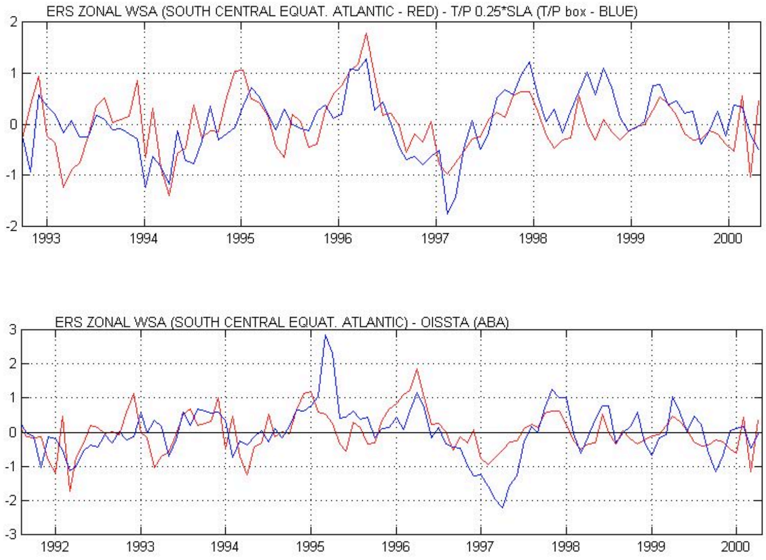


Fig 3.2: Time series of zonal WSA averaged south of the equator (between 5.5S and 0.5S) in the central basin from 29.5W to 9.5W and (a) SLA averaged over the Topex box and (b) OISSTA averaged over the ABA. After Florenchie *et al.,* 2004.

The 1995 and 1996 warm events show positive anomalies with respective local maxima of 12 cm and 10 cm while the 1997 cold event shows strong negative anomalies with a local minimum of -11 cm. Calculations from the slope of Hovmoeller plots of sea level anomalies suggest a poleward propagation rate of between 0.5 and 1 m/s **(Fig. 3.1)**. Such an estimate agrees with the poleward propagations observed in the eastern Pacific by Enfield and Allen (1980) or simulated (Clarke and Van Gorder, 1994). A coastal trapped wave propagation process is consistent with the spreading of anomalies from the equator southward. However, discrepancies between theoretical phase speeds and the slower observed ones may occur because the theory does not take into account coastal shelf and slope bottom topography or bottom friction (Clarke and Van Gorder, 1994; Pizarro et al., 2001).

Analysis of ERS wind stress and Reynolds SST in the equatorial Atlantic (Florenchie *et al.*, 2003, 2004) indicates that, about 3 months prior to the appearance of SST anomalies along the Angola coast, the eastern equatorial Atlantic is directly influenced by remote zonal wind stress anomalies **(Fig. 3.2).** through equatorial wave dynamics (there is less than a one-month lag between the two signals). As noted by Picaut (1985), equatorial oceans tend to respond clearly and coherently to wind fluctuations as seems to be the case here. Anomalies in the trades in the western to central equatorial Atlantic basin excite eastward propagating Kelvin waves that depress or lift the thermocline all the way to the African coast and create subsurface temperature anomalies. On reaching the African coast, coastal trapped waves are generated which propagate southward and induce SSTA in the Angola Benguela frontal area (ABA), where the thermocline reaches the surface **(Fig. 3.3)**.

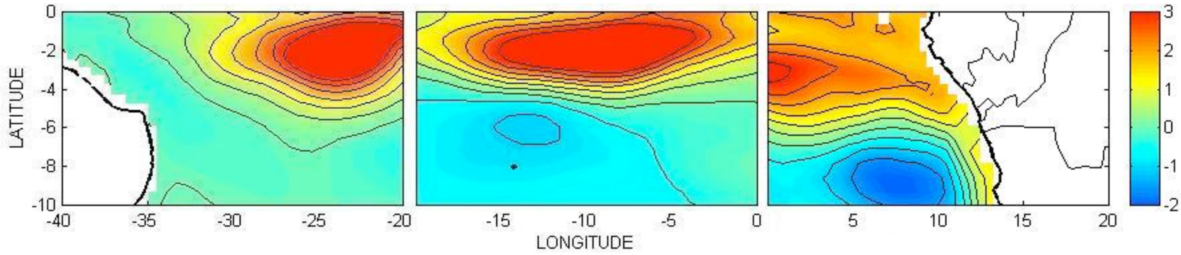


Fig. 3.3: Time – depth evolution 1984 over 1 month, shoaling from 100 to 45 m across tropical Atlantic. After Florenchie *et al.* (2003).

The strong correlation (Fig. 3.4) between SST anomalies in the ABA and interannual zonal wind anomalies just south of the equator over the western and central Atlantic basin suggests a mechanism based on equatorial and coastal trapped waves to explain the equatorial origin of most episodes. SST anomalies become visible at the surface one to two months after the appearance of subsurface temperature anomalies at the thermocline depth. Such anomalies can be attributed to vertical shifts of the thermocline under the action of propagating Kelvin waves initially triggered by zonal wind variations.

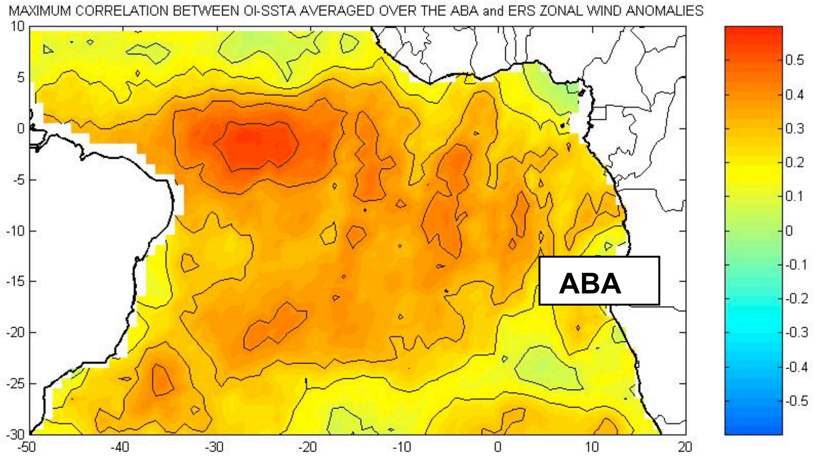


Fig. 3.4 Correlation between SST and ERS zonal wind anomalies After Florenchie *et al.* (2004)

These waves are deviated poleward on approaching the African continent and temperature anomalies become more or less visible at the surface as a function of various factors like the strength of the event, the depth of the thermocline or the upwelling or downwelling-favourable winds. Temperature anomalies start interacting with the atmosphere when and where the thermocline outcrops along the coast. Seasonal variations of the thermocline depth and shape also modulate the surface expression of the anomaly pool.

Analysis of local heat fluxes (Florenchie *et al.*, 2004) suggests that the latent heat flux seems to have a rather passive role on the evolution of events in the ABA and mainly acts as a thermostat to regulate cold and warm events at the surface. Local variations in latent heat flux definitively did not create the higher than normal SSTs in the large Benguela Niños of 1984 and 1995. Furthermore, since the local rain anomalies tend to be positive (negative), and cloud cover increased (decreased) during warm (cool) events, changes in solar radiation tend to weaken the events, i.e., they act in concert with the latent and sensible heat fluxes to moderate the surface expression of the events. Local wind-induced upwelling and offshore Ekman transports may have contributed towards producing lower SSTs during the 1992 and 1997 cool events, but, in general, the local wind regime does not seem to play the major role in the expression of Benguela Niños and Niñas.

Despite the relatively rare occurrence of Benguela Niños and Niñas, warm and cold SST anomalies tend to develop regularly off Angola and Namibia. Monthly standard deviations reveal seasonality with a maximum of surface temperature variability in March/April and a minimum in September/October. Major warm events in phase with late summer are likely to give rise to Benguela Niños since they induce extremely high sea temperatures that affect the ecosystem. By interacting with the atmosphere via moisture fluxes, high SSTs may reinforce the rainfall season of southwestern Africa with sudden flooding and devastating consequences.

Sea level anomalies in the eastern equatorial basin show a strong correlation with the southern SSTA signal. The remote forcing of the SST anomalies highlights the possibility of being able to forecast future extreme events via real-time sea level and wind observations or predictive models. The development of equatorial subsurface anomalies could also be detected in advance using local measurements such as the ones performed by the PIRATA array (Servain et al. 1998). However, the non-linear response of SST anomalies in the ABA to the remote wind forcing emphasizes the need for further work to understand the way different mechanisms seem to control the development of each individual event in the tropical Atlantic basin.

There are also likely to be important links between these events and the West African monsoon. Analysis of NCEP OLR, wind and geopotential height data indicates that the winter intensification of wind-stress off the Angolan coast is linked with convective activity over equatorial West Africa (Risien *et al.*, 2004). Given that some of the moisture feeding into the West African monsoon emanates from the tropical SE Atlantic, better understanding of the teleconnections between monsoonal activity and variability in the heat budget of the eastern South Atlantic is needed. The role of modulations to the South Atlantic anticyclone, which is known to vary substantially on interannual to interdecadal scales (e.g., Venegas *et al.*, 1997; Reason, 2000) as well as respond to ENSO forcing (e.g., Venegas *et al.,* 1999; Reason *et al.,* 2000), in influencing both the SST and upper ocean heat content in the SE Atlantic as well as the moisture flux towards West Africa remains poorly understood.

South Atlantic subtropical / midlatitude SST variability and SWC rainfall

The SWC region of South Africa experiences significant interannual and interdecadal variability in its rainfall, which is predominantly during winter via cold fronts. Previous work (Reason *et al.*, 2002) has found evidence of relationships between interannual winter rainfall variability and anomalies in sea-ice extent near Drake Passage and the eastern Weddell Sea and in SST over the subtropical / midlatitude South Atlantic (Figs. 4.1, 4.2).

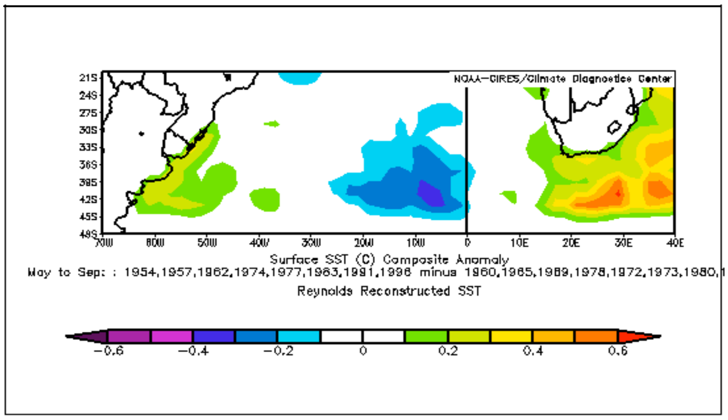


Figure 4.1 SST anomalies (0.1 oC contour interval) derived for wet – dry southwest South African winters 1950-2001 (Reason *et al.,* 2002)

Wet winters tended to be associated with warm anomalies in the Brazil / Falklands confluence region, climatologically an important cyclogenesis area, and also just to the south and upstream of the SWC near the Agulhas Retroflection region suggesting that frontal systems would be enhanced via increased moisture uptake just prior to landfall. Cool SST anomalies tended to be found over the central South Atlantic favouring a strengthening of the baroclinic gradient here as well as a northward shift of storm tracks via potential vorticity conservation. The large scale atmospheric circulation showed a negative SAM pattern with low pressure anomalies stretching northeast towards the SWC from the SW Atlantic (Fig. 4.3). Dry winters showed roughly the reverse atmospheric anomalies but with a more obvious shift in the wavenumber 3 pattern to produce anticyclonic anomalies over southern South Africa.

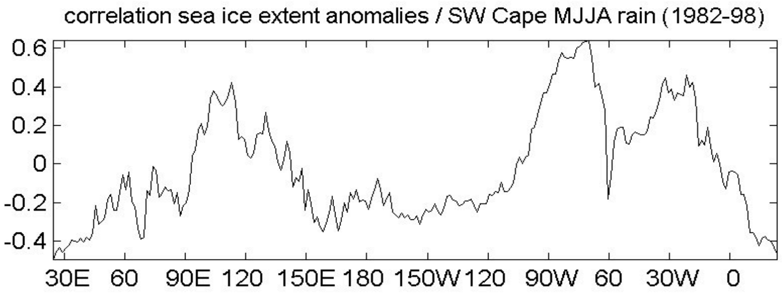


Fig. 4.2. Correlation between sea-ice extent and SW SA winter rainfall – maximum near Drake Passage and Weddell Sea (Reason *et al.,* 2002)

Recent modeling work (Reason and Jagadheesha, 2004) with an AGCM (HadAM3) has shown that the regional atmosphere is sensitive to idealized representations of the SST anomalies observed over the subtropical and midlatitude South Atlantic during wet and dry SWC winters. Earlier, Robertson *et al.* (2003) showed that the atmosphere is sensitive to tropical and subtropical South Atlantic SST forcing during summer using a different AGCM; however, the impacts were mainly expressed over South America, the ITCZ and the South Atlantic Convergence Zone with those over Africa being restricted to West Africa.

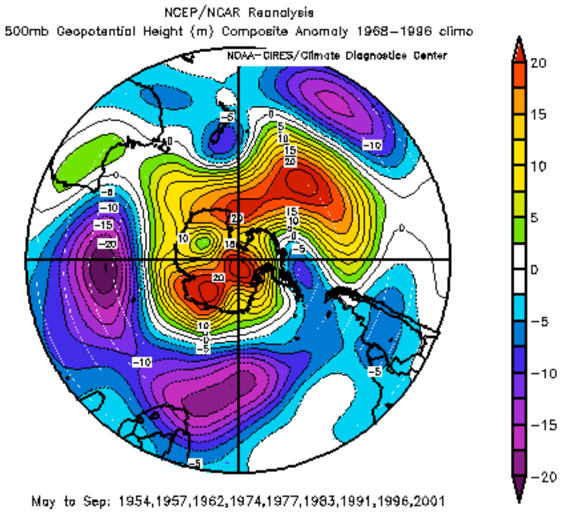


Fig. 4.3. 500hPa height anomalies for wet winter composite (Reason *et al.*, 2002)

Although there do appear to be some robust linkages between South Atlantic SST and SWC winter rainfall, much work remains to be done to elucidate these further. The question of what forces these SST anomalies and how they are related to large scale modes such as ENSO and the SAM remains to be investigated. If predictability is to be realised, then a better understanding of the projection of ENSO and the SAM onto the South Atlantic and the regional atmospheric circulation is needed. In addition, possible relationships between these two modes needs to be investigated as well as that with the Antarctic Circumpolar Wave. As yet, no clear evidence of the influence on the latter on southern African climate has been presented, although it has been claimed (White *et al.*, 2003; Cherry and White, 2002) that it impacts on southern Australian, New Zealand and southern South American rainfall.

Regional forecasting efforts using GCMs and statistical methods

The scientific basis for doing seasonal forecasting originates from the observation that slowly evolving sea-surface temperature (SST) anomalies influence seasonal-mean weather conditions (Palmer and Anderson 1994). Therefore, estimation of the evolution of SST anomalies, which may be relatively predictable, and subsequently employing them in atmospheric GCMs, potentially provides means of generating forecasts of seasonal-average weather (Graham et al. 2000). Although GCMs, commonly configured with an effective resolution of 200-300 km, have demonstrated skill at global or even continental scale, they are unable to represent local sub-grid features, subsequently producing rainfall over southern Africa that is typically overestimated (Joubert and Hewitson 1997; Mason and Joubert 1997). Also, the model representation of rainfall is complex and often not well estimated (Graham et al. 2000; Goddard and Mason 2002). Such systematic biases have created the need to downscale or recalibrate GCM simulations to regional level over South Africa. Semi-empirical relationships exist between observed large-scale circulation and rainfall, and assuming that these relationships are valid under future climate conditions and also that the large-scale structure and variability is well characterized by GCMs, equations can be constructed to predict local precipitation from simulated large-scale patterns (Wilby and Wigley 1997). Recently, empirical remapping of GCM fields to regional rainfall has been demonstrated successfully over southern Africa (Landman and Goddard 2002; Landman and Tennant 2000; Landman et al. 2001).

Predictability studies and forecast model development efforts in southern Africa have extensively sought links between large-scale phenomena, such as El Nino/Southern Oscillation (ENSO), and seasonal total rainfall anomalies in various regions (e.g., Lindesay *et al.*, 1986; Jury *et al.*, 1994; Mason, 1995; Mason, 1998; Jury *et al.*, 1999; Landman *et al.*, 2001). The focus to date has been on using SSTs as the primary source of seasonal predictability. Certainly, there are good associations between rainfall over southern Africa and SSTs in the South Atlantic, Indian and Pacific Oceans (Walker, 1990; Mason, 1995; Reason and Mulenga, 1999). Pioneering forecast efforts used statistical methods such as canonical correlation analysis (Landman and Mason, 1999) and a non-linear discriminant analysis model (Mason, 1998). Other predictors, such as cloud depth and upper zonal winds have also been explored (e.g. Jury, 1999; Jury, 2002).

Local forcing of climate, typically through positive feedback mechanisms with soil moisture (Douville et al., 2001; Zhang and Frederiksen, 2003) and vegetation (Zheng and Eltahir, 1998) is also recognized as an important contributor to seasonal predictability. With this in mind and the various non-linear feedbacks existing in the ocean-atmosphere system, the implementation of general circulation models has become a priority in South Africa. There are three major centres in South Africa that run global atmospheric models that they have acquired from international centres.

The first AGCM used locally is the T30 resolution spectral model, developed at the Center for Ocean-Land-Atmosphere Studies (COLA). The model has been used operationally since 1995 at the South African Weather Service to produce monthly and seasonal forecast guidance. It is applied in a multi-tiered seasonal forecast system (Landman et al, 2001) and in a monthly downscaling system (Landman and Tennant, 2000). The model is described by Kirtman et al. (1997) and its application at the South African Weather Service by Tennant (1999). The model has 18 unevenly spaced sigma layers in the vertical. Prognostic variables include surface pressure, divergence, vorticity, virtual temperature and specific humidity on all 18 levels. The physics include a Simple Biosphere model (SiB) (Sellers et al., 1986).

Secondly, the Hadley Centre Atmospheric Model (HADAM3), a hydrostatic grid-point model with a resolution of 3.75^{o} longitude by 2.5^{o} latitude, is used at the University of Cape Town for research purposes and to produce prototype seasonal forecasts every month. The vertical scheme uses hybrid eta coordinates on 19 levels and the prognostic variables include zonal and meridional wind components, geopotential height, specific humidity and liquid-water potential temperature. A comprehensive description of this model, an evaluation in terms of mean climate and the impacts of the physical parameterizations can be found in Pope et al. (2000). For forecasts over southern Africa it has been found that the original configuration produces little interannual rainfall variability over the continent. Hence the mixed phase precipitation scheme (Wilson,1999) is used which improves the rainfall response of the model. Biases in the asymmetric component of the zonal wind to the south of the continent are also reduced, this relates to the simulation of tropical-temperate troughs which are important for rainfall over the region.

The Mark II version of the nine-level AGCM of the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) at a R21 horizontal resolution (approximately 5.6^{o} by 3.2^{o}) is used for research purposes and experimental seasonal forecasts at the University of Pretoria. In this AGCM, the spectral atmospheric equations in flux formulation (Gordon, 1981) are integrated over nine sigma model levels in the vertical. Details of the physics parameterizations are given in Rotstayn (1997), McGregor et al. (1993) and Watterson et al. (1995).

When used for seasonal forecasting purposes, these three models obtain their SST boundary conditions from CCA forecasts (Landman and Mason, 2001) or from the CSIRO coupled OAGCM COCA forecast model (Ian Smith, pers. Commun., 2003). The latter is a coupled model using the French "CERFACS" OASIS coupler to couple the CSIRO AGCM with the CSIRO OGCM and, after appropriate initialization and "coupled-nudging" produce global SST and atmospheric circulation forecasts up to twelve months ahead (see www.dar.csiro.au/climate/coca.html for more information). In addition to the seasonal forecasts produced for southern Africa in this way, there are also simulations using persisted SST anomalies or perturbation SST forcing for various sensitivity and process-oriented experiments by various workers at the three institutions.

Given that the sharp topographic, vegetation, soil and SST gradients characteristic of the southern African region are unlikely to be adequately represented by these AGCMs, it is important to consider downscaling of their output to the region of interest. Currently, two broad approaches to this are adopted locally; either downscaling using some statistical method or nesting a regional climate model (RCM) within the AGCM output. In terms of the latter, the three local institutions use three different overseas models; namely, MM5, RegCM3 and DARLAM. We briefly discuss some results using RegCM3 at the South African Weather Service (SAWS) and MM5 at UCT and then consider statistical downscaling activities in the region.

Regional climate modelling

The mesoscale atmospheric circulation systems and surface forcing have an important influence on southern African climate and therefore simulations using higher resolution regional climate models (RCMs) are important. At the SAWS, RegCM3 has been nested within NCEP reanalyses data using one way nesting (Giorgi, 1990).

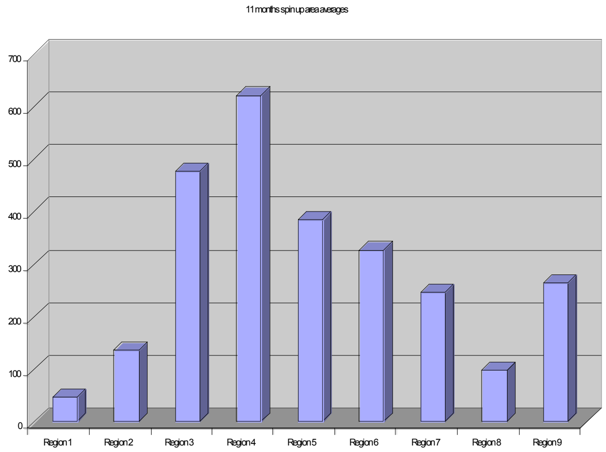


Figure 5.1.1: The area average of the 9 regions over South Africa, Namibia and Botswana using the big domain and a spin up period of 11 months

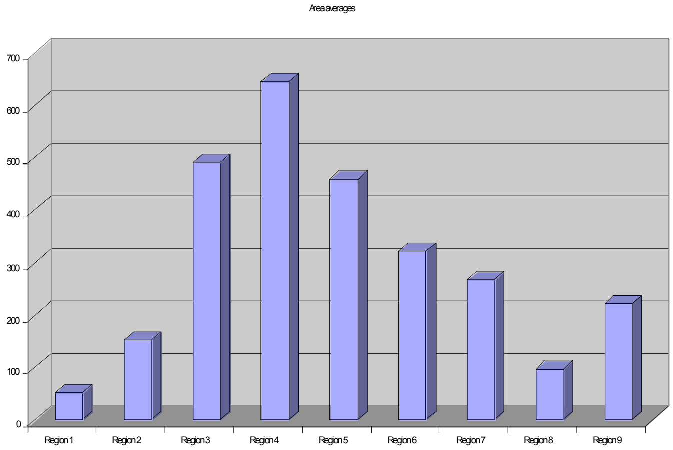


Figure 5.1.2: The area average of the 9 regions over South Africa, Namibia and Botswana using the big domain and a spin up period of 1 month.

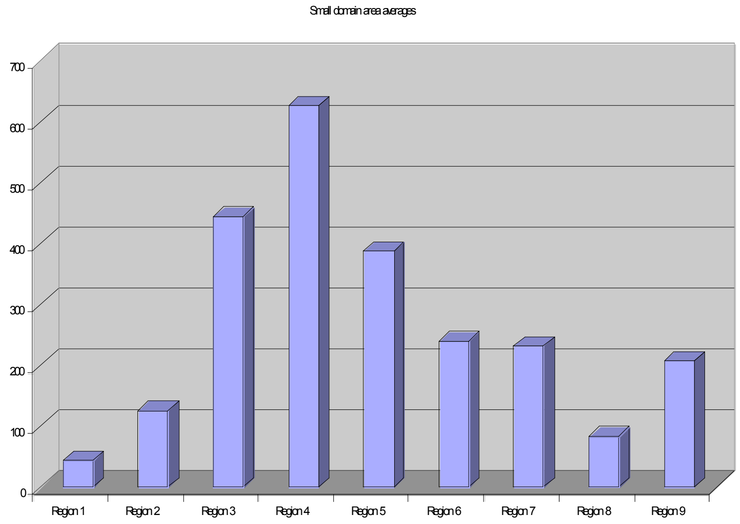


Figure 5.1.3: The area average of the 9 regions over South Africa, Namibia and Botswana using the small domain and a spin up period of 1 month.

The purpose of downscaling using RCMs is to obtain information in high-resolution detail as accurately as possible (Leung and Ghan, 1998). Currently, numerical models are still far from perfect, subject to internal error growth due to non-linearity and instability and external error growth due to model deficiencies (Qian et al, 2003). Therefore the question is, how do we obtain optimal results based on currently available tools? In order to address this question a series of experiments need to be done such as investigating the influence of the domain and also the influence of the spin-up period on the simulations. The experiments will help the regional modeller to identify the best parameters to use in order to get the best possible simulations. In a study at SAWS, the model was run using two different spin-up periods to identify the influence that soil moisture has on the simulations and also with different domains to identify the most appropriate domain.

In order to address the influence soil moisture has on the simulations over southern Africa, the RegCM3 was run for a large domain (extending to north of the equator and east of Madagascar) for a 14 month (January 1982 to February 1983) period and also for a 4 month (November 1982 to February 1983) period. The equilibration period is 11 months and 1 month respectively. The difference between the two simulations is great where the rainfall total is much higher e.g. north of Madagascar and the tropical regions. In South Africa the difference is ±100 mm generally. The patterns of the two simulations (Figures 5.1.1 and 5.1.2) are similar with region 4 having the highest rainfall total amount and region 1 having the least rainfall amount.

Another set of simulations were made for the same four months as above in which case the equilibration period was one month as well, but with a smaller domain. This domain was smaller than the one used above in that the zonal extent was reduced by 7° on the Atlantic side. Since the Indian Ocean is an important moisture source for South African summer rainfall and is complicated by the presence of Madagascar, no adjustment to the eastern boundary was made. The pattern (Figure 5.1.3) of the rainfall was similar to the bigger domain case but the rainfall amounts were reduced. Comparison of the various simulations with observations indicates that the model overestimated rainfall especially over the eastern side of the country and it was concluded that the smaller domain was more appropriate.

Simulations with the smaller domain were run again for 4 months but this time for November 1995 to February 1996. This was a wet season and associated with a La Nina event. The aim of the experiment was to determine if RegCM3 is sensitive to large scale atmospheric forcings. In general, RegCM3 correctly simulated that the 95/96 season was wetter than the 82/83 season (Figure 5.1.5). However, the RegCM3 model, did not correctly simulate the wet anomaly over the east coast and adjacent interior and the Lowveld of South Africa (Figure 5.1.4).

The MM5 regional model is being used at UCT in various research projects relating to extreme events, seasonal forecasting, and interannual climate variability. In addition, it is being used to produce downscaled climate change scenarios as part of an Assessment of Impacts and Adaptations to Climate Change (AIACC) project (http://www.csag.uct.ac.za/aiacc). Before using the model as a downscaling tool it is important to understand how uncertainties in the model configuration (convection scheme, planetary boundary layer etc) and lateral boundary conditions affect estimates of precipitation and temperature. Different combinations of model convection and boundary layer schemes have been tested for wet and dry seasons and reveal important differences in the simulated rainfall. A lack of observations over the region also leads to different representations of the observed atmospheric fields between the NCEP and ERA reanalyses. This is especially apparent in model derived parameters such as moisture but also in upper-level divergence over the continent. It is therefore important to understand the effect of these differences on the MM5 simulations and account for these uncertainties when testing MM5.

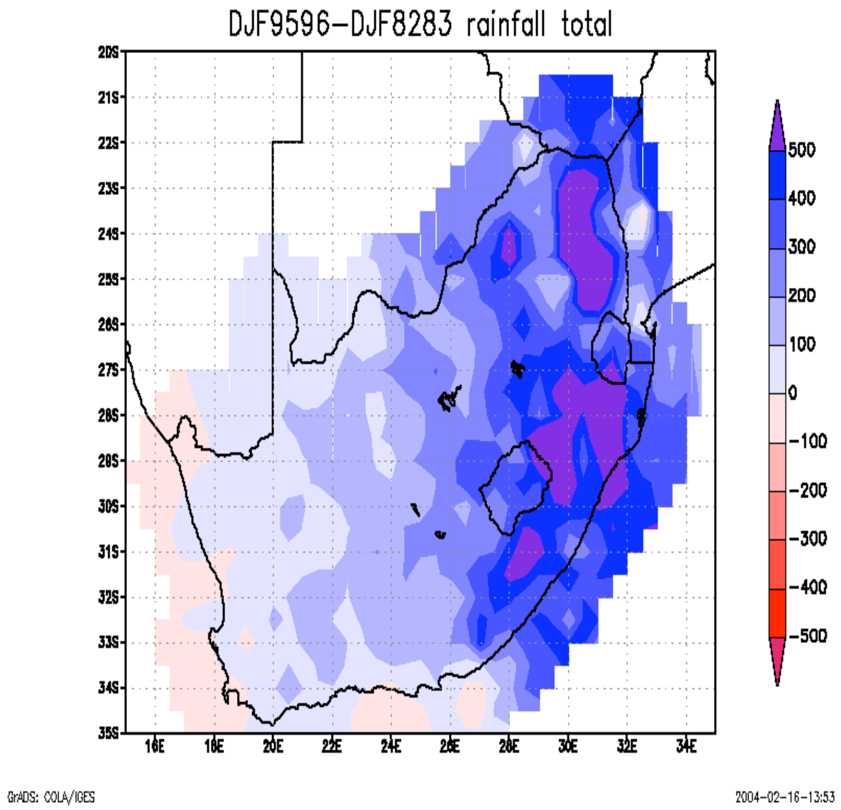


Figure 5.1.4: The observed difference between the rainfall total of December to February of 1995/96 and 1982/83.

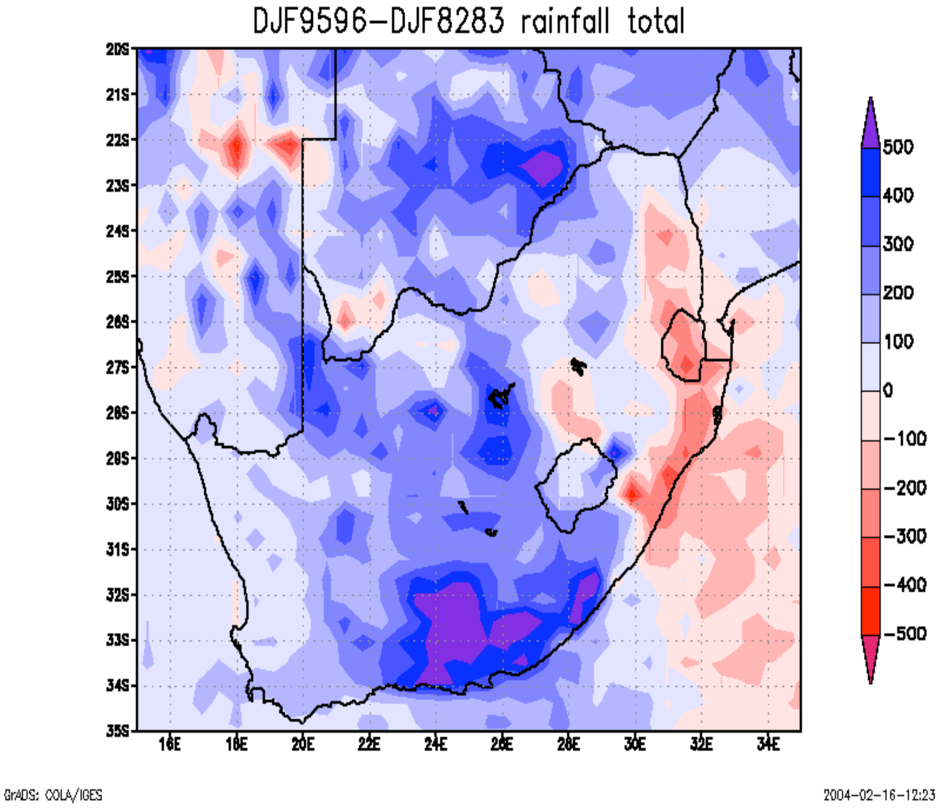


Figure 5.1.5: The simulated difference between the rainfall total of December to February of 1995/96 and 1982/83.

As part of AIACC, 10 year integrations of MM5 within NCEP reanalysis and the control and future climates of ECHAM4, CSIRO and HadCM3 GCMs are being simulated. This will enable high resolution climate change scenarios to be produced and the effect of GCM biases on the MM5 simulations to be evaluated. In particular and as mentioned in section 7, the effect of GCM biases in the westerly flow from the South Atlantic will be important to quantify.

This work is being carried out using computational Linux clusters and ‘home-made’ data storage facilities using PC hard disks and RAID technology. It demonstrates the possibilities with limited resources within Africa and the project is being carried out with researchers in Senegal, Ghana, Zambia, Nigeria and Zimbabwe as well as international partners. Elsewhere in Africa collaborators are able to run MM5 using desktop PCs. They perform simulations of their local area, generally at a higher resolution than those simulations in Cape Town, and are able to provide information based on detailed knowledge of their local environment. However, there are problems when local infrastructure is poor and a common problem, aside from African researchers having to fill a large number of roles, is the supply of power which is intermittent in most countries and restricts the length of simulations.

Additional work with MM5 at UCT involves assessing the sensitivity of both extreme events and seasonal rainfall to regional SST variability, and various modifications to the parameterizations in order to better represent local vegetation and soil moisture forcing. A long term goal is to produce high resolution surface winds and fluxes over the Benguela upwelling system which can then be used to drive ocean and biological models for marine ecosystem management and forecasting.

Statistical downscaling forecasting methods and progress

The inherent variability of the atmosphere requires seasonal climate simulations to be expressed probabilistically. Probabilistic forecasts are made possible through the proper use of GCM ensembles since ensemble forecasting is a feasible method to estimate the probability distribution of atmospheric states (Brankovi_ and Palmer 2000). In addition, errors in the initial conditions as well as deficiencies in the parameterizations and systematic or regime-dependent model errors can be to a large part accounted for through ensemble forecasting (Evans et al. 2000). Moreover, there is inevitable growth in errors of differences between forecasts started from very slightly different initial conditions suggesting that there is no single valid solution but rather a range of possible solutions (Tracton and Kalnay 1993). Information contained in the distribution of the ensemble members can subsequently be used to represent forecast probabilities by calculating the percentage of ensemble members that fall within a particular category (e.g. below-normal, near-normal and above-normal). Figure 5.2.1 shows the ranked probability skill scores obtained from a statistical remapping system using 10 ECHAM3.6 GCM (Deutches Klimarechenzentrum 1992) ensemble members for the DJF season over various southern African regions at a 1-month lead time.

There are advantages in combining ensemble members of a number of GCMs into a multi-model ensemble since GCMs differ in their parameterizations and therefore differ in their performance under different conditions (Krishnamarti et al. 2000). Using a suite of several GCMs not only increases the effective ensemble size, it also leads to probabilistic simulations that are skilful over a greater portion of the region and a greater portion of the time series. Multi-model ensembles are nearly always better than any of the individual ensembles (Dirmeyer et al. 2003, Landman and Goddard 2003, Doblas-Reyes et al. 2000, Krishnamurti et al. 2000). The benefits from combining ensembles are a result of the inclusion of complimentary predictive information since the scheme is able to extract useful information from the results of individual models from local regions where their skill is higher (Krishnamurti et al. 2000). In fact, the most striking benefit obtained from multi-model ensembles is the skill-filtering property in regions or seasons when the performance of the individual models varies widely (Graham et al. 2000). Moreover, increased ensemble size leads to further benefits (Brown and Murphy 1996), but the multi-model approach is only beneficial if the individual systems produce independent skilful information (Graham et al. 2000).

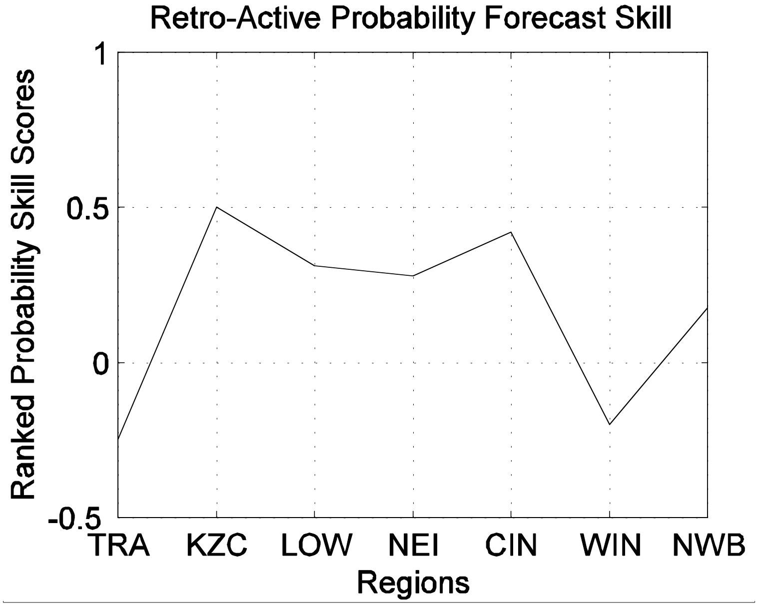


Fig. 5.2.1. RPSS of the 9-year retroactive forecast period from 1991/92 to 1999/2000. The target season is DJF. (TRA: Transkei; KZC: KwaZulu-Natal; LOW: Lowveld; NEI: northeastern interior; CIN: central interior; WIN: western interior; NWB: northern Namibia/western Botswana.

The statistical approach used here to develop equations relating the GCM quantities to a forecast quantity is called Model Output Statistics (MOS) (Wilks, 1995). This approach is normally preferred because it can include directly in the regression equations any influence of specific characteristics, such as systematic errors. These errors can be included because MOS uses predictor values in both the development and forecast stages. Therefore, to develop MOS forecast equations, it is mandatory to have a developmental data set that consists of historical records, preferably more than several decades, of the predictand (regional or station rainfall data) as well as archived records of the forecasts produced by the GCM for the same season on which the predictand was observed. The time lag in MOS forecasts is therefore incorporated in the GCM forecasts. Figure 5.2.2 shows probabilistic forecast skill of a multi-model approach where each of five GCM's simulated DJF rainfall over South Africa and Namibia / western Botswana was first recalibrated statistically to regional level.

A number of ensemble combining algorithms exists. The most simple of these is the unweighted combination of ensembles from different models (Graham et al. 2000, Mason and Mimmack 2002), and is also the one used here. Combining forecasts this way improves on skill levels of individual model forecasts for southern African summer rainfall (Figure 5.2.2). The improvements over the individual ensemble systems are attributed to the collective information of all the models used in the mean of probabilities algorithm. Combining algorithms using Bayesian methods (Rajagopalan et al. 2002) may further improve the forecasts.

Such a multi-model system is in the process of being developed through a four member consortium consisting of the South African Weather Service, the International Research Institute for Climate Prediction, the University of Cape Town, and the University of Pretoria. Four GCM forecasts downscaled or recalibrated to station and regional level will be optimally combined to produce a probabilistic categorized (above-normal, near-normal and below-normal) seasonal forecast for South Africa. Some of the GCMs run at local centres will be forced with prescribed sea-surface temperature (SST) anomalies, each producing a minimum of 10 ensemble members. The prescribed SST anomaly fields consist of two sets of which the first set is global SSTs simultaneously observed with the target period. The skill levels associated with this type of simulation may be considered as an upper boundary of the skill of the GCM. The second SST forcing fields are sets of persisted SST anomalies. The skill assessment of the multi-model approach will only be conducted at lead-times not exceeding a few months. At these lead-times, persisted SST anomalies are a strong competitor for other more elaborate SST forecast models (e.g. Landman and Mason 2001). As a result of having these two distinct set of SST forcing fields, an upper skill limit as well as an operational forecast skill limit of the GCMs can be established. Ensemble members will be generated using established techniques such as the lagged average forecasting technique of Hoffman and Kalnay (1983).

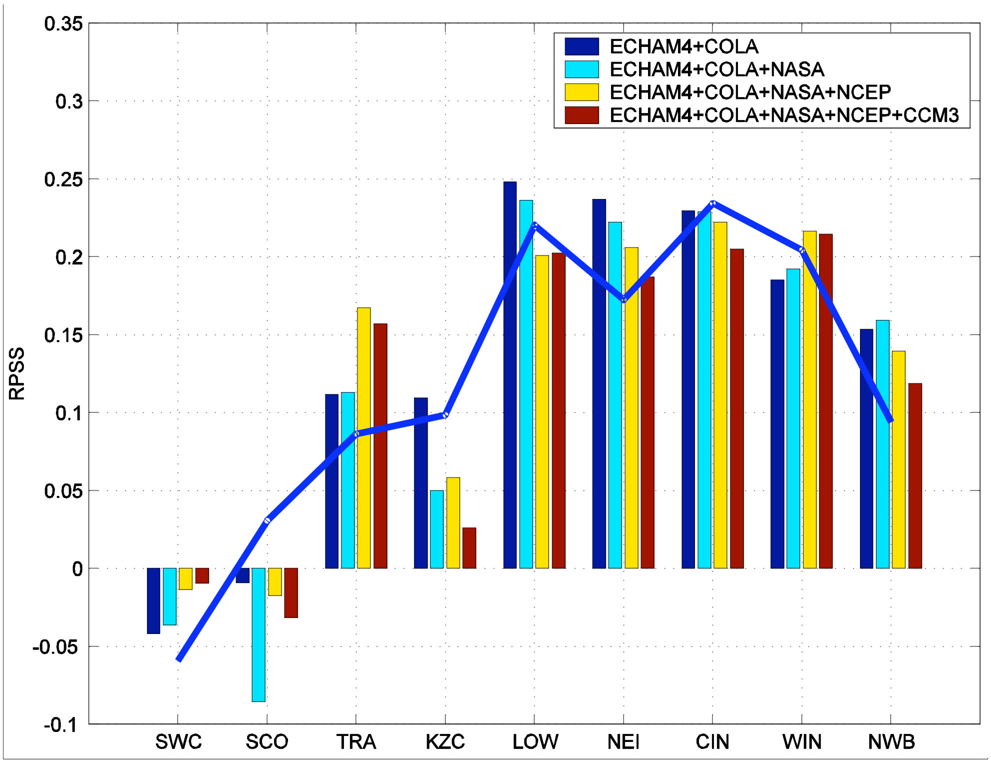


Fig. 5.2.2. RPSS of the 33-year cross-validated period from 1965/66 to 1997/98. The bars are RPSS values for different model combinations, and the solid blue line is the RPSS values of the best model (ECHAM4.5-MOS) The target season is DJF (for region definitions, see Fig.5.2.1).

An empirical downscaling method that is currently being used operationally by the South African Weather Service uses a combination of MOS and perfect prognosis (Wilks 1995). MOS equations are developed using 24-member ensemble ECHAM4.5 GCM simulation rainfall data (the ensemble was forced with simultaneous observed SSTs for each of the 3-month seasons considered) and then 24-member ensemble rainfall real-time forecast fields at different lead-times from the same GCM are subsequently used in these MOS equations to predict rainfall for a 1028 stations. It is therefore assumed that the skill with which the GCM can produce forecast at lead-times is as good as skill obtained from simulation data, reminiscent to the assumption of a perfect prognosis approach where “perfect” forecasts are assumed. For example, the ECHAM4.5 predictions are generated for DJF 2003/04, JFM 2004 and FMA 2004, by persisting observed November 2003 SST anomalies on top of the monthly varying annual cycle of climatological SSTs. At initialization, ensemble members differ from each other by one model day integration for both the simulation and forecast data. Figure 5.2.3 shows an example of a forecast generated by this MOS-perfect prognosis system issued in early December 2003 for the DJF 2003/04 season.

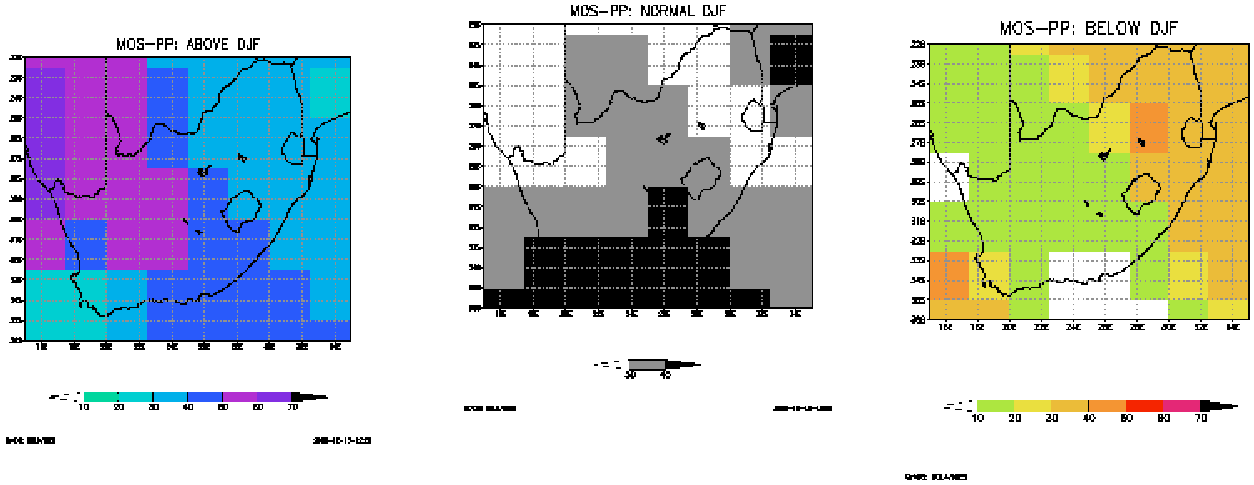


Fig. 5.2.3. MOS-perfect prognosis forecasts for DJF 2003/04.
The forecast is for three categories and presented as probabilities.

The MOS-perfect prognosis issued in early December for the 2003/4 DJF season (Fig. 5.2.3) suggests that over the northeast of South Africa the probability of an above, near and below average rainfall season are about 20-30 %, 20-30 % and 40-50% respectively. By comparison, the observed rainfall for South Africa (Fig. 5.2.4) shows most of this part of the country received below or near average rainfall.

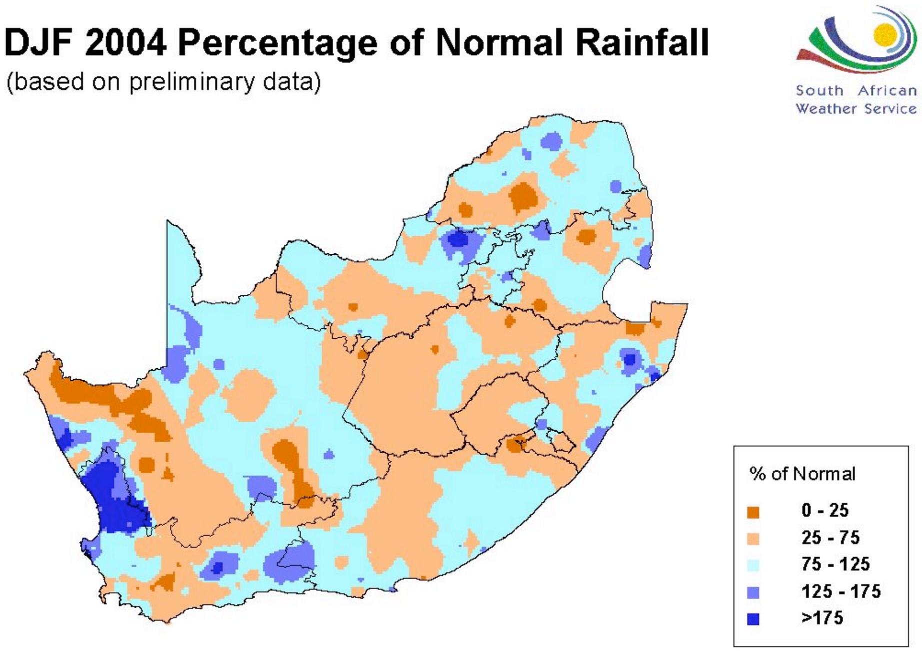


Fig. 5.2.4: Observed rainfall anomalies over South Africa during DJF 2003/4

Applications of seasonal forecasting to user groups, their needs and feedback

The SAWS compiles a consensus seasonal forecast for three rainfall and temperature categories every month using model output from the SAWS, the Universities of Cape Town and Pretoria, the IRI and ECMWF. Figure 6.1 is an example of such a forecast.

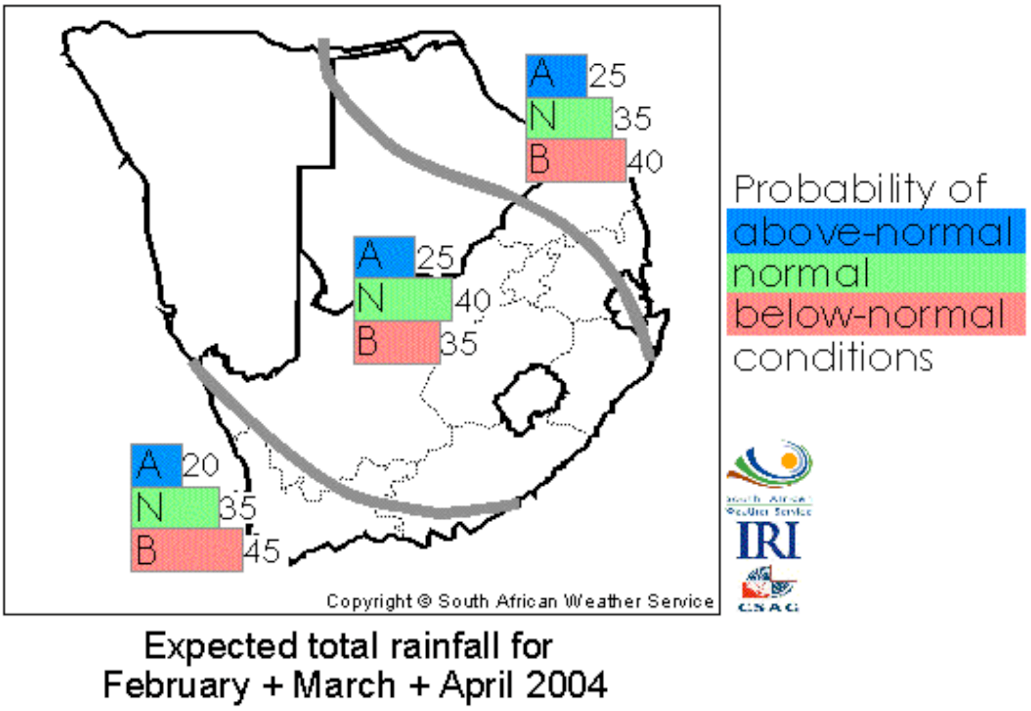


Fig. 6.1. An example of a forecast produced at the SAWS. Forecast maps like this one are also produced for seasonal surface temperatures.

These forecast maps are available at www.weathersa.co.za, but are also presented every month on an agricultural television programme AgriTV. The presented forecast maps are put on the AgriTV website (www.agritv.co.za) immediately following the programme on which they were presented. Forecasts and a short summary are also sent every month to the agricultural magazine Landbouweekblad for publication. Forecasts are also regularly presented to the

National Department of Agriculture and included in their guidance to the agricultural sector via extension officers and various publications.

Elsewhere in southern Africa, seasonal forecasting tends to be done via statistical regression models that relate global SST anomalies (particularly, those in the tropical Pacific) to rainfall averaged over representative regions of individual countries. The latter are often defined using clustering or PCA techniques. A consensus seasonal forecast for large regions of southern Africa is produced at Southern African Climate Outlook Forum (SARCOF) meetings organised by the Drought Monitoring Centre – Harare. The most important meeting, attended by both operational meteorologists, researchers and representatives from various user groups (agriculture, health, water resources), tends to be scheduled in September, prior to the start of the main summer rainy season, and to be located in different southern African centres each year. Previously, almost all the information that was used to produce the consensus forecast was based on regression models; however, in recent times more attention has been paid to the output from AGCMs forced with forecast SSTs.

Given the highly variable rainfall over southern Africa and the need to carefully manage water resources, better forecasting of streamflow and dam levels is a high priority. Since atmospheric GCMs do not explicitly simulate streamflow, work at the South African Weather Service has investigated statistical linkages between GCM-simulated fields (ECHAM3.6) and South African streamflow. Note that the GCM has a much coarser resolution than the distances between the inlets of the dams. Thus recalibrating the GCM output to streamflow is truly a downscaling exercise. The recalibration procedure using hindcast data for forecasting rainfall is next applied to the streamflow at the inlets of six dams in the Vaal and upper Tugela river catchments, which lie within the north-eastern interior region of South Africa. Only the cross-validated forecasts are presented for the period 1971/72 to 1994/95. The naturalized streamflow data used in this paper are not available for the period after early 1995. The same predictor set, the hindcast mode 850 hPa geopotential height field that is used to recalibrate to seasonal rainfall anomalies is used by Landman and Goddard (2002), because streamflow is directly affected by precipitation and its variability should therefore similarly be affected by the variability of the 850 hPa geopotential heights.

Sensitivity runs using cross-validation are performed to obtain the optimal streamflow downscaling model. Using three predictand and five predictor modes in the model produced the highest averaged cross-validation correlation value, with each set of modes explaining more than 90% of the respective total variances. Additional factors affecting streamflow are evaporation and changes in soil moisture, as well as non-meteorological factors such as vegetation cover and the soil surface characteristics of catchments. The association between rainfall and streamflow is therefore complex, and also depends on factors that are not directly related to atmospheric variability. However, none of these factors are explicitly simulated by the atmospheric GCM and thus can not be incorporated into the downscaling process described in this paper. This downscaling model, however, can at least set a baseline against which other more complex downscaling processes can be compared.

The main purpose of this section is to assess if the proposed MOS can be of some value as an operational applications forecast procedure. Cross-validation is performed on each of the five hindcast (prescribed SSTs are obtained by persisting November SST anomalies through the forecast period of DJF) ensemble members and the average of the forecasts is obtained. The correlation values between the ensemble mean MOS and the observed streamflow vary between 0.54 for the Vaal Dam and 0.65 for the Johan Neser Dam (Figure 6.2). A high association is found between the observed streamflow and the observed rainfall of the region that contains the catchments of the dams. The high association is a manifestation of the effect rainfall has on the streamflow at the inlets of these dams, and indicates that the 850 hPa geopoetential height field that contributed to the rainfall prediction skill is a reasonable choice as predictor for streamflow also. Streamflow forecast skill should improve further if other non-atmospheric variables were allowed to participate in the recalibration process. As is the case in the rainfall recalibration, improved streamflow forecasts also occurred after the 1989/90 season.

Based on these results, the South African Weather Service plans to start operational streamflow forecasts in time for the 2004/5 summer rainfall season.

Maize is the staple food for much of southern Africa's population and the onset of sufficient rains for planting has been identified as a seasonal characteristic about which most subsistence farmers would like forecast information. Recent work on the onset of the maize growing season (Tadross et al., *submitted Journal of Climate*) has demonstrated that early onset occurs over South Africa and Zimbabwe when positive daily 500 hPa eddy geopotenial heights are present to the south and east of South Africa. These positive anomalies are associated with increased tendency of synoptic ridging along the south and east coasts of South Africa or the formation of blocking highs in this region which help to increase the low level transport of moist maritime tropical air over eastern South Africa, southern Mozambique and Zimbabwe. The presence of similar high pressure systems during August is also linked to increased rainfall over Madagascar, likely a consequence of a strengthening of the South Indian anticyclone. This difference in pre-season rainfall could prove useful for prediction and may indicate an influx of moisture to the continent before onset. It remains to be seen whether it is this influx of pre-season moisture or the circulation at the time that creates the conditions for early onset.

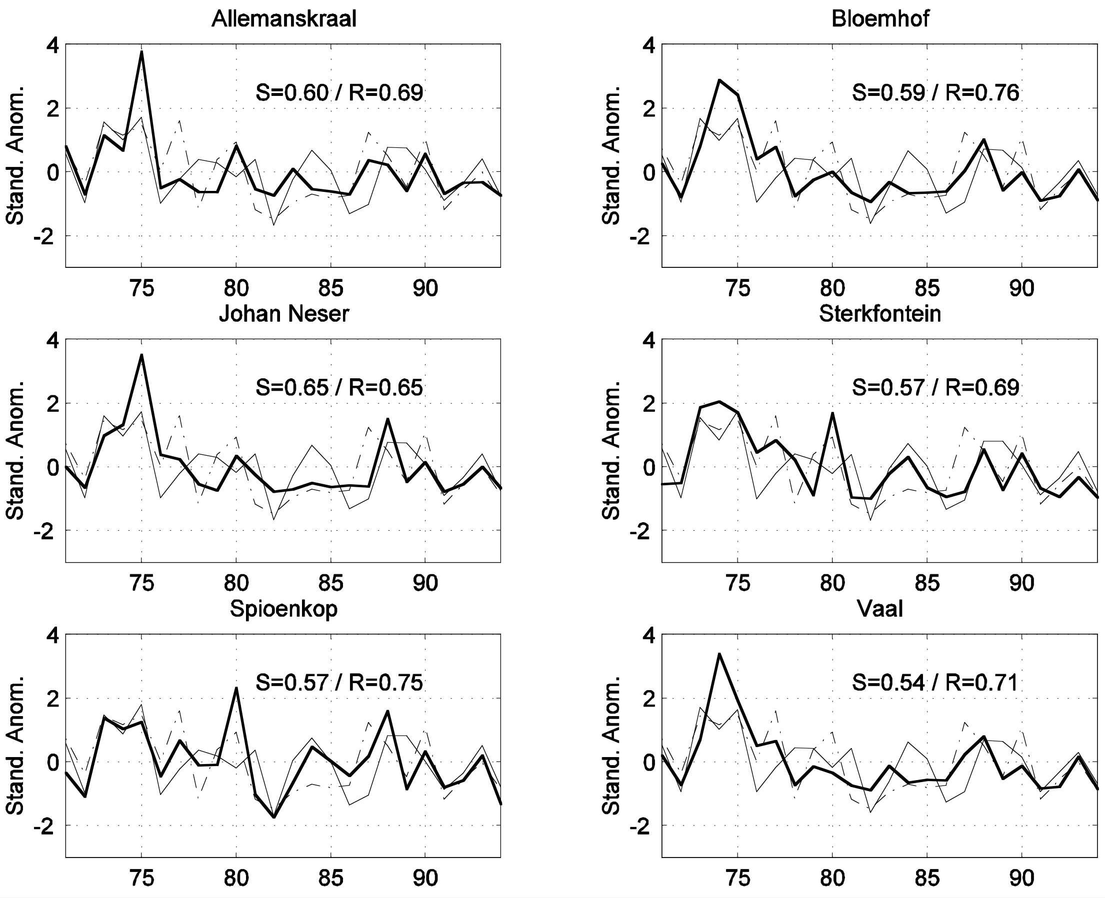


Figure 6.2. Cross-validated MOS normalized DJF streamflow anomalies (thin line) versus the observed DJF normalized streamflow anomalies (thick line) for each of six dams of the Vaal and upper Tugela river catchments of South Africa. Normalized DJF rainfall anomalies (dashed-dotted line) of the northeastern interior are also shown. The correlations between the predicted and observed streamflow anomalies (S) and the observed streamflow and rainfall anomalies (R) are shown in the top right of each dam.

Since 1979, onset over South Africa and Zimbabwe has been occurring later in the season (Tadross et al., 2003) and this is confirmed in interviews with farmers in southern Zambia (P. Mushove, pers comm.) and Limpopo province, South Africa Over South Africa there is evidence of decadal variability, with onset on average being earlier during the late 1950's and late 1970's. Although not a test of predictability, by relating onset to synoptic features it raises the possibility of prediction, though as discussed below GCMs may have difficulties simulating some of these synoptic features.

Tourism is a major contributor to the economies of many southern African countries and national park authorities are aware of the need to better understand the impacts of extreme weather and climate events and to make use of available forecasts. For example, the southern part of the Kruger National Park (KNP) for example suffered significant flooding in February 2000 along with other parts of northeastern South Africa and southern Mozambique. Consultations between the South African Weather Service and parks authorities suggests that early warnings of extreme seasons are likely to be more beneficial to smaller parks which have less flexibility and may be more sensitive; KNP has a basic policy of minimum interference. The type of rainfall season determines the severity of the fire season during the following winter and whether veld burning is likely to be needed. KNP may want a tailored forecast system in place in anticipation of a big natural die-off of wildlife caused by flooding or severe drought. Fig. 6.3 shows the drought conditions over the KNP and other parts of southern Africa during the most recent El Niño for the JFM 2003 season and the forecast issued in November 2002. Dry conditions were experienced over much of South Africa, Namibia and Botswana and were particularly marked over the KNP and neighbouring areas in northeastern South Africa. The forecast was skillful in predicting the more intensely dry conditions in this part of South Africa and that the central part of the country was less severely impacted by this El Niño.

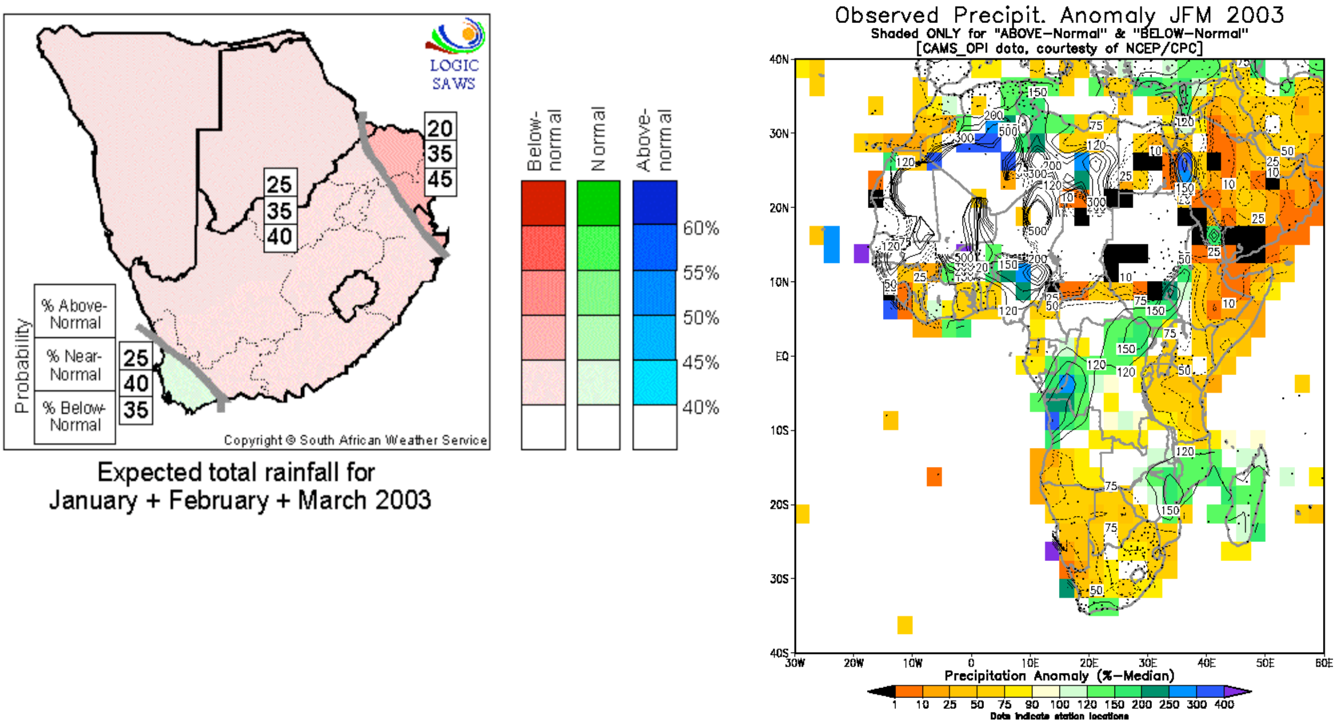


Fig. 6.3 Observed rainfall anomalies for JFM 2003 and SAWS forecast issued in November 2002.

Challenges of improving seasonal forecasting, observing system needs etc

One of the major challenges within southern Africa, which is a region characterised by low incomes and high rainfall variability and whose populations rely on rain-fed subsistence farming, is to provide forecasts that are useful for agriculture. This a challenging prospect as it will involve predicting intra-seasonal rainfall characteristics such as onset, cessation and dry spell frequency. Further research is required but by relating these features to synoptic conditions. the possibility of increasing forecasting skill may be increased. Given the importance of both the zonal (a possible control of onset) and meridional changes in the westerly circulation for rainfall over southern Africa it is logical to enquire how predictable these variations are. As part of the aforementioned AIACC project (http://www.csag.uct.ac.za/aiacc), work at UCT is currently underway to assess how well GCMs represent the climate and westerly circulation in the southern African region. This is important to quantify as they are one of the primary tools used for seasonal forecasting and climate prediction. Simulation of the westerly flow also impacts on any RCMs or statistical downscaling that uses their data to provide downscaled climate change scenarios or seasonal forecasts. Initial results suggest that individual GCMs vary widely in their representation of the westerly flow e.g. it is known that HadAM3 has a bias for stronger than observed westerlies the core of which is placed too far south (Pope et al., 2000). However, compared to ECHAM and CSIRO, HadaM3 appears to better represent the position of troughs and ridges embedded in the mean flow. The CSIRO model suffers because of its low resolution, simulating weaker anomalies and ECHAM is biased towards simulating a higher frequency of low pressure anomalies to the east of the subcontinent.

In terms of its ability to represent the interannual variability of winter rainfall and circulation over southern South Africa, when forced with Reynolds SST, HadAM3 was found to get the sign and tendency correct during the 1990-1999 period studied by Reason *et al.* (2003) but to significantly underestimate the size of the anomaly. This finding suggests that there may be some skill in HadAM3 forecasting whether a winter season might expect above or below average rainfall, given adequate SST forcing, but not in the magnitude of the anomalies. It therefore raises the question as to which is more important for prediction, the zonal or the asymmetric component of the westerly flow and should forecasters be selective about which GCM to use depending on what seasonal characteristic they are trying to forecast ? As an example, it has already been mentioned that HadAM3 better simulates the asymmetric component of the zonal flow which may be important for onset. However during the JFM season HadAM3 has a notable cyclonic bias in the tropical Indian Ocean which disrupts the flow of moisture over the continent. ECHAM appears to better simulate the regional climate at this time and may prove a more useful tool for forecasting rainfall during this season.

Of major concern within the region is the severe decline in atmospheric observations, both of surface parameters such as rainfall, and soundings. This problem is apparent in the rainfall records for most of the continent and can be seen in the recent decline in the number of reporting stations communicating over the General Telecommunications System (GTS). Funding for African NMHs is low and even in South Africa where an extremely valuable rainfall dataset was compiled until 1997 by the Computing Centre for Water Research (CCWR), the last few years has seen a dramatic decline in the records available to researchers. Similar trends can be seen in the atmospheric soundings over the continent and this results in the earlier remarked discrepancies between the ERA and NCEP reanalyses. In particular these discrepancies are apparent over Angola, Mozambique and the DRC where civil war and an almost non-existent funding base has severely restricted data collection. The majority of the work presented in this paper relies on access to observations of a sufficient quality. Climate models can only provide one realisation of the climate if there are no data to check them against and statistical downscaling relies on sufficient training data. Hence, future efforts at realising the potential of forecasting in the region ultimately rely on improvement in the current observing system over both Africa itself and the neighbouring oceans. In terms of the latter, the South Atlantic is not well monitored compared to the North Atlantic. Plans to extend the PIRATA moored array in the tropical Atlantic into the tropical South East and South West Atlantic have not come to fruition as yet. Present Argo float coverage is relatively good near 30°S, the AX8 line between South Africa and the US, and the SR2 line between Cape Town and Neumayer base (Antarctica). Large gaps exist in the tropical South West and South East and midlatitude South Atlantic. Surface drifters are released mainly in the subtropical and midlatitude South Atlantic with again large gaps in the tropics and some midlatitude areas. The recent South Atlantic Climate Observing System (SACOS) workshop concluded that better monitoring air/sea fluxes, SST and upper ocean variability in the subtropics and midlatitudes are needed in order to progress towards better understanding of South Atlantic modes and assessing their predictability.

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Seasonal-to-Decadal Predictability and Prediction of North American Climate - The Atlantic Influence.

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Summary

We consider the question of the impact of the Atlantic on North American (NA) seasonal prediction skill and predictability. Basic material is collected from the literature, a review of seasonal forecast procedures in Canada and the US, and some fresh calculations using the NCEP/NCAR Reanalysis data.

The general impression is one of low predictability (due to the Atlantic) for seasonal mean surface temperature and precipitation over NA. Predictability may be slightly better in the Carribean and 'intra-America', even for precipitation. The NAO is widely seen as an agent making the Atlantic influence felt in NA. While the NAO is well established in most months, its prediction skill is not much better than that of 'weather'. We also found year-round evidence for an equatorially displaced version of the NAO (named ED_NAO) carrying a good fraction of the variance.

In general the predictability from the Pacific is thought to dominate over that from the Atlantic sector, which explains the minimal number of reported AMIP runs that explore Atlantic-only impacts. Caveats are noted as to the question of the influence of a single predictor in a non-linear environment with many predictors. Skill of a new 1-tier Coupled Model System at NCEP is reviewed; we find limited skill in mid-latitudes and modest predictability to look forward to.

There are several signs of enthusiasm about using 'trends' (low frequency variations): a) Seasonal forecast tools include persistence of last ten years averaged anomaly (relative to the official 30-yr climatology), b) Hurricane forecasts (high skill!) are based largely on recognizing a global multi-decadal mode (which is similar to an Atlantic trend mode in SST) and c) two recent papers, one empirical and one modeling, giving equal roles to (North) Pacific and Atlantic in 'explaining' variations in drought frequency over NA on a 20 year + time scale.

1. Introduction.

The central theme throughout this white paper is that of the 'Atlantic' as a possible source of predictability or even actual seasonal prediction skill for North America (NA). We take this rather 'restricted' point of view and stay away for the most part from other predictor areas, such as Pacific ENSO (El Niño-Southern Oscillation), even though ENSO could influence the Atlantic and may have delayed indirect effects on NA if the Atlantic, in turn, influences NA. In a non-linear environment it may be a challenge to isolate the influence of a single factor like the Atlantic (or any other ocean, or other predictors), without considering all at once. But such is our task. This paper also has a practical point of view as it was written by authors who are involved in preparing real time seasonal forecasts.

The question about the influence of the Atlantic on seasonal predictability over NA, when posed to practitioner-colleagues on that continent, leads to a few answers but only hesitantly so. The pre-occupation with ENSO and the Pacific has perhaps taken place at the expense of deep thoughts given to the role of the Atlantic or even the Indian Ocean. This may be because the true predictability due to the Atlantic, however one defines 'the Atlantic', is low, or we, rightly or wrongly, believe it is low, or because insights are underdeveloped. One also has to admit that the role of mid-latitude oceans in general is not well settled. So given the tame character of the tropical Atlantic (compared to the tropical Pacific), questions about the Atlantic are about as difficult to answer as influences due to the extra-tropical Pacific. But since the Atlantic is downstream from NA, forecasters and researchers in NA may still favor the North Pacific over the Atlantic as a source of influence and skill. Indeed the extra-tropical Pacific has been studied a lot more than the Atlantic. In the Caribbean and Central America study of the Atlantic is less neglected, although even here the Pacific and ENSO are thought to be among the leading predictors.

Some possible answers to the question of Atlantic influence on NA climate are listed below. The first three are mainly variations on the NAO theme. The 4th is about local effects and the 5th concerns hurricanes.

a) The NAO plays a clear role in US weather and climate, perhaps as far west as the Rocky Mountains. Clearly, if one defines the Atlantic as just the influence of the NAO, we have a large body of literature. What is behind the predictability of the NAO? What role does the Atlantic Ocean play?. What role do other oceans and continental land surface boundary conditions play? What do lead - lag relations between atmosphere and ocean imply?. There is plenty of literature here.
b) In spite of being a leading mode, the NAO is actually not very predictable as an initial value problem. Already by week 2, little is known for certain about the NAO. Hence the NAO often gets mention in the negative as a 'wildcard' for the seasonal forecast. For instance one might read: "Given that next winter is a Pacific 'warm event', forecasters expect the South East of the US will be cold, unless the NAO is in its positive phase. Is it understood we do not know the phase of the NAO that far ahead of time? Is it an acceptable excuse?
c) Both Canada and the US have had some success using a tool called OCN, (Optimal Climate Normals) in forecasting seasonal anomalies. OCN is essentially persistence of the average of the anomalies (relative to a 30-yr climatology) of the last 10 years. Other tools in use in Canada and the US also attempt to harvest this trend signal. So where does this low-frequency variation come from?? And why 10 years as the optimal average? Many have referred to the low-frequency variations in the NAO as the source of skill in OCN, certainly along the east coast of NA. To be sure: not only the NAO, also the PNA and global change get mention, but the NAO gets prominent mention here due to its variations over the last 30 years suggesting a trend and a possible connection to the global mean temperature as well as the stratosphere.
d) Local effects. Along the west coasts of continents, the role of (perhaps fairly local) SSTA is to enhance predictability of temperature. How about the east coasts?
e) Atlantic Hurricanes that threaten NA originate, as tropical cyclones, in the (sub)tropical Atlantic, so a clear Atlantic 'influence' of a very different nature is very real to NA. The number of hurricanes per season (June through November, but mainly ASO) or other 'net activity' measures display remarkable interannual variability including strong interdecadal variability. The main causes of these variations are several, and they are not all of Atlantic origin. Leaving the ENSO influence aside, the Atlantic appears to play a role through interdecadal modulation. Predictability of statistics such as total number of storms per season in the Atlantic basin, appears to be high.
f) If Atlantic Hurricanes need consideration we should also mention east coast storms, especially in winter.

The paper is laid out as follows. In section 2 we review some of the literature and present a few basics about the NAO. In sections 3 we review seasonal prediction tools used in Canada and the US for their seasonal forecasts, and the extent to which any of these have anything to do with the Atlantic. In section 4 and 5 we review co-variability between the Atlantic and NA, as revealed in data, both simultaneously and at lead. For this we use global data sets 1948-present (NCEP-NCAR Reanalyses, monthly means or longer averages) to do, specifically for this white paper, a number of fresh calculations. This includes comments on seasonality and an attempt to distinguish inter-annual from (inter) decadal time scales. Section 6 is devoted to Atlantic Hurricanes. In section 7 we present a few results from the latest global coupled model at NCEP. We end with conclusions.

2. Review of some literature.

Because of arbitrary boundaries in the subject matter it is difficult to organize the literature on the influence of the Atlantic on NA. Much of the relevant literature is about more than just the Atlantic. And very few studies deal specifically with the impact of the Atlantic on NA. (We try to compensate for the latter in section 4 and 5 with some new calculations.) We here present five sections on a) NAO, b) SST and AMIP runs c) (sub)tropical rainfall, d) East coast storms and e) local effects. We do not separate empirical and model studies, just note here that empirical studies (Enfield 1996 and Giannini et al. 2000, for example) correctly identify and struggle with the relative role of the Atlantic and Pacific in explaining interannual variations over NA. In dynamical models, the problem is posed differently but the non-linearity among signals (and noise) is a noted and infamous problem in disentangling the mid-latitude response to say tropical SST from coupled atmosphere-ocean modes in the mid-latitude itself (Lau 1997; Lau and Nath 2001; Kushnir et al 2002; Alexander et al 2002). This topic remains under review.

2a) NAO.

If one equates the Atlantic influence to just the NAO (quite a jump) there are plenty of studies, although not necessarily focused on the influence of the NAO on NA. Higgins et al(2000) discuss all 'dominant' factors influencing US weather and climate, and sure enough NAO is one of them. We leave aside the short term weather aspects of the NAO (and all studies on blocking, zonal flow etc) except by noting that the NAO is very hard to predict, skill being low after 6 days, like weather itself. Long term trends in the NAO have received plenty of attention (Hurrell 1995; Gillet et al 2003), because they may explain much of the warming in Europe (and the United States) and the cooling in North Eastern Canada during the last 30 years (Shabbar et al 1997). These studies tend to be naturally biased towards winter. Trends, due to the NAO or otherwise, are of interest in seasonal prediction (Huang et al 1996) because the anomaly averaged over the last K years is a primary forecast tool. The attribution of the NAO trends to a specific cause is not universally accepted (Wunsch 2000), on the ground that an apparent trend may be produced by any red noise process over a restricted portion of its record.

Although the NAO is the most important, popular and least disputed teleconnection in the NH, it is not universally accepted, nor is there a strict definition. One never sees the NAO in pure form in reality, not even when the index is extreme, see Fig.1, which shows a 5 day mean height anoamly. There is a tendency in nature to break the NAO into western and eastern Atlantic patterns (Wallace and Gutzler 1981; Shabbar et al 1997). Since the influence on NA is the issue that distinction may be relevant. Furthermore, redefining NAO into AO creates a further complication (Thompson et al 2002). Some lessons can be learned by studying a detailed seasonality of the 1st empirical 'mode', see section 4 - a pure NAO across the entire ocean basin may occur in some months, but modes with emphasis in the west and east Atlantic in other (Barnston and Livezey 1987). The 'NAO' is definitely seasonal, i.e. the same stations cannot be used optimally for defining an NAO-index in all seasons (Portis et al 2001). To the extent that the NAO is related to the uncertainty in latitude for the Atlantic jet to settle in on, we must expect alternative positions, and indeed, in section 4, we report on an Equatorially Displaced NAO (ED_NAO).

To make the interpretation more difficult, Hoerling et al(2001) report on tropical impacts from both the Indian and Pacific Oceans on the NAO, especially on its trends. We should also mention stratospheric impacts on the NAO, or perhaps more specifically the Northern Hemisphere 'annular mode'(Thompson et al 2002) which manifests itself very much like the NAO in the troposphere. Because trends are more dominant in the stratosphere than the troposphere this connection may have forecast implications or give a physical basis to existing tools such as OCN (Huang et al 1996). Another NAO modification via the stratosphere-troposphere connection may relate to stratospheric QBO and stratospheric warmings (Thompson et al 2002).

2b) SST and AMIP

If one equates the Atlantic to the influence of the oceanic lower boundary condition in that sector, there are some (not many) GCM-modeling studies on the impact of prescribed SST on the seasonal atmosphere (sometimes reduced to the NAO), see Rodwell(2003) for a nice review. (Such studies have a bias towards winter and away from NA.) There are many drawbacks to prescribed SST (often ‘AMIP’ runs), see list below at the end of section 2b, yet such runs have an appealing logic. A For instance one can make multiyear GCM runs with globally varying observed SST (annual cycle plus anomalies) such that all oceans may provide a signal to the atmosphere. Observed SST can be looked upon as an upper limit perfect ocean, although that view is debatable. Additionally runs can be made in which one ocean (or part of it) is disabled, meaning that SST is just a climatological annual cycle only (no anomalies) in the disabled ocean basin. The difference should tell us about the impact of the SST anomalies in the disabled area. The assumption is that prescribed SSTA adds to the atmospheric variance, so if one ocean is disabled the decrease of atmospheric variance tells how much this ocean contributes. One can alternatively compare GCM runs with global climatological SST to runs in which one ocean basin has been enabled. The analysis of variance (ANOVA) in combination with AMIP runs makes logical sense and leads to a model based definition of Potential Predictability (PP). This technique has been widely used to study ENSO in ‘Pacific only’ versus SST in all oceans (Lau and Nath 1994; Hoerling and Kumar 2002), or to study tropical oceans impacts vs global SST.

We found few AMIP runs in which the role of the Atlantic is the focus, and especially its role in predictability over NA. The experiment that is tailored closest to our requirement was made by Conil(2003a;b) who used the LMD model (version 3.3) for a 1950-1994 seventeen member AMIP run with global SST and sea-ice (GLOBAL). This control run was compared to nine runs in which the Atlantic (north of 14°N) was disabled (NOATL), and nine runs in which only the Atlantic (ATL) had realistic SST and sea-ice anomalies. Table 1 describes the standard deviation of seasonal Z500 over a Pacific North American sector (Conil 2003a; his Table 3.5).

	ATL	NOATL	GLOBAL
Total variance	55.7	59.9	63.0
Internal variance	54.8	50.3	55.4
External variance	9.7	32.6	30.1
Pot.Pred (PP) [%]	2.4	29.4	22.7

Table 1: Standard deviation of seasonal mean Z500 over the PNA area in gpm for three multiple membered AMIP runs. The SST forced variance was calculated by Conil as the variance of the ensemble means corrected for the spill-over of internal variance. The PP is defined as SST forced variance divided by total variance and given in percent.

The area, designated ‘PNA’ by Conil, used for the variance calculations is 145E to 80W and 20 to 80N, which is North America plus much of the Pacific. The influence of the Atlantic on this PNA area is extremely weak, if not absent or negative. The best Potential Preditability in DJF for the PNA area is actually obtained when we disable the Atlantic, a pathetic result. This could in part be a flaw of the ANOVA technique that cannot account for destructive interference of signals, because it looks upon variance (the square of the signal) as additive. But it certainly does not point to the Atlantic as a major source of predictability over NA. [Conil’s results for the North Atlantic and Europe show modest predictability as do results from Robertson et al (2000), who (based on single runs over 30 years) reports a large increase in 500mb height variance due to prescription of realistic SST in the Atlantic, some or all of this impact coming from the tropical and, amazingly, the southern Atlantic.]

AMIP runs and ANOVA have the following problems: 1) We do not know SST perfectly ahead of time. 2) Variance is not (necessarily) additive when physics is non-linear. 3) Prescribing SST is cutting the physics of atmosphere-ocean interaction. AMIP runs are known to have bad air-sea fluxes over many parts of the global oceans. 4) In view of 2) one may question AMIP runs that do not include proper land-surface treatment. That is, we may never know the impact of oceans in a non-linear system until we can model the land properly (and vice versa). 5) Results are no better than the atmospheric model used. The LMD model used by Conil (2003a) had 4X5degree resolution. 6) Because of chaos, one needs (very) large ensembles. Studies like Robertson et al(2000) have just two runs.

2c. (Sub)tropical rainfall.

Seasonal rainfall variation across 'inter' and tropical America (50S-50N or less poleward) appear to relate to Pacific SST with an important secondary Atlantic influence (Enfield 1996; Moron et al 2001; Giannini et al 2001). The Atlantic SST is the primary influence during the early season (MJJ) on precipitation in the Caribbean (Taylor et al 2002; Enfield and Alfaro 1999), but during the height of the hurricane season the Pacific takes over (see section 6). Enfield et al (2001) report on a trend in Atlantic SST, now called Atlantic Multi-decadal Oscillation (AMO), which relates to modification of mainly summer precipitation over southern NA. A similar mode is used in hurricane prediction (section 6). Giannini et al(2001) appear to have a different view on this as they report NAO trends to conspire with ENSO so as to cause trends in the Carribean precipitation. The mode now called AMO was described much earlier in Kushnir(1994).

2d) East coast storms.

East coast storms in NA are impressive and a potential Atlantic influence suggests itself. Storms do shape the seasonal precipitation totals, but are seasonal totals over land related to predictable Atlantic inter-annual variation?. Usually 'weather' is looked upon largely as the noise component in 'potential predictability' as defined empirically by Madden(1976). Hartley and Keables(1998) quote western Atlantic SST as a factor in high snowfall events in New England, but secondary to the more obvious NAO and storm tracks.

2e) Local effects.

Along the west coasts of continents, the role of (perhaps fairly local) SSTA is to enhance predictability and persistence of surface air temperature anomalies along the coast and inland over an e-folding distance of 100km (depending on orography this could be more/less), Van den Dool and Nap(1985). Judging from a lack of literature, such effects do not occur, at least not to the same extent, along the east coasts. (Only a few islands have strong air temperature persistence.) This is because the prevailing winds are from the west. So the Atlantic SST does not contribute clearly to local effects and enhanced seasonal prediction skill along the east coast of NA, leaving an occasional sea-breeze event in Boston aside. Even the Gulf of Mexico appears to have little influence through enhanced air temperature persistence (Gulf is too shallow).

3. Review of seasonal forecast procedures

For a review of prediction methods and tools used in Canada and the US for their seasonal forecasts see separate paper in same workshop: Van den Dool(2004)

4. Co-variability of Atlantic and NA - diagnostic relations.

In section 4 and 5 we present some new calculations regarding the influence of the Atlantic on NA. (This was done because while the literature is vast, it does not sufficiently focus on the question of the impact of the Atlantic on NA.) The areal extent of the domains are as follows: a) Atlantic SST: all ocean points north of the equator, between longitudes 100W and 60E, with the exclusion of Pacific points between 100W - 75W, and Eq to 20N, b) Atlantic + NA Atmosphere: all gridpoints north of equator between longitudes 130W and 60E and c) NA surface: all land points north of 10N between 170W and 45W, with the exclusion of Hawaii and Greenland. We keep the Atlantic atmosphere large enough so it could contain the NAO. The data used is the NCEP/NCAR Reanalysis 1948-2003 (Kistler et al 2001), except for temperature in section 4 which was taken from the CAMS data set maintained at CPC.

In this section we present first a modal uni-variate analysis of Z500 across the combined Atlantic and NA domain. This discussion is independent of what we may want to forecast over NA. The modes, obtained by 'rotated' PCA (Barnston and Livezey 1987; Lau and Nath 1990; Peng et al 2000) on seasonal mean Z500 over 1949-2003, have been organized into one plot so as to show the mode resembling the NAO the most in the same polarity for all 4 seasons, see Fig.2. Note a problem with exact definitions. The 2^{nd} author ran his rotated EOFs (over certain years, domain...), and the pattern that looks the most like NAO (a judgement requiring a preconceived notion) is declared to be the NAO. In most seasons that is the 1st mode. With the exception of summer it is close to unambiguous which mode is the NAO. Nevertheless the 'NAO' is seasonal, an observed fact that is somewhat violated when data at fixed stations are used to form time series of an NAO index.

In all seasons we also find a mode we hereby name 'equatorially displaced NAO' (ED-NAO), see Fig.3. In summer this mode explains more variance than the NAO itself. Although the preferred anomalous jet runs from Newfoundland to Scotland there are clearly alternative latitudes, and ED_NAO represents a nodal line running from the Carolinas to the Iberian Penninsula. Physically there may well be a continuum of latitudinal positions but in terms of explained variance (EV) we find only two dominant latitudes. The ED-NAO appears to look like the 'East Atlantic Pattern' reported as mode 6, 3, 8 and 4 in November through February in Barnston and Livezey(1987). With the addition of more data since 1987, the ED_NAO now seems more important and year-round (and not particularly 'east' in the Atlantic).

All calculations were repeated for data that have frequencies lower than 1 cycle per ten years removed. Results for high pass filtered data for periods less than 10 years (10-20% less variance than total) are more or less the same as for the raw data.

From all plots collectively we see a considerable influence of the NAO on NA as far as circulation (Z500) is concerned. This is also true for surface conditions. Correlations between the NAO and ED-NAO time series and surface air temperature (T2m) over NA show noteworthy values in most seasons, see Fig.4 for the NAO, and these correlations are not necessarily restricted to the eastern half of NA. Similar calculations for (ED-)NAO index versus NA precipitation show only small and scattered correlations and are probably not significant (not shown).

We redid the EOF analysis on monthly mean data for all 12 months for a more complete sense of the annual variation. A break up of NAO into East and West Atlantic pattern, suggests itself in some months like January, while an ocean spanning NAO can be seen in say December and February.

A simultaneous CCA between Atlantic SST and Z500 in DJF reveals the somewhat famous tripole SST pattern to be associated with the NAO. But as with EOF on Z500 alone, two versions show up (not shown), the 2^{nd} associated with ED-NAO.

5. Co-variability of Atlantic and NA - predictive aspects.

(For the definition of the domains and the data sets see the first paragraph of section 4.) The EOF type analysis in section 4 does not address cause and effect, only simultaneous relationships. We here move to time lagged relations, which are, at the very least, suggestive of cause and effect. To this end we employ the CCA software used at CPC (Barnston 1994) and elsewhere (Johansson et al 1998) for both research and for producing operational forecasts. This particular version of CCA is very close to maximizing the covariance between two data sets via singular vector decomposition (SVD; Bretherton et al 1992; Lau and Nath 1994). The number of predictor/predictand maps is huge (too large for presentation). This is in part because it takes order 5 canonical modes to capture most of the covariance between the predictor and predictand data sets, and because there are 4 predictors seasons. Moreover there are several predictors and we want to cover the annual cycle. Hence, in order to simplify matters we collapse the four predictor seasons into one and consider only the one month lead time (an example of a 1 month lead forecast: predict DJF T2m over NA from ASO SST in the Atlantic). Still this leaves about 20 combined predictor/predictand maps to depict the four main season's temperature predictions due to a single predictor (for which we pick SST). For added realism and honesty, when quoting skill levels of the CCA, a full package of cross-validation was used.

Fig. 5 shows the first CCA mode between ASO SST and DJF T2m over NA. Zonal bands of warm Atlantic near 20N and 55N, with cold near 40N in the west Atlantic in ASO appear associated with warmth in Southwest US and NE Canada, as well as cold in central America and Alaska in the following DJF. The time series (blue for SST; red for T2m) expresses both interannual and interdecadal variations but the latter dominates. The R value in the graph refers to the correlation between the red and blue time series. The SST pattern of mode#1 is not the pattern one gets when the ocean is forced by an atmosphere in pure NAO state, but rather looks like the 'horseshoe' pattern discussed by Czaja and Frankignoul (2002). (Our CCA does produce the standard tri-pole SST and NAO for simultaneous SST and height fields, in agreement with Czaja and Frankignoul(2002)). We will see the horseshoe pattern repeatedly below.

Fig.6 shows the same for all 4 seasons. I.e. the first mode for the predictand T2m in target season DJF, MAM, JJA and SON when coupled to the predictor SST in antecedent ASO, NDJ, FMA, MJJ. All seasons show a large amount of trend in the time series, and an association between a warm Atlantic and a warm SW US and NE Canada. To first order the SST pattern is independent of season, and so are the time series, with a maximum in the 1950's and a minimum around 1990.

Fig.7 is the same as Fig. 6 but now NA seasonal precipitation is the predictand. We are somewhat amazed to find that the 1st mode for predictands T2m (Fig. 6) and precipitation (Fig. 7) are essentially the same in all 4 seasons. The time series and SST patterns are very similar among Figs 6 and 7. It took some coordination of choices of polarity in Figs 5 thru 7 to bring this out.

The quantitative bottom line is one of modest predictive ability due to Atlantic SST, the anomaly correlation (AC in %) for NA T2m being 15.7, 9.0, 20.4, and 20.6 respectively for DJF, MAM, JJA and SON. Although modest, CCA beats persistence in all seasons except spring (AC values are 8.2, 12.0, 7.9 and 13.1 for persistence).

The number of modes retained is 5 (except for DJF when it is 4). This truncation is based on cross validated skill upon the admission of a new mode. Of the (squared) covariance retained by 4-5 modes it takes 2 modes to explain 80%, but as seen from the AC values this may be no more than 5% of the predictand's variance.

Fig. 8 shows forecast skill as a function of lead and target season (all 12) for temperature (on the left) and precipitation (on the right). In this graph we have used all 4 predictor seasons for some added skill. With the Pacific included, not shown, skill would be much higher in seasons 1- 4. But even with the Atlantic alone we have some skill (the authors were not disappointed!), especially in summer and fall for T2m.

We redid all calculations with a 10 year time filter applied to create high and low frequency data. I.e. we prepared one version of CCA that used high frequency data (which accounts for 78-87% of the variance in seasonal mean data) and another that used low frequency data (which accounts for the remaining 13-22% of the variance). In both cases however, we verified the cross-validated forecasts against unfiltered data. The high-frequency CCA has certified zero skill!! Rather stunningly we thus did not find any prediction skill due to interannual variations in Atlantic SST. All skill we reported before is due to trends or interdecadal variation. To some degree this was already clear from Fig. 6 and 7. Additionally one may wonder whether this skill has anything to do with the Atlantic specifically.

6. The Atlantic tropical cyclones and hurricanes and their prediction.

In September 2003, a northwestward bound category 2 hurricane named Isabel made landfall in northeastern North Carolina along the mid Atlantic coast of the US and as the hurricane traversed inland west of Washington D.C., it devastated life and property. Hurricane Isabel was reportedly responsible for a loss of 16 lives and about US $1.7 billion in property damages (NHC: 2003 Atlantic Hurricane Season Summary).

During 1970-99 a total of about 600 fatalities occurred in the contiguous US and its coastal waters associated with tropical storms (Rappaport, 2000). The property damages in 1992 due to a single Hurricane Andrew (category 5) alone, the most expensive hurricane to hit the US, is about 35 billion US (2000) dollars. Hence a forecast, both long lead and short range, of these tropical systems is of great value to coastal population of the United States and the Caribbean.
A typical North Atlantic Hurricane season, which officially runs from June through November, features about 10 tropical storms (TS), 6 hurricanes (H) and 2 major hurricanes (MH). In the short range forecast, about 10-12 % of all Atlantic basin tropical cyclone forecasts issued by the National Hurricane Center (NHC) from 1976 to 2000 are for landfalls along the US coast line. Below we discuss the long-lead forecasts only.

Much of the North Atlantic hurricane activity is due to tropical disturbances that originate in the Main Development Region (MDR, see Fig.9). Seasonal and multi-decadal variations in the Atlantic hurricane activity have been linked to El Niño/Southern Oscillation (ENSO) (Gray 1984a; Bove et al. 1998), an Atlantic Multi decadal Oscillation (AMO) in Sea Surface Temperature (SST, Goldenberg et al. 2001, Vitart and Anderson 2001) and west African monsoon variability (Hastenrath 1976, Landsea and Gray 1992). The long lead seasonal forecasts of the Atlantic hurricane activity, pioneered by Prof. William Gray and his colleagues since 1984 (Gray 1984a,b), plus revisions in Landsea et al. (1994), is based on regression methods. The overriding issue in the forecast is the modulation of the vertical wind shear in the central tropical Atlantic, by factors such as ENSO, the AMO, etc. Some secondary influence of Atlantic SST, the structure of the African Easterly jet etc has also been noted.

The National Oceanic and Atmospheric Administration (NOAA) which began issuing long lead forecasts of the N. Atlantic hurricane activity in 1998, uses an 'Accumulated Cyclone Energy' (ACE) Index (defined as the sum of squares of the estimated 6_hourly maximum sustained wind speed for all named storms while they are at least tropical storm strength) to measure the overall storm/hurricane activity (Bell et al. 2000). There is tremendous interannual and interdecadal variability in the Atlantic hurricane activity as measured by ACE (Fig. 10). Chelliah and Bell (2004) and Bell and Chelliah (2004) identified a tropical multi-decadal mode (TMM) and an interannual mode (ENSO) in all seasons including the August-September-October (ASO) period, the peak Atlantic hurricane season. The spatial and temporal characteristics of the leading interdecadal mode are robust and is independent of whether the seasonal tropical (30N-30S) surface temperature anomalies are used or 200 mb velocity potential anomalies are used as the analysis variable.

While the characteristics of the interannual ENSO mode are well known in literature, the leading TMM is associated with an east-west seesaw in anomalous tropical convection between three key regions, the west African monsoon region, tropical South America and the central equatorial Pacific. Hence the mode accounts for large explained variance not only in the MDR but also in other regions of the globe, thus bringing the global association with the interdecadal variability of the Atlantic Hurricane activity. It is found that the coherent large-scale and regional-scale atmospheric anomalies and levels of activity associated with seasonal hurricane extremes are recovered when the tropical multi-decadal mode and ENSO are in phase. Fig.11 shows the NOAA's forecast and verification of tropical N. Atlantic Hurricane activity from 1998 through 2003. Based on these 6 years very high skill is suggested, much higher than anything we are used to in traditional seasonal prediction. However, the Atlantic itself may not play a big role. The AMO appears to be closely related to the global TMM, which raises some doubt as to whether the AMO is really of Atlantic origin.

7. Results with new NCEP Coupled Forecast System

Recently the new Coupled Forecast System (40 level global ocean, T62L64 atmosphere; 1-tier system; Saha et al 2003; known as CFS) was run in forecast mode on 10 different initial conditions per month for all months during 1981-2003. Each forecast run is 9 months long, so a total of over 2000 years of coupled model integration is available for inspection. The Niño3.4

prediction appear as good as any method we have seen, and certainly better than the previous coupled model.

Using monthly data as basic units, we calculated forecast skill (anomaly correlation) for a) monthly means, b) (10 member) ensemble mean monthly means, and c) ensemble mean seasonal means. And we added d) 'predictability' (of the first (!) kind) by correlating a single member against the mean of nine other members (perfect model assumption). The correlations should normally increase when going from a to d. For brevity we present results for integrations from July. For global tropical SST we have substantial skill, and still higher predictability, see Fig.12, where prediction skill and predictability are shown to decrease only very slowly from August (a) till next March (m). Locally, the highest skill/predictability is found in the Pacific, the Niño3.4 area, while skill in the tropical Atlantic (not shown) is respectable but not nearly as high as the Pacific. In contrast, the extra-tropical North Atlantic shows no skill at all in SST forecasts after month 1 (not shown), but moderate predictability is suggested. In terms of Z500 current skill of the CFS in the North Atlantic (and North Pacific) is small and the potential not much above a 0.3 - 0.4 correlation in the best seasons (J,F), see Fig. 13.

8. Conclusions and recommendations

We have considered the question of the impact of the Atlantic on North American (NA) seasonal prediction skill and predictability. Basic material is collected from the literature, a review of seasonal forecast procedures in Canada and the US, and some fresh calculations using the NCEP/NCAR Reanalysis data.

The general impression is one of low predictability (due to the Atlantic) for seasonal mean surface temperature and precipitation over NA. Predictability may be slightly better in the Carribean and 'intra-America', even for precipitation. The NAO is widely seen as an agent making the Atlantic influence felt in NA, but its prediction skill is not much better than that of 'weather'. We also found year-round evidence for an equatorially displaced version of the NAO (named ED_NAO) carrying a good fraction of the variance.

In general the predictability from the Pacific is thought to dominate over that from the Atlantic sector, which explains the minimal number of reported AMIP runs that explore Atlantic-only impacts. Skill of a new 1-tier Coupled Model System at NCEP is reviewed; we find limited skill in mid-latitudes and modest predictability to look forward to.

How one decides on the influence of the 'Atlantic' on a certain target is not all that clear. In general determining the influence of a single predictor (be it the Atlantic or anything else), in a non-linear system subject to several predictors truly is problematic. The response to predictors interacts, constructively and destructively. So an empirical study of the output of such a system may be beyond linear statistics. The 'easiest' circumstance is when one of the predictors dominates over the others. Isolating the Atlantic in model experiments is equally problematic because application of ANOVA assumes additive variance. Even the prediction skill due to SST of all oceans may be impossible to determine, unless we solve at the same time issues related to all other predictors (global land, stratosphere, atmospheric dust, chemical composition atmosphere, solar radiation....).

Recent Reanalyses of both Oceanic and Land conditions allows new research as to how SST and Soil Moisture are related. The NA area, more than Europe, is often stressed by limited soil moisture, and prediction for the warm seasons appears to benefit from knowing initial soil moisture over NA. However, is there any long lead forecast skill for land conditions, taking only antecedent oceanic conditions into account? This may be a somewhat unexplored topic although Shabbar and Skinner (2004) have recently found a strong relationship between winter Atlantic SSTs and the following summer's drought index. Van den Dool et al (2003) report successful summer forecasts following the 1997/98 winter ENSO events which left a strong imprint on the US in terms of a wet(dry) lower boundary across the south(north). The interdecadal trends in soil moisture on a global scale (Fan and Van den Dool 2004) are fairly striking, and the causes poorly known.

The topic of most interest, in terms of novelty, enthusiasm and practical interest, is that of trends. We were somewhat surprised to find that 1) all CCA-skill over NA due to Atlantic SST is of a low frequency nature and 2) regardless whether we predict temperature or precipitation CCA mode#1 (calculated from unfiltered data) is always very similar and has the same low frequency time-series in all seasons. While trends in SST can be debated and questioned (caused by changes in observing system?), we would not expect spurious trends in SST to come out so similarly in combination with trends in T2m and precipitation. The latter two may be flawed also, but certainly not in the same way. It therefore appears there is 'something' that orchestrates interdecadal up-and-down time series for the upper ocean as well as the continents. It is not clear at all that SST really predicts the seasonal climate over land in the next season. It may well be that all three variables react to some common cause of very low frequency (in which case a reverse CCA would show similar results). There are thus several signs of enthusiasm about using 'trends' (low frequency variations): a) Seasonal forecast tools include persistence of last ten years averaged anomaly (relative to the most recent 30-yr climatology), b) Hurricane forecasts (high skill!) are based largely on recognizing a global multi-decadal mode (which is similar to an Atlantic trend mode in SST) and c) two recent papers, one empirical and one modeling, McGaben et al (2004) and Schubert et al(2004), giving equal roles to (North) Pacific and Atlantic in 'explaining' variations in drought frequency over NA on a 20 year + time scale. Whether there is any predictability over and beyond what we harvest already via OCN remains to be seen, but we can certainly learn more by trying to understand these interdecadal variations.

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Seasonal-to-decadal predictability and prediction of South American climate

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Abstract

The dynamical basis for seasonal-to-decadal climate predictions and predictability over South America is reviewed. It is shown that while global tropical SST affect both predictability and predictions over South America, the lack of SST predictability over the Atlantic represents a severe limiting factor to seasonal climate predictions over some parts of the continent. It is also shown that current two-tier approaches to predict seasonal climate variations might represent a major limitation to forecast coupled ocean-atmosphere phenomena like the South Atlantic convergence zone. It is also discussed the possible effects of global climate change on regional predictability of seasonal climate. The paper presents some methodology utilized to produce operational seasonal climate forecasts over South America.

Introduction

South America represents an interesting area concerning seasonal climate variability. The largest fraction of the continent lies within the tropics, where seasonal climate predictability is higher compared to mid latitudes. Also, South America encompasses important elements of the climate system, like the Amazon rainforest, which covers a considerable fraction of the continental area and contributes to the important source of upper level mass and heat at lower latitudes; thus impacting both the general circulation of the atmosphere and the local climate (Buchmann et al., 1995). South America is also subject to the effects of and interferes in two atmospheric convergence zones: the Intertropical Convergence Zone (ITCZ) and the South Atlantic Convergence Zone (SACZ). The ITCZ is modulated in part by surface features, like the interhemispheric gradient of Sea Surface Temperature anomalies (SSTA) over the equatorial Atlantic (Hastenrath and Druyan, 1993; Wagner, 1996; Chang et al., 2000), and it modulates interannual variability of seasonal rainfall over eastern Amazonia and northern Nordeste (Hastenrath and Heller, 1977; Moura and Shukla, 1981; Nobre and Shukla, 1996).

Atmospheric general circulation models (AGCM) simulate seasonal rainfall interannual variability over Nordeste strikingly well when observed global tropics SST are prescribed as lower boundary conditions (Goddard and Mason, 2002; Marengo et al., 2003). The SACZ, on the other hand, is also influenced by SSTA over the southwestern tropical Atlantic, has a strong impact on the rainfall regime over southern Nordeste, Southeast and Southern Brazil, and contributes to modulate underlying SSTs over the SW tropical Atlantic (Chaves and Nobre, 2004).

Differently from the ITCZ, however, the SACZ is observed predominantly over negative SSTA (Robertson and Mechoso, 2000), suggesting that atmospheric-forcing coupling is operative at zero lag. AGCM experiments using direct SST thermal forcing generates simulations with near zero or even negative skill simulating SACZ (i.e., rainfall) variability (Marengo et al., 2003). The high reproducibility by AGCMs of seasonal rainfall interannual variability over Nordeste contrasts sharply with the low reproducibility over southeastern Brazil, indicating that different processes shall be operating to modulate seasonal rainfall over those regions.

The southern region, encompassing southern Brazil, Uruguay, Paraguay, and northern Argentina also presents some degree of predictability, which nevertheless is hardly realized during the actual exercise of seasonal climate predictions (Berri et al., 2003). The results of observational as well numerical studies indicate, however, that a large fraction of seasonal climate predictability over southern South America is originated from links to the equatorial Pacific ENSO phenomenon (Coelho et al., 2002; Mestras-Nunez and Enfield, 2001; Paegle and Mo, 2002; Pezzi and Cavalcanti, 2001; Ropelewski and Halpert, 1987). ENSO is also a major player to modulate seasonal rainfall interannual variability over northern South America and the Caribbean (Martis et al., 2002).

In short, seasonal climate prediction over South America presents two major challenges: first, for the regions in which the mean state of the atmosphere is modulated by external forcing, like SST, effective forecasting tools are needed to predict the future state of the oceans; second, for phenomena that can not be reproduced by the “ocean forcing” paradigm of climate variability, it is necessary to develop coupled models which include not only the ocean and the atmosphere, but also interactions with the biosphere, the cryosphere, and the stratosphere to simulate the complex interactions among these many realms.

On larger time scales, from decades to centennial, South America also plays an important role in the climate system. Primarily, due to the supposed hole of the Amazon forest as a carbon dioxide sink in today’s CO_2-rich atmosphere. Yet, recent global climate change research indicates that the capacity of tropical and temperate forests to grow – and therefore extract carbon dioxide from the atmosphere through photosynthesis – is limited to a certain amount of temperature increase, beyond which the biological systems reach breakdown, and start liberating large amounts of CO_2 to the atmosphere (Cox et al., 2001). It is not yet known to what extent seasonal climate predictability will change on regional scales in a scenario of global climate change; whether it will increase (in the case of increased dryness over semi arid regions) or will diminish (e.g., in the case of increased frequency of extreme events on a warmer and more humid atmosphere). In any case, the prospects of regional climate change are robust enough to justify a continuous scientific undertaking to improving the models and monitoring the environment to help society to learn to adapt to a changing climate.

Seasonal Predictions and Predictability

Seasonal to interannual and longer climate variability comprises two components: (a) the externally forced component, which is the response to slowly varying external boundary forcing (SST, sea ice, albedo, soil moisture, and snow coverage) and radiative forcing (greenhouse gases and aerosol concentration); (b) the internally forced component, which is the atmospheric variability induced by internal dynamics and the weather noise (Brankovic et al., 1994; Koster et al., 2000; Zheng and Fredericksen, 1999). Climatic variability of a region can be strongly influenced through teleconnection patterns originated by forcing anomalies in distant regions, such as in the El Niño-Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO) phenomena.

Over South America, interannual anomalies in rainfall over eastern-central Amazon and Northeast Brazil (Nordeste) appear to be the opposite to regions such as Southern Brazil (Ropelewski and Halpert, 1987), and all of these regions are sensitive to SST anomalies both over the tropical Atlantic and in the equatorial Pacific. The SST gradient between tropical North and South Atlantic is the key element associated with rainfall anomalies during summer and autumn in Amazon and Nordeste, while the ENSO signal on precipitation anomalies over southern Brazil seems to be weaker in summer than in spring and it exhibits considerable spatial variability (Grimm et al., 2000). Moreover, there are variations in the precipitation anomalies over all these regions among different ENSO warm events or among different ENSO cold events that cannot be clearly associated with the variability of the tropical Pacific SST anomalies solely (Marengo et al., 1998).

Nordeste and Amazonia:

SST anomalies in the equatorial Atlantic Ocean affect the meridional position of the ITCZ and thus the interannual variability of rainfall in Nordeste (Hastenrath and Heller, 1977; Moura and Shukla, 1981; Wagner, 1996; Nobre and Shukla, 1996; Folland et al., 2001) and the Amazon basin (Marengo, 1992; Uvo et al., 1998). Enfield and Mayer (1997) and Enfield and Alfaro (1999) have identified the relative influence of the eastern Pacific (ENSO) and equatorial Atlantic SST over rainfall over the Caribbean and northern South America. Experiments using the CPTEC/COLA AGCM were also performed by Pezzi and Cavalcanti (2001) to analyze the influence of Pacific and Atlantic Ocean on precipitation over South America.

Land surface characteristics and processes also serve as slowly varying boundary conditions on climate simulations. Realistic representation of land surface-atmosphere interactions is essential to a realistic simulation and prediction of continental scale climate and hydrology. Experiments on changes in land-surface, such as regional and large scale deforestation in the Amazon basin (See reviews in Marengo and Nobre (2001) and Costa and Foley (2000)) have identified the sensitivity of rainfall to changes in vegetation and soil moisture conditions in the region. Koster et al. (2000) suggest that both on the real world and the modeling system, the "memory" associated with continental moisture and the limited ability to forecast land-surface moisture state reduces predictability in some regions of South America.

Experiments using the CPTEC COLA AGCM (Marengo et al., 2003) show that the model systematically underestimates rainfall during the January-May peak of the rainy season in Amazonia. The underestimation of rainfall in northern-central Amazonia is found in other global models: Goddard Institute for Space Studies GISS (Marengo and Druyan, 1994), Geophysics Fluid Dynamic Laboratory GFDL (Stern and Miyakoda, 1995); European Centre for Medium Range Weather Forescast ECMWF, (Brankovic and Palmer, 1997); National Center for Atmospheric Research NCAR CCM3, and the Hadley Centre HadCM3 (P. Cox, personal communication), and deficiencies were linked to the convection and planetary boundary layer schemes in various models.

In the adjacent Nordeste, the model tends to overestimate rainfall. Yet, the model depicts a realistic annual cycle and interannual variability of rainfall anomalies. The large scale forcing associated with large SST anomalies in the equatorial Pacific during El Niño determines a quite realistic simulation of rainfall anomalies over Nordeste and eastern Amazonia, while during La Niña or neutral years the models do not always simulate the observed rainfall variability. The model reproduced the low rainfall amounts in those two regions during the El Niños 1982-83, 1986-87 (Marengo et al., 1998; Marengo et al., 2003) and during 1997-98, while in normal years the simulation is not as successful as during the extreme El Niño years. These simulations from the CPTEC/COLA AGCM are comparable to the interannual variability of rainfall in Nordeste with the PROVOST experiments using persisted SST (Folland et al., 2001) and with the original and revised AMIP simulations by Sperber et al. (1999), with all of them showing negative rainfall departures during 1983, 1987 and 1990, and large positive rainfall departures during 1985 and 1989. The deterministic and probabilistic scores presented for this region as derived by Sperber et al. (1999), Goddard et al (2001), and Marengo et al. (2003) also demonstrate a good skill in simulating rainfall anomalies at interannual time scales.

South/Southeastern Brazil:
The Southern and Southeastern regions of Brazil are highly populated, with large agricultural areas and high hydroelectrical power capacity. These regions are affected by climate anomalies associated with interannual and intraseasonal atmospheric variability. In the interannual scale, the El Niño-Southern Oscillation (ENSO) is related to floods and droughts in the southern region. The anomalous wet or dry ENSO years in Southern Brazil occur with opposite sign of the seasonal rainfall anomalies over the Nordeste (Cavalcanti et al., 2001). Southeastern Brazil, which is a transition area between the tropical Northeast and extratropical Southern region, does not present a clear sign related to ENSO. In some years the Southeast presents the same sign of the tropical Nordeste and some years the same sign of the extratropical South. However, this region is affected by intraseasonal variability which plays a role in the summer season convection (Castro and Cavalcanti, 2003).

The dependence of rainfall variability over these regions to extreme SST forcing in tropical oceans is better documented and established for southern Brazil as compared to southeastern Brazil (see reviews in Marengo et al. (2003)). Southern Brazil exhibits the impacts of El Niño during spring time and model experiences (Marengo et al., 2003) show in southern Brazil a systematic underestimation of rainfall during January-September.

On the interannual variability, in southern Brazil, despite the large scatter among members of the ensemble, the model captures quite well the extremes of the observed interannual rainfall variability; especially the above normal values observed in 1983 and the drought conditions in 1989. The circulation anomalies over southeastern Brazil in the spring of El Niño years are mostly due to remote influences from the tropical east Pacific, while in the subsequent summer, when the monsoon-like circulation is enhanced, they are probably due to local influences (Pisciottano et al., 1994). Coelho et al. (2002) documented that Southeast Brazil represents a region of a sharp transition between positive and negative SST-rainfall anomalies, defining the boundary from drier conditions in Nordeste and wetter conditions in southern Brazil during El Niño regimes.

Southeast Brazil exhibit a relatively low predictability for seasonal to interannual variability, and it seems that for this region external SST forcing from tropical oceans may be dominated by internal chaotic behavior of the climate system. Chaves and Nobre (2004) used an atmospheric and an oceanic GCM to study the feedback processes linking SST and SACZ variability. Their results suggest that the frequently observed negative SSTA under the SACZ (Robertson and Mechoso, 2000) is predominantly an ocean response to the reduction of downward solar radiation due to increased cloudiness during the formation of the SACZ. Their results thus support the speculation that the poor performance of AGCM simulations over the SACZ region is the consequence of the lack of coupled interactions between SST and the model atmosphere. In this region, AGCMs exhibit a robust inability to simulate interannual rainfall variability, as compared to the model skill in simulating rainfall variability in northern Amazonia, Nordeste, and southern Brazil during the peak of their rainy seasons. Koster et al. (2000) focuses their analyses on precipitation variance, and they analyze the contributions of ocean, atmosphere, and land processes using a simple linear model. The resulting clean separation of the contributions leads to the conclusion that land and ocean processes have essentially different domains of influence, that is, the amplification of precipitation variance by land–atmosphere feedback is most important for regions such as southeast Brazil and the South American monsoon, while for the tropics (Amazonia and Nordeste) rainfall variance is more affected by surface temperatures. This is also true for southern Brazil.

The relative influence of Pacific and Atlantic Ocean on South America precipitation was analyzed in Pezzi and Cavalcanti (2001). Composites of SST from strong ENSO episodes and strong “Atlantic dipole conditions” were combined to integrate the CPTEC/COLA AGCM in order to analyze the influence of the Pacific and Atlantic Oceans on the South America precipitation. The paper shows that the northern Nordeste is affected by the Atlantic Ocean, when there is anomalous warm water in the tropical South Atlantic, even in a strong El Niño episode (Fig.1), while southeastern and southern Brazil were not affected by the tropical Atlantic anomalies when the Pacific Ocean had warm anomalies; indicating that the Pacific was dominant in inhibiting convection over sourthern and southeastern Brazil. On the other hand, the Atlantic was dominant in La Niña episodes and the northeastern and northern sectors of Southeast changed sign depending on the sign of the SSTA “dipole.” Southern Brazil had also different behavior in this case.

The negative association between northern South America rainfall anomalies and ENSO, as suggested in the AGCM results of Pezzi and Cavalcanti (2001) (Fig. 1), is verified on observations, as shown in the work of Martis et al. (2002) (Fig. 2).

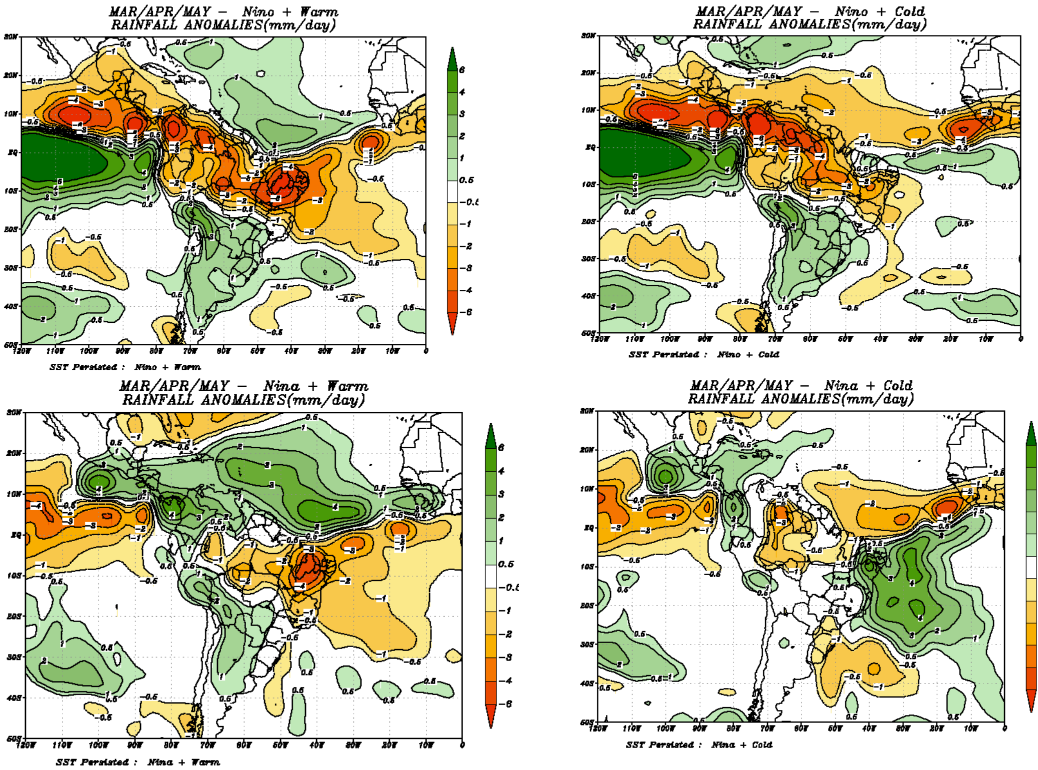


Figure 1 – Composite simulated March-April-May rainfall anomalies using CPTEC AGCM forced with combination of SST scenarios of Niño/Niña over the equatorial Pacific and Warm/Cold northern tropical Atlantic, as described on each panel (Pezzi and Cavalcanti, 2001).

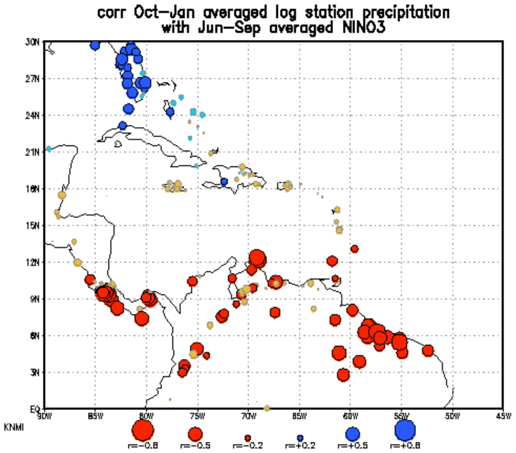


Figure 2 – Lagged correlations between Niño 3 SST index during Jun-Sep with raingauge series during Oct-Jan. over northern South America and the Caribbean (Martis et al., 2002).

Northern Argentina and Uruguay:

Much of the skill for the prediction of departures from mean seasonal rainfall totals or temperature averages is based on the boundary conditions at the earth's surface that influence the atmospheric circulation patterns, either because they change slowly or because they are predictable at seasonal scale. SST and, in some continental regions, soil wetness and snow cover are the more decisive surface conditions affecting climate. The continental area in southern South America (SSA) is relatively narrow compared with the huge oceans that surround it, and thus, the slower timescale of the SST is a potential source of predictability. Consequently, most of the work done to understand interannual climate variability was focused on SST conditions.

On the other hand, though most of Argentina and Uruguay are under the influence of the subtropical circulation, they are frequently reached by westerly disturbances, which might contribute to reduce the seasonal predictability of the region. This could be one of the reasons why the operational prediction systems used both in Argentina and Uruguay have been hardly successful for seasonal prediction, as will be shown in this article. These results seem to contradict the fact that southeastern South America (SESA), which includes subtropical Argentina and Uruguay, is one of the extratropical regions whose climate is most affected by ENSO events, and hence having a potential for seasonal prediction.

The connection between South Atlantic SST anomalies and precipitation in SESA has deserved less attention than the ENSO link. However, it abounds the literature with respect to the SACZ. Since interannual variability of rainfall in subtropical Argentina and Uruguay during summertime is closely related to this system (Doyle and Barros, 2002), it is convenient to briefly introduce some aspects of the SACZ.

The SACZ is one important climatological feature of the austral summer in South America. This band of intense convective activity emanates from the Amazon region extending from the tropical South America southeastward into the South Atlantic Ocean (Kodama, 1992; Figueroa et al., 1995). What matters, here, is its connection with rainfall in Argentina and Uruguay. Nogués-Paegle and Mo (1997) found evidence of a seesaw pattern in the convection over the SACZ, with each phase lasting no more than 10 days and that the intensification (weakening) of the SACZ is associated with rainfall deficit (abundance) over the subtropical plains of South America, including eastern Argentina and Uruguay. Doyle and Barros (2002) showed that this dipole behavior appears also as a distinctive feature of the interannual variability of rainfall, and that in western Argentina, precipitation tends to vary in phase with SACZ rainfall. Gandu and Silva Dias (1998) explored the physics of this dipole with numerical experiments, showing that a strong SACZ activity is associated with enhanced subsidence to the south of it.

Barros et al. (2000) found that, during summer, both the intensity and position of the SACZ are related to the SST to the south of it, being displaced northward (southward) and more intense (weaker) with cold (warm) SST anomalies. However, this relation does not mean that SST governs the SACZ variability. There are evidences that the phases of SACZ respond to Rossby wave activity (Liebmann et al., 1999; Robertson and Mechoso, 2000) and to the MJO (Carvalho et al., 2004). However, a numerical experiment shows that there is a positive feedback between cold SST in the subtropical South Atlantic and intense SACZ activity (Robertson et al., 2003), and therefore the SST influence on the SACZ, and consequently on the subtropical rainfall cannot be discarded.

The SACZ connection between SST and rainfall in subtropical Argentina and Uruguay could be one of the mechanisms that relate the interannual variability of SST in the South Atlantic with precipitation in those countries. This relation was studied by Díaz et al (1998), finding the existence of an association between wet (dry) rainfall anomalies in the northern sector of Uruguay and southern Brazil and warm (cold) SST anomalies in the SACZ region and the equatorial Atlantic in the November-February period. Barros et al (2000) found that during summer, SESA rainfall is related to both the intensity and position of the SACZ, but also independently of the SACZ, to the SST of the neighboring Atlantic Ocean. Doyle and Barros (2002) found that the midsummer interannual variability of the low-level tropospheric circulation and of the precipitation field in subtropical South America are associated to the SST anomalies in the western subtropical South Atlantic Ocean. Composites corresponding to extreme SSTs in the area 20ºS-30ºS and 30ºW-50ºW show two different low-level circulation and precipitation patterns.

The aforementioned studies reveal the potential importance of the South Atlantic in the SESA climate variability. However, since the SACZ also responds to remote atmospheric forcings, the predictability of the regional climate based on South Atlantic SSTs is still an issue that requires further research.

Since 1997, the International Research Institute for Climate Prediction (IRI) elaborates global seasonal forecasts of temperature and precipitation anomalies containing an outlook for the coming 3-month season and an extended one for six months in advance. The IRI's operational climate forecasts are issued every month for the globe (http://iri.columbia.edu/climate/forecast/net_asmt/). Model skill estimates based on hindcast simulations with prescribed SST are also available. The outlook is prepared using coupled ocean-atmosphere model predictions of tropical Pacific SST, forecasts of the tropical Indian ocean using a statistical model and global AGCM predictions of the atmospheric response to the present and predicted sea-surface temperature patterns. Seasonal outlooks provide the probability that average temperature and total accumulated precipitation fall into each of three categories. These categories are defined as the lower, middle, and upper thirds of the climatological distribution. When forecasts with probabilities for the three categories are the same, namely a third each, they are designated as climatology (CL). For each location and season, the terciles correspond to temperature and precipitation ranges based on a set of historical observations. Consequently, when using tercile forecasts, users need to know the ranges to which the terciles refer.

Berri et al. (2003) made an evaluation of the IRI´s seasonal precipitation forecasts for SESA, issued between 1998 and 2002. They showed that the regional IRI´s forecasts have a small positive Ranked Probability Skill Scores (RPSS) in northwestern Uruguay and some part of northeastern Argentina, a region with strong ENSO signal (Fig. 3a). The small positive RPSS means that forecasts were better than climatology though rather modest. On the other hand, results in western Argentina are worst than climatology. This is a semiarid region with strong interannual variability where in general, GCM have difficulties to simulate rainfall (Camilloni and Bidegain, 2002).

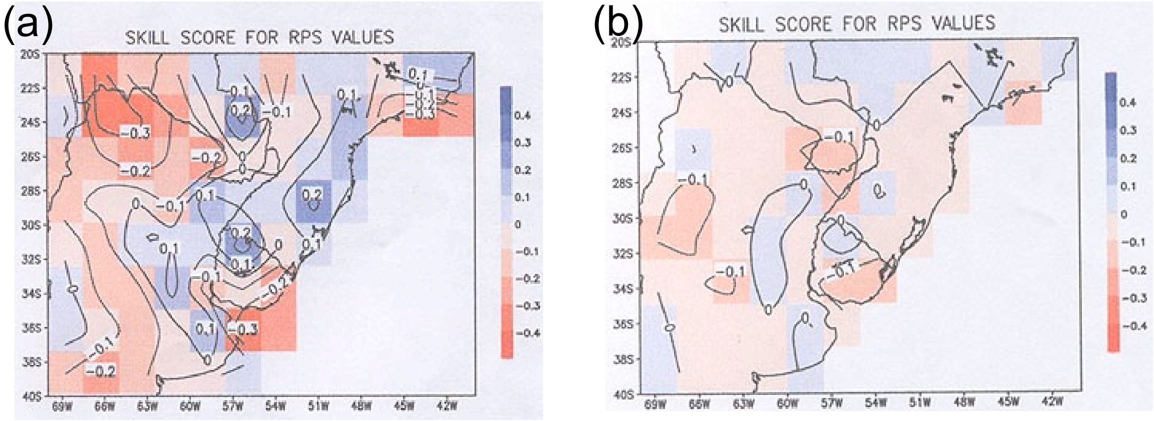


Figure 3- Ranked Probability Skill Scores (RPSS) for sixteen (a) IRI´s seasonal precipitation forecasts and (b) Climate Outlook Fora seasonal precipitation forecasts for SESA between January 1998 and May 2002 (From Berri et al 2003).

Other source for predictions of seasonal average temperatures and precipitations for Uruguay and Argentina, available at the web, is the NASA's Seasonal-to-Interannual Prediction Project (NSIPP) (http://nsipp.gsfc.nasa.gov/main.html). NSIPP runs its coupled global ocean-atmosphere-land model to produce 12-month forecasts with NSIPP SSTs and with NCEP/IRI SSTs inputs, issuing three types of forecasts. The first type presents the precipitation anomaly from an 18 member ensemble mean. Anomalies are calculated with respect to the 1993-2001 model climatology. The second one is the raw category forecast, based on the individual ensemble member forecasts. The three categories are above normal, normal and below normal according to the model climatology. The numbers presented in the forecast are the percentage of the ensemble members that fall in each category. Finally, the calibrated category forecast is based on the ensemble mean of the forecast and reflects the past performance of the model in the three above-mentioned categories. Areas with no forecast skill are also indicated. In this case, numbers represent the probability in percent that forecast will verify.

Since December 1997, 18 climate outlook fora (COF) for SESA were convened to produce seasonal climate forecasts for temperature and precipitation anomalies in the region bounded by 20°S, 40°S, the Atlantic coast, and the Andes. These COFs were organized by governmental organizations of Argentina, Brazil, Paraguay, and Uruguay. The participants were climate experts and operational forecasters, which reach a consensus to forecast the coming 3-month season. The COF also discuss the implications of probable climate outcomes for climate-sensitive sectors. Following the IRI's methodology, the COF estimates the probability of the seasonal mean of precipitation and temperature to be in the lower, middle, and upper thirds of the climatological distribution.

Berri et al (2003) evaluate the COF´s forecasts with the same method used with the IRI's outlooks. Over most of the region, the COF´s seasonal forecasts have a very small negative RPSSs, being therefore slightly worst than climatology. As in the case of the IRI's forecasts, there is a region with positive RPSSs in northwestern Uruguay, but with even lower skill and in a smaller area (Fig. 3b). The fact that RPSS are very near zero all over the domain, both in their positive and negative values, reflects the worthless of the consensus method in this case. These consensuses generally tended to smooth out the different opinions, and thus, forecasts resulted not very different from climatology.

Misra (2004) studied the predictability of the austral summer seasonal precipitation over South America using the atmospheric general circulation model of the Center for Ocean-Land-Atmosphere Studies (AGCM-COLA). The AGCM-COLA was run with prescribed observed SST. Consequently, the estimated skill represents the upper bound or the potential skill that can be attained by using predicted SST. The potential skill in predicting the interannual variability of mean January-February-March is lower in central Argentina than over the tropical areas of Northeastern Brazil, the Amazon River Basin and the SACZ, suggesting a lack of skill in the tropical-extra-tropical interactions. The AGCM-COLA underestimates the mean seasonal precipitation over central Argentina by almost a 50% in some areas, but it does better over Uruguay. The root mean square error of the seasonal totals over central Argentina is so large that it can be inferred that the AGCM-COLA has no predictable skill in this region. Over Argentina and Uruguay, the skill of the operational seasonal forecasts ranges from modest, but better than climatology, to useless. The skill is confined to the northeast of Argentina and north of Uruguay, a region with an important ENSO signal.

There is a number of reasons for such humble result. First, models and statistical tools used for seasonal prediction relay primary on the SST slow changes or their predictability. In spite of the well-known mean regional climate response to ENSO, this indeed is limited to only some areas and some months. But still in these months and areas, there is a large inter-event variability that may hinder predictions based on statistical mean response or even model ability since in some cases, it is not clear that this variability obey to predictable causes.

The importance of MCS in the total seasonal precipitation is likely one of the reasons for the poor skill that atmospheric and ocean coupled models show for seasonal prediction over subtropical Argentina and Uruguay. Though the frequency of these systems seems to respond to ENSO, the locations where they occur are extremely variable. It remains to be understood to what extent the contribution of these systems to seasonal precipitation is unpredictable over this region.

There is a connection between SESA precipitation and the South Atlantic SST, as well as with the SACZ, at least during summertime. However, since the SACZ also responds to remote atmospheric forcings, the predictability of the regional climate based on South Atlantic SSTs is still an issue that requires further research.

The Antarctic oscillation index is correlated with precipitation in Argentina and Uruguay during part of the year (Silvestri and Vera, 2004). Since this oscillation is suspected of being unpredictable, at certain frequencies, an understanding of the mechanisms, which relates it to SESA rainfall, is required.

Scenarios of global climate change over South America

Climate modeling has proven to be extremely useful in building projections for climate change and scenarios of future climate under different forcings. General circulation models have demonstrated their ability to simulate realistically the large-scale features of observed climate; hence, they are widely used to assess the impact that increased loading of the atmosphere with greenhouse and other gases might have on the climate system. Although there are differences among models with regard to the way they represent the climate system processes, all of them yield comparable results on a global basis. However, they have difficulty in reproducing regional climate patterns, and large discrepancies exist among models. In several regions of the world, distributions of surface variables such as temperature and rainfall often are influenced by the local effects of topography and other thermal contrasts, and the coarse spatial resolution of GCMs cannot resolve these effects. Furthermore, the intrinsic limitation of not-resolving clouds in GCMs is a major limitation to predict the changes on the frequency of extreme events on a CO2-rich atmosphere. Consequently, large-scale GCM scenarios should not be used directly for impact studies, especially at the regional and local levels (Von Storch, 1994); downscaling techniques are required.

The predictions of future climate change, while differing in details from model to model, consistently indicate that global changes of the current climate state are going to materialize. Due to the inertia of the climate system, even if we were able to stabilize greenhouse-gas concentrations today (what means an overnight reduction in global carbon dioxide emissions of about 70%), a further 1 °C of additional global warming, and around one meter of sea-level rise would occur from emissions that have already taken place over the last 100 years. As shown in previous Hadley Center reports, sea level will go on rising for many hundreds of years after greenhouse-gas concentrations have been stabilized (e.g., see: http://www.metoffice.gov.uk/research/hadleycentre/pubs/brochures/B2000/predictions.html).

Results of a coupled atmosphere-biosphere model simulation by Cox et al. (2001), which included some form of feedback of climate on the carbon cycle, suggests that after a certain threshold of global warming, carbon kept in the soil and the biomas of tropical forests, like the Amazon, would be partially released through respiration as carbon dioxide into the atmosphere, with the inflection point between CO_2 sink becoming a CO_2 source by mid 21st century. These results, if confirmed by further research and diagnostics, represent the most alarming indication up to date of the seriousness and magnitude of global climate change for the earth system.

Is climate variability likely change regionally?
There are many more atmosphere-ocean coupled GCM projections of future climate available than was the case for the IPCC Second Assessment Report (IPCC, 1996). We concentrate on the IS92a and draft SRES A2 and B2 scenarios of the IPCC Third Assessment Report (2001). Results of experiments using those climate change scenarios show that most tropical areas have increased mean precipitation, most of the sub-tropical areas have decreased mean precipitation, and in the high latitudes the mean precipitation increases. In addition, there is a general drying of the mid-continental areas during summer (decreases in soil moisture). This is ascribed to a combination of increased temperature and potential evaporation that is not balanced by increases in precipitation.

The capability of models to simulate the large-scale variability of climate, such as the ENSO (a major source of global interannual variability) has improved substantially in recent years, with an increase in the number and quality of coupled ocean-atmosphere models, and with the running of multi-century experiments and multi-member ensembles of integrations for a given climate forcing. IPCC (2001) indicate that the results from these models must still be treated with caution as they cannot capture the full complexity of these structures, due in part to the coarse resolution in both the atmosphere and oceans of the majority of the models used.

Although many models show an El Niño-like change in the mean state of tropical Pacific SSTs, the cause is uncertain. In some models it has been related to changes in cloud forcing and/or changes in the evaporative damping of the east-west SST gradient, but the result remains model-dependent. For such an El Niño-like climate change, future seasonal precipitation extremes associated with a given ENSO would be more intense due to the warmer mean base state. There is still a lack of consistency in the analysis techniques used for studying circulation statistics (such as the North Atlantic Oscillation) and it is likely that this is part of the reason for the lack of consensus from the models in predictions of changes in such events.

The possibility that climate change may be expressed as a change in the frequency or structure of naturally occurring modes of low-frequency variability has been raised. If true, this implies that GCMs must be able to simulate such regime transitions to accurately predict the response of the system to climate forcing. This capability has not yet been widely tested in climate models. A few studies (Osborn et al., 1999; Paeth et al., 1999; Ulbrich and Christoph, 1999) have shown increasingly positive trends in the indices of the NAO and the SST interhemispheric gradient in the tropical Atlantic in simulations with increased greenhouse gases; although this is not true in all models, and the magnitude and character of the changes varies across models (see reviews in the IPCC 2001).

One intriguing aspect of climate variability under a scenario of climate change is the likelihood of augmented available potential energy due to a warmer and moister troposphere. There are indications that the number and intensity of tropical storms may increase as a consequence of a warmer troposphere and upper ocean, with deleterious social and economic consequences. One extraordinary example of a phenomenon over the South Atlantic is the recent extratropical cyclone that hit the coast of Brazil on March 26th, 2004. It was the first time in the record that such large synoptic system developed over the South Atlantic, reaching proportions of a hurricane. Interestingly, the path of this cyclone coincided with the area of augmented probability of cyclogenesis predicted on climate change scenarios constructed by the Hadley Center, UK. Even though the single realization of a cyclone of such proportions over the South Atlantic may not be statistically significant to suggest that we are experiencing the dawn of a changed climate, it is nevertheless intriguing and shall be very much studied in the months and years to come.

Predictability of seasonal climate under climate change scenarios
The tropical SST anomalies impact more on the predictability over the Pacific/North America sector than the Atlantic/Eurasia (Cheng and Dool, 1997). In the former sector more significant and positive impacts are found during El Niño and La Niña than during the neutral phase or inactive period. Predictability is significantly higher during El Niño than La Niña phases. This was confirmed by Marengo et al. (2003) for regions in the Atlantic sector such as Nordeste, northern Amazonia and southern Brazil-northern Argentina. The predictability of seasonal means exhibit large seasonality for both warm and cold phases of the ENSO cycle, and during the warm phases a high level of predictability is observed during December to April, where the rainy season peaks in tropical South America east of the Andes. Most of the decadal Pacific variability comes from the western Pacific.

Thus, for regions that show some association with Tropical Pacific SST and El Niño some predictability can be expected, while for regions such as Amazonia and Nordeste this predictability will depend on the characteristics if the tropical Atlantic and becoming higher whenever there is an extreme of the ENSO. At the ends, most of the models show for climate change scenarios more frequent El Niño like conditions, and this would in fact overcome SST anomalies in the tropical Atlantic. One could think that being the Amazon, Nordeste, and the Southern Brazil regions very sensitive to ENSO these would actually gain some predictability for rainfall anomalies in global warming scenarios. The Hadley Centre HadCM3 model show El Niño-like conditions since the 2050, with dryness in Amazonia and Nordeste, and rainfall above normal in southern Brazil. However, the degree of uncertainty is not low, and if most of the climate models projection for Nordeste show increases in air temperature and rainfall for the extreme scenario IPCC A2, the Amazon basin shows an unclear signal of rainfall (varying from slightly above to below normal), there is a detected warming trend 5.8 °C in some models. The observed warming trend in Amazonia since the early 1900's is +0.85 °C/100 years.

Seasonal climate predictability over South America
The potentially predictable component of atmospheric interannual variability is assumed to be that due to oceanic forcing, together with the unpredictable internal component. Rowell (1998) concluded that the model-based predictability estimate has large variations throughout the annual cycle. The highest predictability occurs over the tropical oceans, particularly the Atlantic and Pacific, for which a better knowledge of the influence of SST on diabatic heating is important for understanding the variability of teleconnected regions. Land-areas displaying high predictability tend to support existing empirical studies, such as the Amazon basin, while other do not exhibit such high degree of predictability as in the South American monsoon (Marengo et al., 2003). Servain et al. (2000) identify two interannual modes of variability that have the same physics as the annual variability does, which is related to the latitudinal displacement of the ITCZ. Furthermore, it is suggested that the ocean dynamics (as opposed to the thermodynamic processes) is the principal cause of climate variability in the region, and this works also at decadal time scales. The observed decadal changes in the Pacific, detected as changes in the frequency of intensity of ENSO events during the middle 1940's and 1970's (IPCC 2001), as decadal changes identified in the tropical Atlantic also show a possible change in predictability on decadal time scales.

A number of studies have reported the existence of decadal and longer time-scale variability in South American rainfall and river discharge, related to ocean surface changes in those timescales in both Pacific and Atlantic Ocean (Zhou and Lau, 1998; Robertson and Mechoso, 1998; Mehta, 1998). Decadal time scales for the Pacific and Atlantic Oceans have been linked to variations of rainfall in the Amazon and Nordeste regions (Wagner, 1996; Nobre and Shukla, 1996; Mehta, 1998; Robertson and Mechoso, 1998. Mehta [, 1998 #510) suggested a distinct decadal time scale (12-13 year) of SST variations in the tropical South Atlantic, whereas no distinct time scale was found in the tropical North Atlantic SST variations. Previously, Mehta and Delworth (1995) identified in the observations and the GFDL model a multidecadal variability in the SST time series with approximately opposite phases between the tropical North and South Atlantic, exhibiting an inter-hemispheric gradient of SST anomalies. Dommenget and Latif (2000) found that the decadal variability in both tropical North and South Atlantic are uncorrelated, and that this variability of the upper-tropical Atlantic Ocean is forced by the atmosphere while dynamic feedbacks are less important.

The role of the ocean in tropical Atlantic decadal variability is investigated by Seager et al (2001). They suggest that the tropical Atlantic is largely passive and damping; and SST anomalies are largely stationary in the deep tropics. Previously, Carton et al. (1996) suggested that decadal time scale variability in the tropical Atlantic is controlled by latent heat flux anomalies and is primarily responsible for SST anomalies off the equator. Ruiz-Barradas et al. (2000) examine the connection between the tropical Atlantic and other basins. They found that ENSO events cause patterns of winds, heating and SST resembling the interhemispheric gradient of anomalous SST and dipole pattern of atmospheric heating.

In southern Brazil and northern Argentina, recent studies (Barros, personal communication) have detected increased rainfall and river discharge in the region since the mid-1970s; these increases are linked to changes in the regional circulation, i.e. the southward displacement of the subtropical Atlantic high. Robertson and Mechoso (1998) suggested some predictability on decadal time scales in the southern Brazil region, associated with a near-decadal oscillation in SST along southeastern South America.

For the Amazon Basin, decadal variations of rainfall have been identified in both northern and southern Amazonia, with shifts in the mid-1940s and 1970s. After 1975–76, northern Amazonia received less rainfall than before 1975. Changes in the circulation and oceanic fields after 1975 suggest an important role of the warming of the tropical central and eastern Pacific on the decreasing rainfall in northern Amazonia, due to more frequent and intense El Niño events during the relatively dry period 1975–98.

In Nordeste, Folland et al. (2001) study the predictability of rainfall using the HadAM2b model, and they demonstrate a relatively high degree of predictability, with its sources lying mostly in the tropical Atlantic and Pacific SST. On this region, the SST gradient between the northern and southern tropical Atlantic appears to be the most important influence, though El Niño can be dominant when it is strong. This high predictability is the base of empirical predictions in that region, as the forecasts by Greischar and Hastenrath (2000). Their method used 1921-57, and their performance was validated on the independent record 1958-89. The forecasts were in close agreement with the observed rainfall during the 1990's, with exception of the extreme El Niño 1998. A possible cause of this failure is seen in the lack of comparably extreme Pacific warm, events within the training period 1921-57, and the frequency of intense El Niño has changed from the middle 1970's. This conclusion on predictability can be also applicable to the Amazon basin. So, the notion of a rapidly changing climate represents a major quest for the predictability of climate variations on interannual time scales because most methods and models, both statistical and dynamical ones, are based on the presumption of stationarity of the mean state statistics considerably longer than the time span of the predictions.

Dynamical downscaling of regional climate predictions

The disadvantage of using AGCM for regional climate predictions on intraseasonal to interannual and longer timescales is the inability of present day models to resolve sub-grid atmospheric processes of fundamental importance (e.g. clouds and regional scale inhomogeneities of surface fluxes), which are likely to play a determining role on climate statistics. On interannual climate prediction, for instance, the use of regional atmospheric models have suggested that it might be possible to predict higher statistics of the regional climate like the probability density function (pdf) distribution of daily rainfall over a region. Nobre et al. (2001) obtained encouraging results using a regional model nested on the outputs of an

AGCM to predict the daily rainfall pdf and the spatial distribution of consecutive number of days with no rainfall over Nordeste during the period of February to May 1999. Sun et al. (2004) (2004) used essentially the same dynamical downscaling technique of Nobre et al. (2001), but over a period of 30 years, and demonstrated that the regional model can simulate the interannual variability of daily rainfall pdf over Nordeste, better than the AGCM in which it was nested. These results represent a milestone for seasonal climate prediction, as they point to the possibility of climate predictions beyond seasonal averages of atmospheric variables, first suggested by Shukla (1981).

Seasonal climate predictions over South America

Presently, there are several centers in South America and other parts of the world that issue regular seasonal climate assessments and outlooks for South America. On its majority, these centers use two-tier approach to generate the predictions; first using various methods to reach the "best estimate" of global tropics SST prediction for the following four to six months; then the SST forecasts are used to force AGCMs to generate ensembles of individual predictions starting from slightly different atmospheric initial conditions. A detailed explanation of this type of methodology can be found in Goddard et al. (2002) and Marengo et al (2003), for example. There are several centers that currently provide seasonal climate predictions over South America, such as NCEP, NSIP, IRI, ECMWF, UKMET, INMET, CPTEC, and FUNCEME. The methodology followed on the last two of these centers is described below:

CPTEC

Uses the CPTEC/COLA spectral AGCM forced with prescribed SST globally. The model horizontal truncation is triangular at wavenumber 62 and 28 sigma levels unevenly spaced in the vertical. Atmosphere-biosphere model is SIB; deep convective cloud parameterization is Kuo. A total of 30 ensemble members are computed every month; 15 atmospheric initial conditions (analysis fields obtained from NCEP) are taken two months prior to the start of the forecast period; soil moisture and snow cover at initial condition are climatological; sea ice is kept climatological throughout the integration. The AGCM is then integrated for two months forced with observed global SST; then two sets of SST predictions are used: one uses a composite of NCEP coupled model SST predictions for the equatorial Pacific and CPTEC canonical correlation analysis (CCA) SST predictions over the tropical Atlantic (Repelli and Nobre, 2004) for the following four months, with persisted SST anomalies over the remaining oceanic areas. The second set of 15 integrations (using the very same set of atmospheric IC as above) uses persisted SST anomalies over all the oceans during the same four months of prediction. Ensemble means of the monthly output fields are then used to generate the consensus forecast.

FUNCEME

Over the last 20 years, Ceará State Foundation for Meteorology and Water Resources (FUNCEME), in partnership with National Institute for Space Research (INPE) and other Brazilian and foreign meteorology institutions, has worked on a conceptual model of climate forecast that is supported by several regional and global climatic models. In addition, information about oceanic and atmospheric patterns that have a significant influence on the rainy season quality over Ceará and Nordeste are analyzed too.

Every year, FUNCEME holds a workshop in Fortaleza, which is attended by its technical staff and experts from national and international institutes and universities, to make the analysis of such oceanic and atmospheric variables that are significant for the identification of rainy period, and make forecasts based on the application of several numeric models. At the end of the workshop, the panel of researchers and experts issue a climate forecast for the main rainy period (February-May) in both the State of Ceará and the northern portion of Nordeste.

One particularity of FUNCEME's methodology is the use of NCEP's Regional Spectral Model (RSM) nested on the ECHAM5 AGCM outputs generated by the IRI to predict seasonal rainfall anomalies over Nordeste. An ensemble of ten members is generated with the regional model integrated for a period of six months from December AGCM forecasts. SSTs are persisted global SSTAs. Running in hindcast mode, the regional model generated seasonal rainfall hindcasts which were consistently more accurate than the corresponding AGCM hindcasts.

The forecast is read out publicly on the last day of the workshop at a session attended by the major users (EMATERCE, Civil Defense, COGERH, SEAGRI, agricultural businesspersons, and other stakeholders). Forecasts are usually covered and published by the local media (press and TV). It should also be highlighted that, prior to the public disclosure of forecasts, a team of professionals led by the President of FUNCEME, submits the workshop conclusions to the Governor of the State of Ceará.

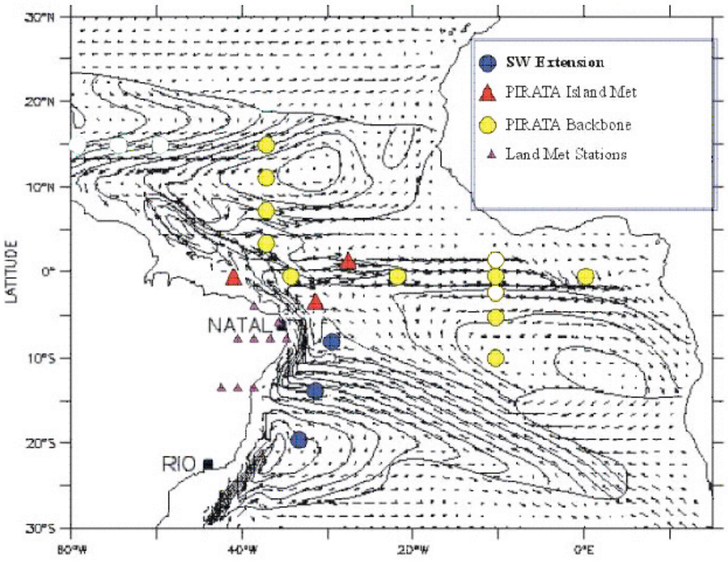
Once the first forecast for a particular year is issued, FUNCEME team continues to monitor the oceanic and atmospheric patterns. Eventual changes in forecasts is published in technical releases and informed immediately to the end-users. This remains available in the web site of FUNCEME (http://www.funceme.br).
It should be pointed out that climate forecast issued in December is considered as an initial approach, as it is based on oceanic and atmospheric conditions observed in November. Previous experiences have shown a high forecast reliability when observations made in January-February are used.

This anticipated climate forecast, combined with the daily monitoring of sea and atmosphere conditions, has helped the State of Ceará over all those years to plan actions for agriculture (e.g. Time to Plant Program), water resources (reservoir management), civil defense (alerts against extreme rainy events in Fortaleza Metropolitan Region), civil construction (best periods for concrete application), etc. General society has also benefited of such forecasts through a range of measures taken by the civil defense, Secretariat of Agriculture, Secretariat of Water Resources, Civil Construction, and other sectors that use meteorological information to carry on their activities.

Research and data needs.
As it discussed above, seasonal climate predictions over South America can partly benefit from “ocean-driving” conditions of atmospheric circulation and precipitation patterns. Therefore, slowly varying ocean temperature fields as those associated to the ENSO over the equatorial Pacific and the meridional gradient of SST anomalies over the tropical Atlantic imprint seasonal predictability to the climate. However, model improvements and research quality data are in need to both increase predictions skill and lead time. Furthermore, the evidences pointing to the dynamical limitations of using AGCM forced by prescribed boundary conditions to predict SACZ variability is a major limitation in current prediction techniques used. Yet, due to present limitations of coupled ocean-atmosphere models to predict tropical Atlantic climate and ocean variability, the scientific puzzle ahead of us to predict the coupled variability of the tropical Atlantic basin represents a huge challenge to our ingenuity and resources: human, models, data, financial, and scientific wise.

Future implementations on the atmospheric component of the CPTEC coupled ocean-atmosphere model are related to the improvements of physical parameterizations, new vegetation maps, and more realistic soil humidity fields. Other implementations comprise the increase of the models resolutions, optimization of codes, and new methods of model analyses, including super-ensemble mean, clusters, and predictability.

On the observational side, Brazil recognizes the scientific and practical merit, and is deeply committed, to develop a comprehensive observational ocean-atmosphere network over the equatorial and South Atlantic. The PIRATA project of moored ATLAS buoys in the tropical Atlantic (Fig. 4), in which Brazil participates with France and the United States, constitutes the embryo of such observational network.



[Background map from: Lazar et al. 2001]

Figure 4 – PIRATA array of moored buoys over the tropical Atlantic (yellow circles); island meteorological stations (red triangles); and the Southwest Extension of the PIRATA array (blue circles). Background map showing simulated currents by Lazar et al. (2002).

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Seasonal-to-decadal predictability and prediction of European climate

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Introduction

As a means of motivating this topic, we first consider the European summer heatwave of 2003. Figure 1 shows the summer 2003 mean 2m temperature anomalies (Schär et al., 2004). Temperature anomalies peak at over 4K (and 5 standard deviations) above the 30-year mean over France and Switzerland. Figure 2 (personal communication, Mark Liniger) shows that European rainfall during June - August (JJA) 2003 was also reduced, particularly over southern France. This heatwave is thought to have been responsible for (or at least accelerated) the deaths of nearly 15,000 people in France, caused billions of Euros in damage to crops and initiated fires which destroyed a billion Euros' damage to forests in Portugal alone. The effects were wide ranging with detrimental impacts on, for example, metropolitan pollution levels and alpine glaciers. Here we use this heatwave to introduce the concepts of predictability and prediction of European climate.

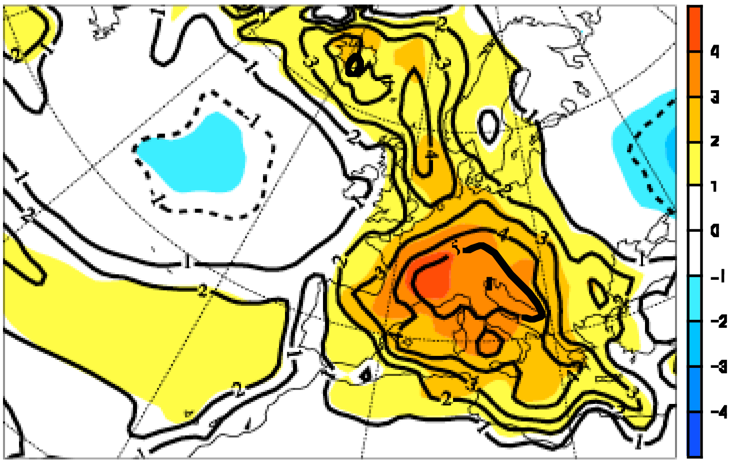

Fig. 1 Observed 2m temperature anomalies for June-August 2003 from ERA40 1961-90. Units are K (shaded) and standard deviation (black contours). From Schär et al (2004).

Also shown in black and grey in Fig. 3 are medium-range forecasts (initiated on 1 June and extending to 9 June), monthly forecasts (initiated on 4 June and divided into weekly-mean periods) and seasonal forecasts (initiated on 1 June and divided into monthly-mean periods), all made at the European Centre for Medium-range Weather Forecasts (ECMWF). The black curve shows a single control forecast, traditionally known as the "deterministic forecast". It follows quite closely the observed rise in European temperatures during the first 10 days of June. The forecast that temperatures would rise in the medium range turned out to be quite accurate. The grey curves show an 'ensemble' of equally likely forecasts, each identical to the control except that there are (small) perturbations made to its initial conditions and tendencies in order to reflect chaotic uncertainties. The ensemble members are seen to spread-out quite rapidly but there is a bias towards increasing temperatures. Since all members show a temperature greater than normal on the 8 June, a prediction could be made that there is almost 100% probability that the temperature will be above normal on that day. We say "almost" because there is an assumption that the model represents faithfully the dynamics and physics of the real system and that the ensemble (with 51 members) captures the full range of chaotic uncertainty. Although the deterministic forecast did verify quite well on this occasion, it is clear that only a

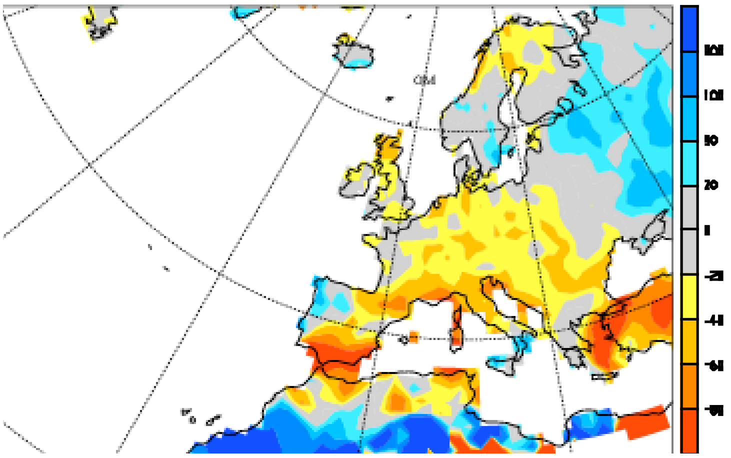

Fig. 2: Observed precipitation anomalies for June-August 2003 from GPCC 1961-90. Units are percentage difference from normal (Personal communication, Mark Liniger).

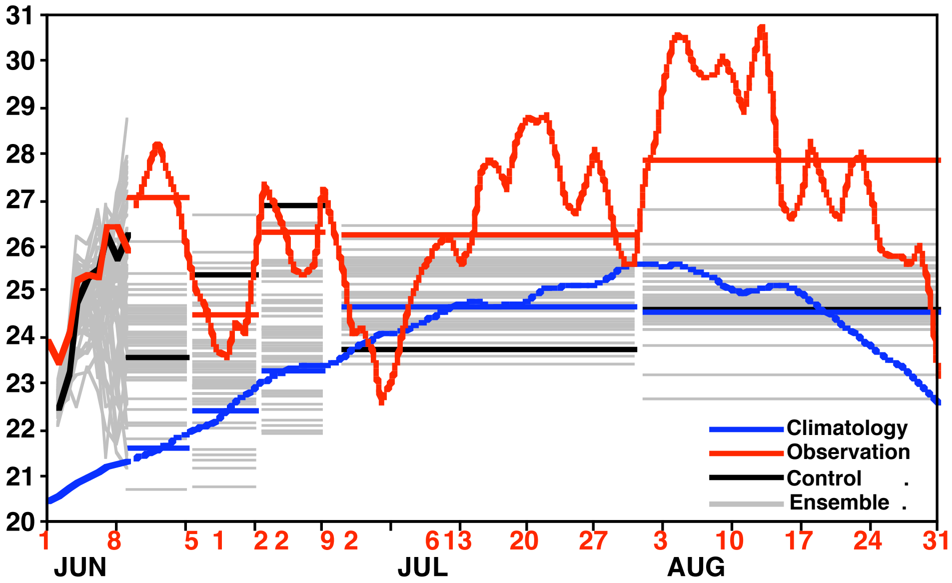

Fig. 3: Observations (red) and forecasts (black and grey) made by ECMWF at the beginning of June of European 2m land temperatures. Also shown (blue) are the climatological mean values based on ERA40 (1962-2001). Horizontal lines show weekly and monthly-mean values. For the period 2-9 June the control forecast (black) is made at a resolution of T511 and the ensemble forecasts (grey) are made at a resolution of T255. The weekly-mean forecasts 9-15 June, 16-22 June and 23-29 June are based on T159 forecasts started on 4 June (black signifies the first member of the ensemble). The monthly-mean forecsts for July and August are based on T95 forecasts initiated on 1 June (black signifies the first member of the ensemble). All results are spatially averaged over the land points in the box [5^{o}W-25^{o}E, 35-55^{o}N].

"probabilistic forecast", that takes chaos into account, can truly indicate determinism of the outcome. If we are happy to sacrifice 100% determinism, we can make the forecast that the temperature on 8 June will be 3K warmer than normal with a probability of 75%. In this case, the 'event' (that $T_{8June}>T_{clim}+3$) also verified in the observations. More generally, for a "reliable" forecast system, an event with 75% probability of occurring would verify 75% of the time. Weather forecasts at this range have a clear benefit to society. For example, French nuclear power plants mainly use river water as a coolant. During the heatwave, there was a potential risk to river ecosystems as river flow-rates dropped and temperatures rose. Nevertheless, several power plants were given permission (on 11 August) to continue operation. Medium-range weather forecasts of the imminent withdrawal of the heatwave were a factor in the justification, by Electricité de France (EDF), for this decision. Similar permission was granted in the Netherlands and results from coupling the ECMWF medium-range forecast output to a model for river water temperatures were used to justify the decision (personal communication, Robert Mureau).

For longer lead-time forecasts, predictability of the timing and existence of individual synoptic systems is lost but it is possible that there may still be predictability about the average conditions over a period of time. Such predictability comes (if it exists) from the 'boundary forcing'. For climate change forecasts, the boundary forcing includes the radiative impact of greenhouse gases. Such forcing is likely to change mean temperatures but could also affect the statistics of variability too. Such results have a clear *impact* on policy decisions via bodies such as the Inter-governmental panel on climate change (IPCC). In the context of the recent summer heatwave, Schär et al. (2004) emphasize a possible dramatic decrease in the return period of such events from 46,000 years (based on the recent observational record) to 2 years by the end of the 21st century (based on particular greenhouse gas emission scenario assumptions). Environmental groups have highlighted France's reliance on river water, rather than sea-water as a coolant for it's nuclear industry. It is clearly conceivable that this climate change result could have an *impact* on the location of future power plants.

For monthly and seasonal forecasts, although strictly interactive, sea-surface temperature and soil moisture for example may provide a boundary forcing that allows some atmospheric predictability. Predictability for 2m temperatures for the week 9-15 June (from forecasts initiated on 4 June) (see Fig. 3) is likely to arise from a combination of information in the initial conditions and the boundary forcing. The results indicate a 98% chance of $T_{9\text{-}15June}>T_{clim}$ and a 90% chance of $T_{9\text{-}15June}>T_{clim}+1^{o}C$. Indeed, there appears to be predictive skill to the end of June with 80% probability that $T_{16\text{-}22June}>T_{clim}$ and 75% probability that $T_{23\text{-}29June}>T_{clim}$ both verifying in the observations. For July as a whole, there appears to be very little signal in the ensemble forecast (initiated on 1 June) although the observations do fall within the ensemble spread. For August, when peak temperatures were particularly severe and the greatest damage done, the ensemble forecasts (initiated on 1 June) failed to encompass the observations. If this very extreme event was unpredictable (sensitive to infinitesimally small changes in the initial conditions) then it is not necessarily a bad thing that it is not encompassed by a 40-member ensemble. However, a return period for the event of 46,000 years does not necessarily mean it was unpredictable. Atlantic and Mediterranean SST and European soil moisture were all extreme during this season and it is possible that these could have provided the boundary conditions, in a more perfect forecasting system, to allow a degree of predictability. See later for more details.

It may be that other variables (e.g. 500 hPa geopotential heights) or larger-scale modes of variability (e.g. the North Atlantic Oscillation) may be more predictable than local temperatures and precipitation. Clearly the predictability of the NAO is an important research topic and could be of interest to a specific user (*e.g.* in the financial derivatives market). The winter NAO has a particularly strong relationship with Scandinavian precipitation. In the late 1990's Norsk Hydro were working on the assumption that the recent 30-year trend in the NAO would continue and were basing infrastructure planning on an expected 20-30% increase in Norwegian precipitation (personal communication, Hans Alesel Hausen). However, the timeseries of the observed winter North Atlantic Oscillation (NAO) shows considerable decadal variability. Indeed, this decadal variability appears to distinguish the NAO from a simple red-noise process. If the recent trend in the NAO is not simply a manifestation of climate change, then these 'predictions' for future Norwegian precipitation may be invalid. (There could, for example be a downward trend over the next decade). More generally, a users' meeting, held as part of the recent EC-funded PREDICATE project, demonstrated a great interest on the part of the European utilities and financial sectors in decadal forecasting. However, it is unclear at present whether there is sufficient decadal predictability (above that from anthropogenic climate change) to make such forecasts useful.

We would argue that a forecast, whatever its skill, is of no value if it does not have a beneficial impact on decision making. In the preceeding paragraphs, it was clear that medium-range forecasts and climate forecasts do have such an impact. For monthly, seasonal and decadal forecasting, skill is likely to be quite low and so the utility of these forecasts needs to be quantified more carefully. Indeed, the existence of (financial) benefit may involve optimization of the whole "end-to-end" process involving the climate forecast model and the user's decision-making model.

In this paper, we discuss the observational and model-based evidence for seasonal to decadal predictability. We also discuss model-based studies that investigate the mechanisms of this predictability and techniques to validate model predictability. We discuss further the "end-to-end" approach to forecasting and highlight two classes of user action that can differ considerably in their effect. Finally, we highlight and demonstrate key issues for future development. We draw heavily on the results of two recent EC-funded projects: PREDICATE and DEMETER. PREDICATE investigated the coupled and un-coupled ocean-atmosphere system with a view to assessing seasonal to decadal predictability and the feasibility of making decadal forecasts. DEMETER was aimed at investigating "end-to-end" seasonal predictability and constructing a multi-model operational seasonal forecasting system.

Our aim is to address the following questions: What is the level of predictive skill in present forecasting systems? What is the uncertainty in these estimates? What are the sources of this predictability? What are the mechanisms that tie these sources to the weather that the user is interested in? What are the ultimate levels of predictive skill and what is the uncertainty in these estimates? What is the potential value of seasonal to decadal forecasts for the user? What are the key issues that need to be addressed to improve forecasting for the European region?

Observational evidence of predictability over Europe

Firstly, we consider ocean temperatures as possible quasi-boundary conditions that may lead to climate predictability. A natural starting point in the search for evidence of an oceanic influence on climate variability is to consider correlations (or covariances) between oceanic and atmospheric fields. Simultaneous correlations, however, tend to be dominated, particularly in the extratropics, by the ocean's response to atmospheric variability. Hence it is necessary to consider lead/lag correlations, in which the ocean fields lead the atmosphere fields. Czaja and Frankignoul (2002) performed a lagged maximum covariance analysis (MCA) between Atlantic ocean sea surface temperatures (SST; 20^oS-70^oN) and Atlantic sector 500 hPa geopotential height (Z_{500}). Their results indicate a significant influence of Atlantic Ocean conditions on the circulation of the atmosphere over the North Atlantic region in early winter (Nov-Dec-Jan). Figure 4, taken from their study, shows the leading MCA mode between summertime SST and early winter Z_{500}. The SST pattern has a horseshoe shape, while the Z_{500} field shows a dipole structure that is similar to the pattern of the North Atlantic Oscillation (NAO; Hurrell, 1995). The sign of the association is that positive SST anomalies in the low latitude North Atlantic are associated with a negative NAO index (according to the usual NAO sign convention). The timeseries is dominated by multi-annual variability (but note that the lowest frequencies were removed from the analysis).

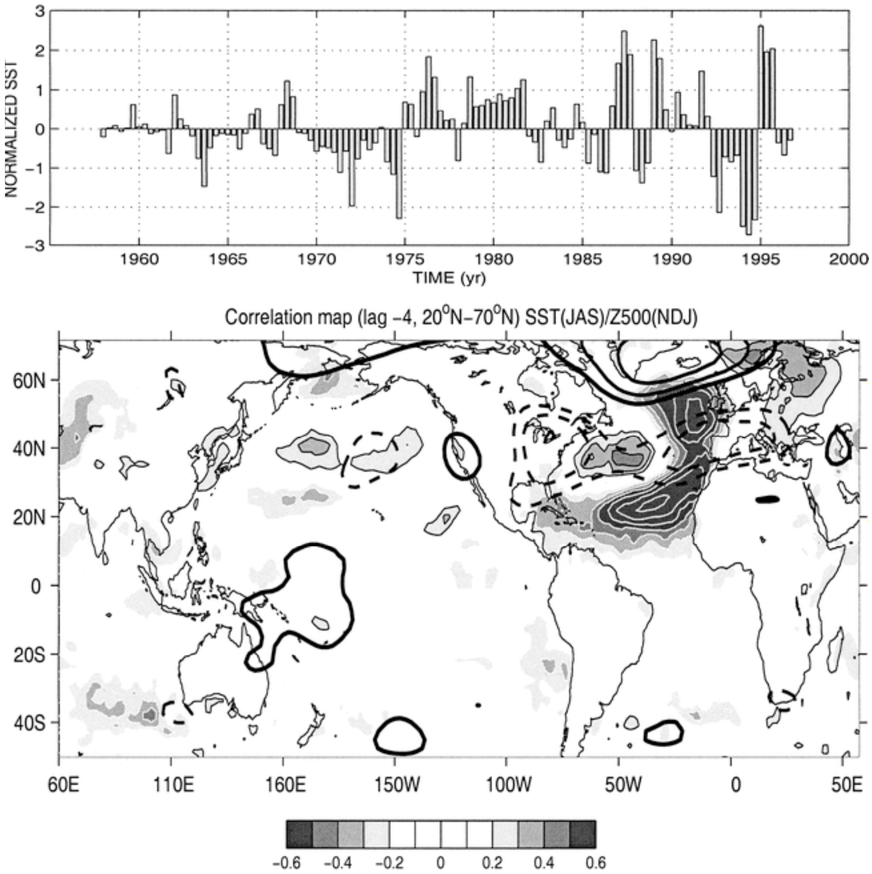

Fig. 4: Observationally-based maximal covariance analysis (MCA) results. (top) Normalised sea-surface temperature (SST) timeseries from the first MCA mode of Jun-spt SST and Nov-Jan 500 hPa geopotential height (Z500) in the midlatitude box [100°W-20°E, 20°N-70°N]. Each year consists of three vertical bars (jul-Aug-Sep). (bottom) Correlation maps between the above timeseries and Z500 (thick black contours, CI=0.1) and SST (shaded, with white contours for postive values and black contours for negative values, only correlations with amplitude ≥0.2 are indicated, CI=0.1). From Czaja and Frankignoul (2002).

The absence in Fig. 4(bottom) of significant correlations with SST variations outside the Atlantic basin is consistent with the suggestion that this mode is evidence of an Atlantic Ocean influence on climate. It is difficult to be certain, from an observational analysis, which SSTs are the most important for this apparent forcing but Czaja and Frankignoul (2002) suggested a major role for the midlatitude SST anomalies. In addition it should be noted that, because of the 4 month lag employed, we cannot infer that the atmosphere responds to the SST pattern indicated in Fig. 4; rather, it must respond to whatever ocean conditions develop from this pattern in the subsequent autumn and early winter. We may anticipate a significant degree of persistence in the pattern but the evolution will also be influenced by, for example, advection in the ocean and air-sea fluxes.

Rodwell and Folland (2002) performed a similar analysis to Czaja and Frankignoul (2002), and again found a significant association between the wintertime North Atlantic Oscillation and preceding anomalous conditions in the Atlantic Ocean. They used monthly SST data rather than 3 month means and found that a pattern of SST in the preceding May provided the best predictor of the subsequent wintertime (DJF) NAO, yielding a statistically significant correlation skill of 0.45. They suggested that the insulation (after May) of upper ocean temperature anomalies below a shallow summer layer and the subsequent mixing back to the surface in the following autumn and winter may provide memory for the forecast.

Kushnir (1994), following Bjerknes (1964), investigated the timescale dependence of the relationships between the atmosphere and Atlantic Ocean. He suggested that interdecadal timescale changes in SST associated with, for example, the Thermohaline circulation (McCartney and Talley, 1984) and the Gulf-stream/gyre circulation (Greatbatch et al., 1991) may have been responsible for the strong rise around 1970 in 15-year mean MSLP over the area 20°-40°W, 40°-50°N.

SSTs from other regions (e.g. the Indian Ocean, Hoerling et al., 2001, the South Atlantic, Robertson et al., 2000) could also have an influence on North Atlantic (and possibly European) climate and this may imply predictability at seasonal or longer timescales. Additional observational lagged MCA analyses in Rodwell and Folland, (2002) do highlight the importance of El Niño / La Niña SST anomalies for North Atlantic winter climate although the response does not necessarily involve the NAO. van Oldenborgh et al (2000) report a European March - May precipitation signal that appears to be a lagged response to December - February El Niño-Southern Oscillation SST anomalies.

Arctic sea ice anomalies may also play a role in North Atlantic climate although most of the evidence for this comes from model-based studies (see later).

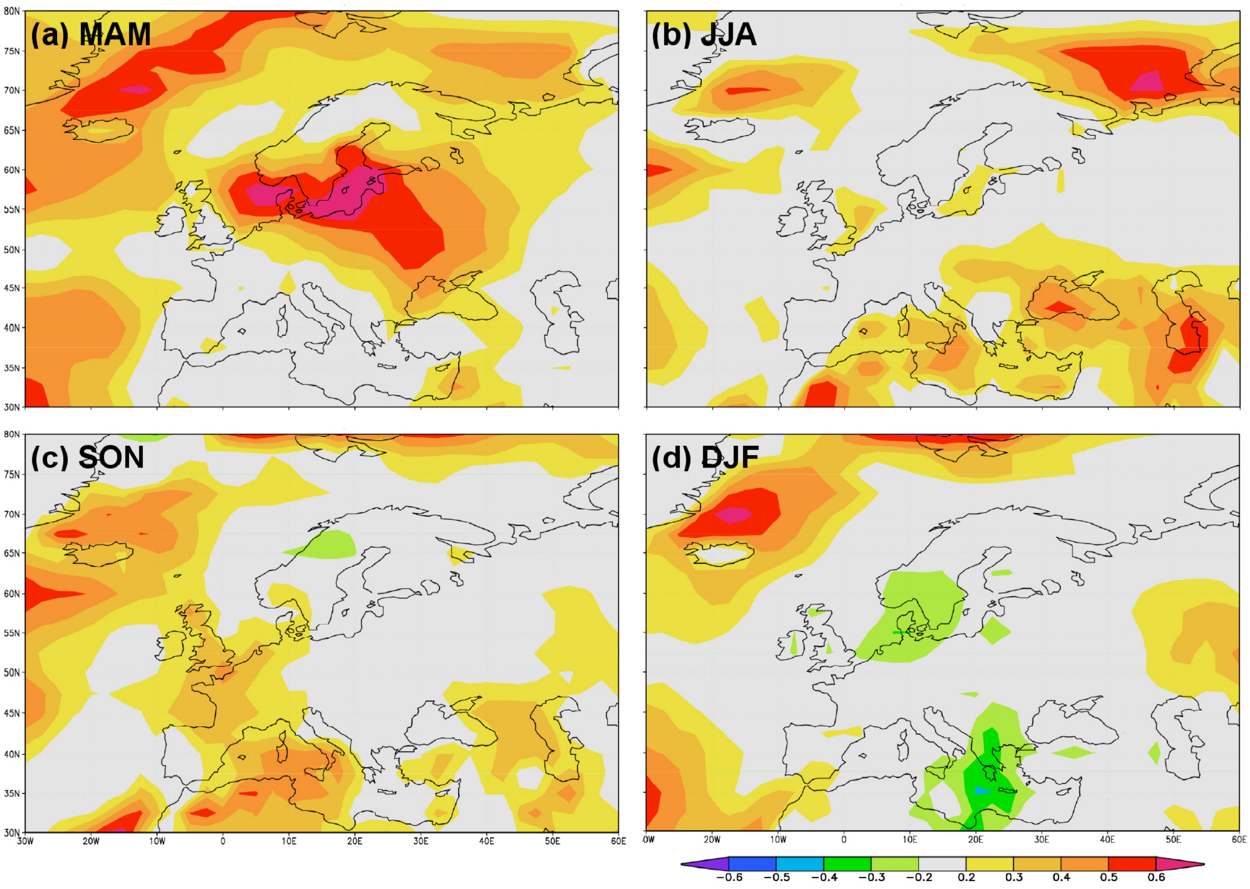

Fig. 5: Observationally-based local seasonal persistence forecasts (anomaly correlation skill) for 2m temperatures. (a) March-May (MAM) from January anomalies. (b) June-August (JJA) from April anomalies. (c) September=November (SON) from July anomalies. (d) December-February (DJF) from October anomalies. Data comes from ERA40 1959-2001. These plots can be readily constructed by the reader at climexp.knmi.nl.

For 2m temperatures, Fig. 5 shows that local persistence can provide some limited seasonal predictability for Europe. This may come from the persistence of local boundary conditions such as soil moisture (for example in summer in the more arid regions of Europe associated with a change in the Bowen ratio, Fig. 5b), snow-cover (for example in spring associated with albedo and latent heat effects, Fig. 5a) and coastal SST (the Baltic seems particularly influential in spring). For winter, atmospheric internal variability is strong and this reduces the skill of persistence forecasts, Fig. 5d. However, for winter, there is some observational evidence (*e.g.* Baldwin et al, 2003) that stratospheric annular mode anomalies lead the surface "Artic Oscillation" by a couple of weeks. How this apparent predictability translates into European-scale predictability is still unclear.

Observational studies, such as those highlighted above, are clearly essential if we are to validate our climate models and bench-mark the skill of their forecasts. On the other-hand, the shortness of the observational record and the inability to perform sensitivity studies means that model-based studies are also required to investigate the mechanisms through which the predictability arises. In the next two sections we quantify model-based predictability (in the boundary-value-forced AGCM context) and discuss mechanisms and model validation.

Potential predictability from forced AGCMs integrations

SST forcing

An assumption that has been traditionally made within predictability studies is that the SSTs can be considered as true boundary conditions (so that time variations of SSTs are independent of the atmosphere that we wish to predict). This assumption has been convenient because it has allowed the exploration of the climate system with atmospheric general circulation models (AGCMs) that have been more widely available and cheaper to run than coupled ocean-atmosphere models. Although two-way ocean-atmosphere coupling in the real world at the intraseasonal timescale (e.g. Barsugli and Battisti 1998, Bretherton and Battisti 2000) strictly invalidates the assumption that the SSTs are true boundary conditions the assumption remains a useful one because, for example, it provides a first estimate of "potential predictability" (an upper-bound of true predictability).

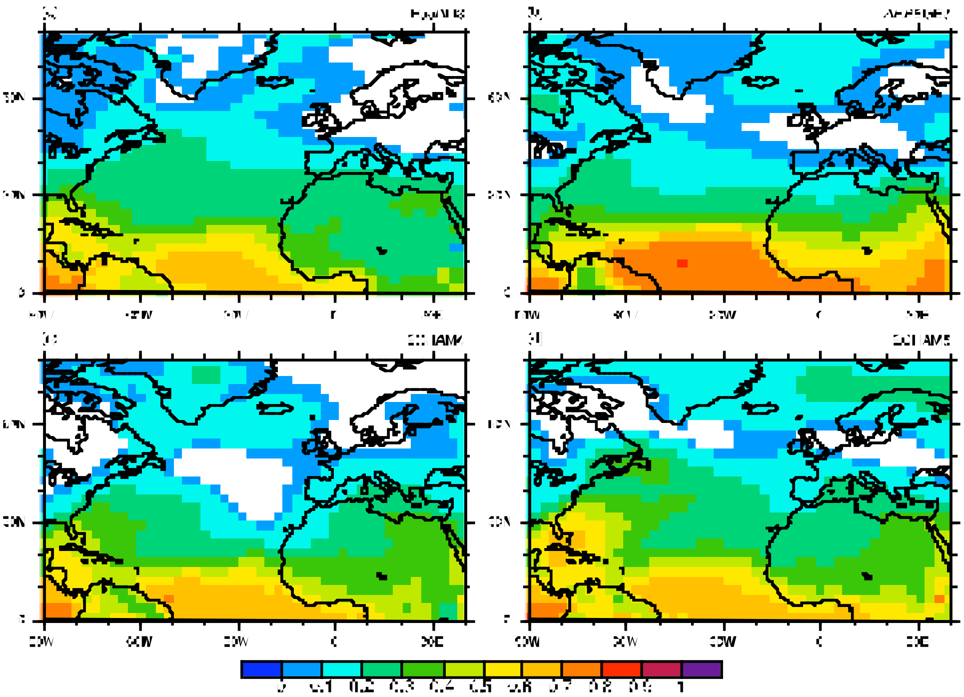

Fig 6: Atmospheric model potential predictability of December-February mean sea-level pressure estimated using ensembles of simulations from four atmospheric models. (a) UK Met Office HadAM3, 10 members, 1948-1998. (b) CERFACS ARPEFE3 8 members, 1948-1997. (c) MPI ECHAM4 6 members, 1951-1994. (d) MPI ECHAM5 4 members 1949-1997, run at DMI. Statistically insignificant values are shown in white.

For a given AGCM, an ensemble of simulations can be made which differ in their initial conditions but which are all forced with the same time-varying SST boundary conditions. “Potential predictability” is defined as the fraction of atmospheric variance that is explained by SST forcing (*i.e.* common to all ensemble members). It can be estimated using the analysis of variance (ANOVA) technique (see, e.g., Rowell and Zwiers, 1999). The word "potential" refers to the assumption that the model is "perfect enough" to make the estimate an achievable, upper bound for predictability if we could predict the SSTs perfectly. Comparison of the potential predictability estimated using different models can be a useful indicator for the sensitivity of true predictability to the representation of different physical processes.

Figure 6 shows potential predictability of winter mean sea-level pressure estimated, within the EC-funded PREDICATE project, using ensembles of simulations over the period 1950-1999 from four different AGCMs. The general picture, which is a well-known result (see, *e.g.*, Kushnir et al. 2002), is that there is relatively high potential predictability in the tropics and subtropics but that this drops-off rapidly as we move to mid-latitudes. There appears to be very little potential predictability, based on SST forcing alone, for Europe. In each model, there appears to be a region of relatively more potential predictability around Iceland and this is consistent with the fact that extratropical North Atlantic predictability studies have tended to focus on the NAO. Note that there are rather large differences between the models, even in the tropics, but it is unclear from these figures whether this represents true model differences or simply sampling uncertainties.

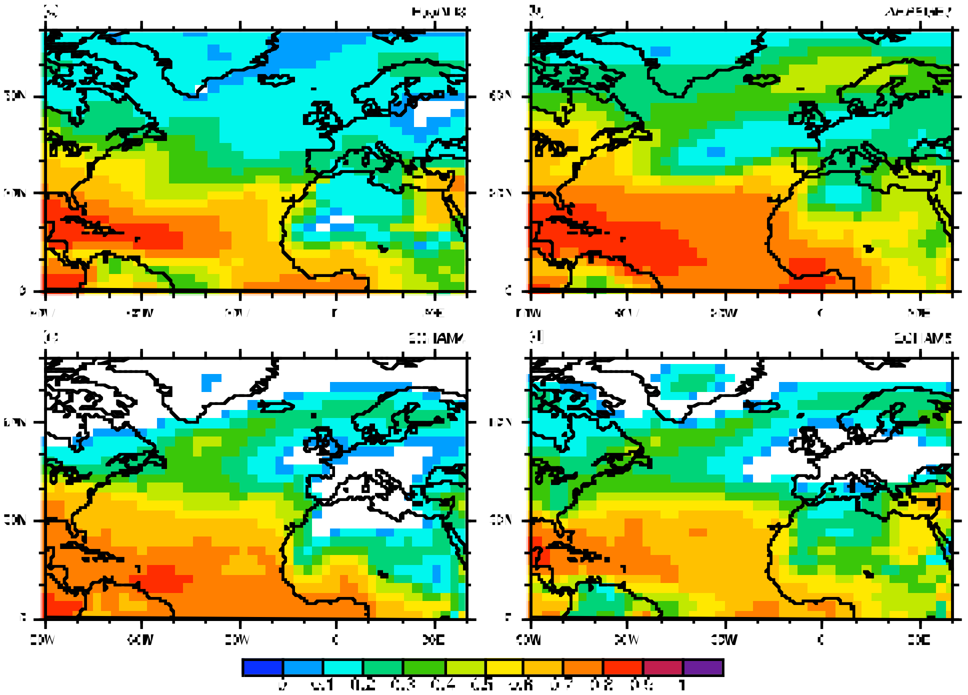

Fig 7: Atmospheric model potential predictability of low-frequency June-August mean sea-level pressure estimated using ensembles of simulations from four atmospheric models. (a) UK Met Office HadAM3 10 members 1948-1988. (b) CERFACS ARPEGE3 8 members 1948-1997. (c) MPI ECHAM4 6 members 1951-1994. (d) MPI ECHAMS5 4 members 1949-1997, run at DMI. Statistically insignificant values are shown in white.

There are somewhat more optimistic sets of results than those shown in Fig. 6. For example, the summer (June - August) tends to be more potentially predictable than winter, partly because JJA has weaker internal variability. In addition, the ANOVA technique can be extended in the frequency domain (Rowell and Zwiers 1999) and results suggest that the percentage of total variability that is forced by SSTs tends to increase as longer timescales are considered. Figure

7, which shows the most optimistic set of results, gives potential predictability for June - August fluctuations in MSLP that are longer than about 6.5 years. The increased potential predictability for longer timescale fluctuations is presumably a reflection of the fact that internal variability in the atmosphere has a white spectrum whereas SST variability displays a redder spectrum. The Caribbean basin is the main center of decadal variability of the SST forcing and related convection activity. It could influence the North Atlantic region through Rossby wave teleconnections (Hoskins and Sardeshmukh, 1987). In addition, the so-called tropical Atlantic interhemispheric mode has more power at decadal timescales. ARPEGE3 appears to show the highest estimates of extratropical potential predictability. However, statistical significance is even harder to achieve at these longer timescales and apparent model differences may be more due to sampling uncertainties.

Autumn values are generally close to summer ones in the tropical-subtropical band while becoming very weak and barely significant at higher latitudes. Potential predictability minima are obtained for the spring season for all models.

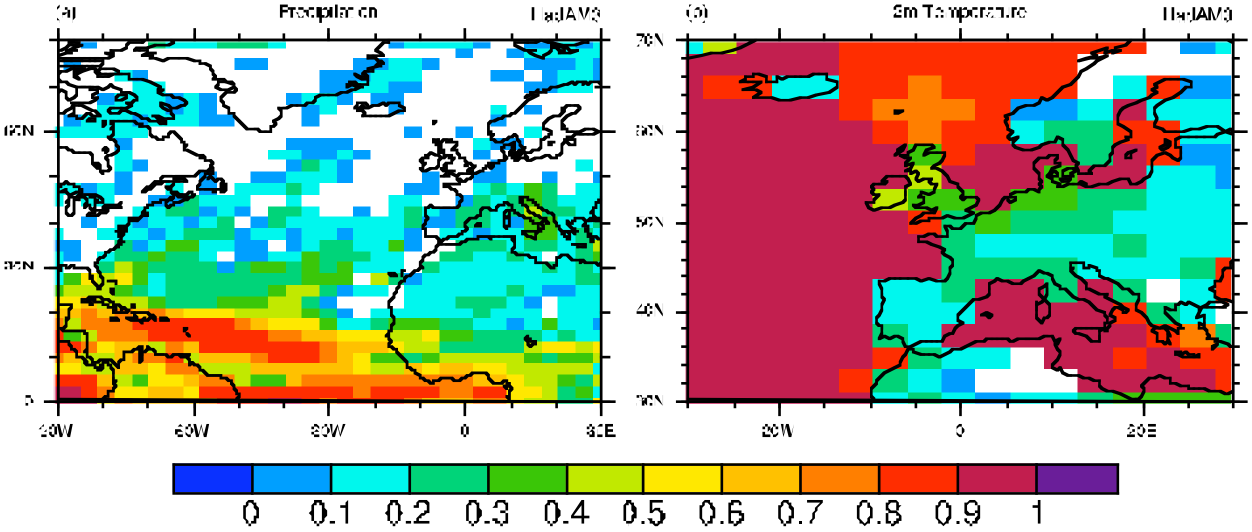

Fig. I: Atmospheric model potential predictability of low frequency June-August. (a) precipitation and (b) 2m temperature, estimated using a 10-member ensemble of simulations from the atmospheric model HadAM3 for the period 1948-1998. Statiscally insignificant values are shown in white.

Figure 8a shows that precipitation displays very weak potential predictability, even at low frequencies, except within the tropical band and to a much lower extent, over the Mediterranean and surrounding land areas. European 2m temperatures (Fig. 8b) also appear to be only weakly potentially predictable from SST forcing.

It is important to recall here that potential predictability, based on the ANOVA methodology, is a simple estimate for predictability and should be viewed with caution. Many hypotheses are necessary to perform and legitimise the variance decomposition. For instance, the interaction between internal and forced variability is generally neglected (Peng and Robinson 2001). In addition, the source of the predictability (*i.e.* which ocean basin is most important for the forcing) is not indicated. Above all, the model is assumed to be perfect; an imperfect model could over-estimate or under-estimate the potential predictability depending on how well it represents the salient physics.

Instead of estimating potential predictability, we can assess how well present (imperfect) AGCMs can “predict” the observed atmosphere. Within the AGCM framework, we continue to assume that the SSTs are perfectly predictable boundary conditions and so we define the "potential predictive skill" to be the correlation between the ensemble mean response and the observations.

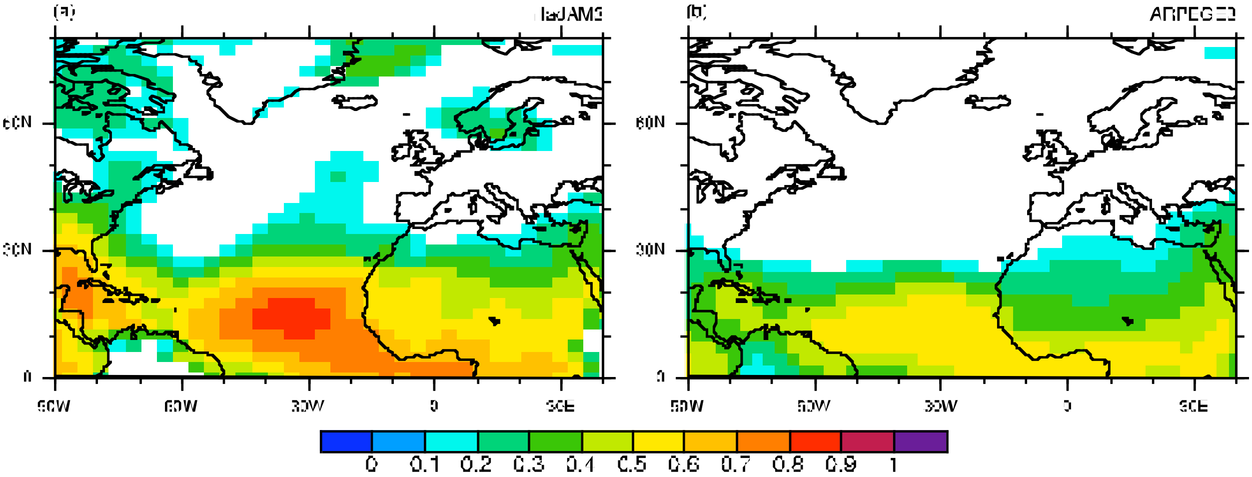

Fig. 9: Atmospheric model potential predictive skill of December-February mean sea-level pressure estimated using ensembles of simulations from two atmospheric models. (a) UK Met Office HadAM3 10 members 1948-1998. (b) CERFACS ARPEGE3 8 members 1948-1997. Statistically insignificants values are shown in white.

Figure 9 shows the DJF potential predictive skill for MSLP from two of the models. While the potential predictive skill results tend to confirm the higher levels of potential predictability for the tropics, there is very little statistically significant predictive skill in the extratropics. This could indicate that each model's ensemble members agree with each other too well in the extratropics (thus inflating the potential predictability) *or* that all the models fail to capture an important physical process (thus deflating the potential predictive skill). Although the role of tropical SST in forcing the atmosphere is thought to be better understood than that of extratropical SST, the differences between the models in Fig. 9 suggests that further work is still required, even for the tropics.

It is possible that more potential predictive skill may be achieved for particular modes of variability. Several studies, starting with Rodwell et al (1999) (see also Mehta et al, 2000 and Doblas-Reyes et al, 2003) have shown some potential predictive skill in reproducing the historical record of variability in the winter NAO (an interannual correlation of 0.41 was achieved with 6 ensemble members over the period 1947-1997). These studies suggest a significant oceanic influence on modes of variability of North Atlantic climate, but there is some debate about which regions of the ocean are most important. For the NAO mode, Rodwell et al (1999) emphasised the role of SST anomalies in the Atlantic basin, whereas Hoerling et al (2001) suggested that the rising trend in the NAO index that was observed in the later part of the twentieth century was primarily a response to SST changes in the tropical Pacific and Indian Oceans, with little role for the Atlantic. Cassou and Terray (2001) found relationships between modes of atmospheric variability in the North Atlantic region and both ENSO and Atlantic SST although it was unclear whether these represented independent forcing mechanisms. Cassou and Terray (2001) also suggested that extratropical North Atlantic SST anomalies may be the signature of the atmospheric response to tropical Atlantic SST forcing. Further investigation is required to resolve these differences over which SSTs are important.

PROVOST considered a multi-model approach to potential predictive skill. Figure 10 (open bars) shows potential seasonal predictive skill of area-averaged European Z_{500} from four atmospheric models. There does appear to be some skill in all seasons but this is rather weak (and somewhat mixed in autumn). Notice that the best individual model changes from season to season. Figure 10, filled bars shows the potential predictive skill of the multi-model mean.

Interestingly, the multi-model mean shows a similar level of potential predictive skill to that of the best individual model for each season. It has been demonstrated that this is not simply due to the multi-model having a larger ensemble size (Doblas-Reyes et al. 2000).

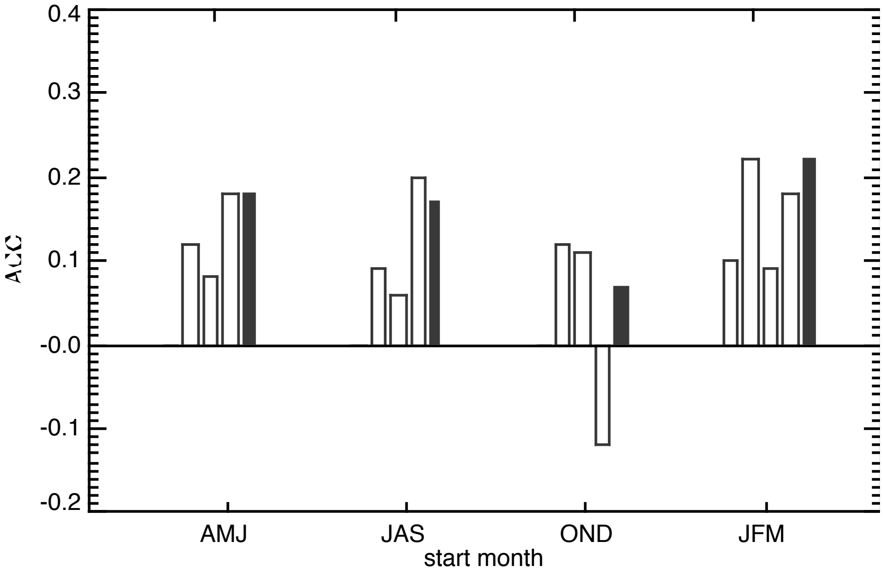

Fig. 10: Atmospheric model forecast correlation skill for European 500 hPa geopotential height anomalies 1979-1993, first averaged over the box [12.5°W-42.5°E, 35°N-75°N] and over the forecast months 2-4 from (open bars) the individual models used in the EC-funded PROVOST project forced with observed SST and (filled bars) the mean of all models. The seasons shown are April-June (AMJ), July-September (JAS), October-December (OND) and January-March (JFM). Verification data comes from ERA40.

Clearly potential predictability and predictive skill measures need to be completed with a more mechanistic approach (sensitivity experiments to a given SST pattern for instance). A discussion of such mechanisms is given in section 4. Firstly, however, the effects of other "boundary forcings" are considered.

Sea Ice forcing

Model sensitivity studies also show that Arctic sea-ice anomalies can affect surface heat-fluxes. Generally, the surface heat flux anomaly appears as a dipole centred over the new ice-edge and this can lead to a direct small-scale baroclinic response (Deser et al. 2004) and an indirect barotropic response (which projects onto a large-scale mode (the NAO) of internal variability).

Land surface "forcing"

Land properties such as soil moisture and snow depth also show significant persistence at the monthly to seasonal timescale. Although it is less justifiable to consider these properties as pure boundary conditions for the atmosphere, they are in closer proximity (than SST) to the land weather variables we wish to predict. Land properties may, therefore, represent another potential source of seasonal predictability.

Delworth and Manabe (1988 and 1989) showed that interactive soil moisture may substantially increase the variability of near-surface temperature and relative humidity, especially in summer at midlatitudes (see also Koster et al. 2000). Moreover, they found that soil moisture anomalies could persist over monthly to seasonal time scales, suggesting the relevance of initial soil moisture conditions for seasonal climate simulations. However Koster et al. (2002) showed that the relevance of the land surface feedback could be highly model dependent.

Global estimations of soil moisture can now be derived from operational land surface data assimilation systems (Houser et al. 2004) or by driving land-surface models (LSMs) with analyses of precipitation and solar radiation. This latter technique has been used in the Global

Soil Wetness Project to provide global soil moisture datasets (IGPO, 1998). Atmospheric simulations for the summers 1987 and 1988 have been shown to better capture seasonal precipitation anomalies over Eurasia when the soil moisture from an LSM is prescribed or relaxed-to (Dirmeyer 2000, Douville and Chauvin 2000; Douville 2002).

Douville (2004) performed several ensembles of boreal summer hindcasts, spanning the period 1979-1993 and initialized with the ERA15 reanalysis using interactive, relaxed and fixed soil moisture conditions. While it was shown that interactive soil moisture strongly contributes to climate variability, it does not represent a significant source of predictability in most continental areas, including Europe. He concluded that the relevance of soil moisture for seasonal forecasting is mainly an initial value problem.

Fennessy and Shukla (1999) showed that the impact of initial soil moisture was mainly local and was largest on near-surface fields. Kanamitsu et al. (2003) found a significant initial soil moisture impact on near-surface temperature in arid/semiarid areas. However, Douville and Chauvin (2000) and Dirmeyer (2003) highlight problems in estimating predictability if there is significant drift of soil moisture in the model. Figure 11 and Table I (personal communication, Laura Ferranti) show the effect of perturbing *initial* soil moisture conditions for seasonal forecasts started on 1 June 2003. Drier conditions lead to warmer surface air temperatures, presumably by increasing surface sensible heat fluxes at the expense of surface latent heat fluxes (evaporation). The initial soil moisture anomalies gradually decay over the course of the season but still lead to statistically significant temperature anomalies in July and August. The ECMWF operational analysis had a European average soil moisture content of about 75% on 1 June 2003. However, there is some doubt about the accuracy of this initialization. Table I suggests that a value of 25% would have increased the ensemble 2m temperature forecast for August (see Fig. 3) by around 2°C. If the soil moisture content had been initialized at 50%, this would still have led to a higher temperature forecast and thus have had a beneficial impact on the seasonal forecast.

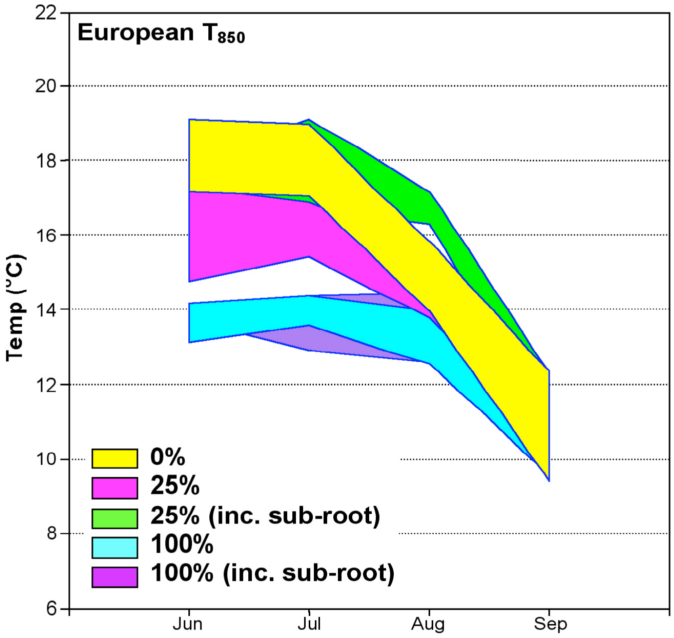

Fig. 11: European 850hPa temperatures (T_{850}) averaged over 40-50°N, 0-20°E based on five 9-member ensembles of atmospheric model simulations started from 1 June 2003. Each ensemble is initiated with different soil moisture conditions (as indicated). The model is the European Centre for Medium-range Weather Forecast model cycle 26R3. (Personal communication, Laura Ferranti).

	Jun	Jul	Aug
Z_{500} (m)	+16	+2.5	
T_{850} (K)	+3.4	+3.5	+2.0
Z_{1000} (m)	-6	-23	-17
T_{2m} (K)	+4.0	+3.5	+2.0

Table I. *Monthly-mean European sensitivity (averaged over the box 10°W-30°E, 37°N–60°N) to a change in initial soil moisture content. Results are the difference between the means of two 9-member ensembles of atmospheric model simulations with 25% and 75% initial soil moisture content, respectively. Simulations were started on 1 June 2003. The model is the European Centre for Medium-range weather forecast model, cycle 26R3. Results from Laura Ferranti.*

Aerosol forcing

Recently, a new aerosol climatology has been introduced into the ECMWF forecasting system. Reduced Saharan dust levels lead to reduced shortwave absorption in the boundary layer and thus a reduced tendency to destabilize the atmosphere. The result was a dramatic decrease in systematic error in the north African monsoon and major changes (up to 4 ms^{-1}) in systematic surface wind error over the subtropical and tropical north Atlantic. Such wind changes are in the correct sense so that they could, in a fully coupled system, also improve the zonal gradients in thermocline depth (many coupled models, including that at ECMWF, presently show a positive west-to-east SST gradient in the tropical Atlantic rather than the observed negative gradient, personal communication, Tim Stockdale). This example is included here to demonstrate that there are still major systematic errors within models. Clearly this particular improvement is very likely to improve forecasts of precipitation anomalies over the Sahel (as well as the model's mean climate) but through tropical / extratropical interactions (see next section) it could also have a beneficial effect on European predictability.

Mechanisms and model validation

The analysis of variance (ANOVA) technique was used above to identify potential predictability from SST forcing. Here we attempt to identify which SSTs are most important for forcing a North Atlantic region atmospheric response, investigate the mechanisms involved in the forcing and attempt to validate models with observations. The issue of predictability is of less interest in this section.

Sutton and Hodson (2003) used an optimal detection method (Venzke et al, 1999) to analyse the years 1871-1999 from a 6-member ensemble of ACGM simulations performed at the Hadley Centre with the HadAM3 model. This approach, which is based on an analysis of signal to noise ratios, is attractive because it provides an objective way to identify which regions of the ocean are most important for forcing the atmosphere.

Figure 12, taken from Sutton and Hodson (2003), shows the leading mode of SST-forced variability in North Atlantic wintertime MSLP. The MSLP pattern exhibits a dipole over the North Atlantic that has similarities to the NAO pattern. The timeseries displays interannual variability that appears to be superposed on a much longer timescale, multidecadal, variation. The SST pattern, which is obtained by regression on the timeseries, shows the highest fraction of variance explained in the tropical North Atlantic region. Sutton and Hodson concluded that SST in the tropical North Atlantic may have the dominant role in forcing this mode.

As part of the EC-funded PREDICATE project the same analysis as shown in Fig 12 was carried out on ensemble simulations with three other atmosphere models: ECHAM4, ARPEGE3 and ECHAM5. ARPEGE3 and ECHAM5 showed a similar leading mode to that of HadAM3 but, for reasons that are unclear, ECHAM4 displayed a dominant response to ENSO.

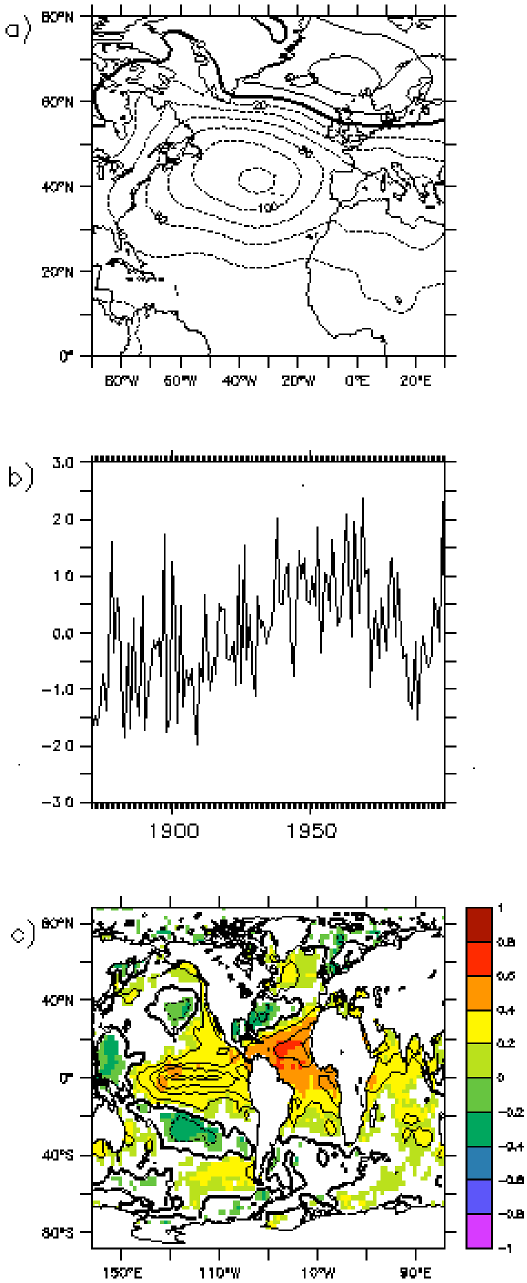

Fig. 12: The leading mode of se-surface temperature (SST)-forced mean sea-level pressure (MSLP) variability in winter (Decmber-February, DJF) over the north Atlantic region from a 6-member ensemble of 1871-1999 simulations of the UK Met Office's HadAM3 atmospheric model. (a) Contours show mean seal level pressure in Pa. (b) The normalised time series. (c) the SST patterns derived by regression on the timeseries (contour interval is 0.1K), shading shows the square-rrot fraction of the SST variance explained, multiplied by the sign of the regression coefficient. White regions are those where the regression coefficient is not significant at the 93% confidence level. From Sutton and Hodson (2003)

Fig. 13: As Fig 12 but for the leading mode of SST-forced variability of detrended, low-pass filtered MSLP. From Sutton and Hodson (2003)

When low frequencies were analysed separately, Sutton and Hodson (2003) found that the significant SST-forcing regions extended into the extratropical North Atlantic (Fig. 13) and they suggested this was indicative of a link to the Thermohaline Circulation (Delworth and Mann, 2000). The implication is that, if it proves possible to predict variations in the THC, it may also be possible to predict some of the multidecadal variability in North Atlantic / European climate. A high frequency analysis emphasised a dual influence of ENSO and tropical Atlantic SST.

A critical question, of course, is what is the mechanism via which Atlantic SST anomalies induce the atmospheric responses shown in Fig.12 and Fig.13? The mechanism could involve the influence of tropical SST anomalies on local convection. Associated with the tropical precipitation anomalies will be anomalous diabatic heating and a Rossby wave source (e.g. Hoskins and Ambrizzi 1993). Ambrizzi and Hoskins (1997) showed that for a zonally extended source, such as that associated with ITCZ anomalies in the tropical Atlantic, theory predicts the excitation of Rossby waves that propagate meridionally into midlatitudes, and exhibit a zonal scale similar to that of the source.

An interesting aspect of this mechanism is that it suggests that the influence on climate of interannual variability in the tropical Atlantic ocean may be modulated by variability on longer timescales. The reason is that the sensitivity of tropical convection to SST is highly nonlinear, hence the magnitude of the convective response will depend not simply on the magnitude of the SST anomaly but also on the absolute SST. If the ``background'' SST varies on multidecadal timescales as a consequence of, e.g., variability in the Thermohaline Circulation, then we might expect that the strength of the atmospheric response to be correspondingly modulated. This idea offers a possible explanation for the non-stationarity of the oceanic influence on North Atlantic / European climate that was found by Sutton and Hodson (2003).

Figures 6, 7 and 9 showed differences in the estimated potential predictability or potential predictive skill between the models. Because of the relative shortness of the simulations and the rather small ensemble sizes it is not clear how much of these differences represent real differences in model response. Hence there are also uncertainties in the mechanisms of the response. Rodwell et al (2004) conducted some highly controlled experiments, with a fixed annual cycle in SST anomalies, with the PREDICATE AGCMs (and also the CAM2 AGCM from NCAR) to determine more clearly the model differences. They found surprising agreement between the models in their global response to north Atlantic SST anomalies. The multi-model mean response, Fig. 14, was generally larger in magnitude than the intermodel differences. Much of the large-scale response appeared to be forced by the tropical north Atlantic SST anomalies (this is also in agreement with the results of Cassou and Terray 2001 and Terray and Cassou, 2002). For the response over Europe, SST anomalies in the Caribbean region and over the extratropical north Atlantic appeared to be important. Although Europe does not stand out in ANOVA results as a region that is generally affected by SST variability, this controlled experiment showed that there could be “windows of opportunity” when a strong (possibly predictable) European signal could arise for particular SST anomaly patterns. Rodwell et al (2004) point to two timescales for which SST anomalies could be important for extratropical climate variability: a 2-year timescale associated with responses to mixed-layer temperature anomalies (Alexander and Deser, 1995) and a 30-year timescale associated with, for example, fluctuations in the thermohaline circulation.

The SST anomaly patterns that Rodwell et al (2004) used came from a lagged maximal covariance analysis (MCA) of observed SST and Z_{500}. The Z_{500} patterns that result from this lagged MCA (Fig. 15) are estimates of the observational atmospheric response to the SST anomaly patterns and can be compared with the multi-model response (Fig. 14, row 3). Pattern correlations between the multi-model response and the observational response (in regions where the multi-model response is statistically significant) are indicated in Fig. 15. For MAM and JJA similar extratropical Rossby-wave-like patterns, that appear to emanate from the Caribbean region, were seen in both multi-model and MCA results. SON also showed reasonable agreement, particularly in the subtropics, between multi-model and MCA. There was a complete failure of agreement in DJF when internal variability in the observations may be a factor.

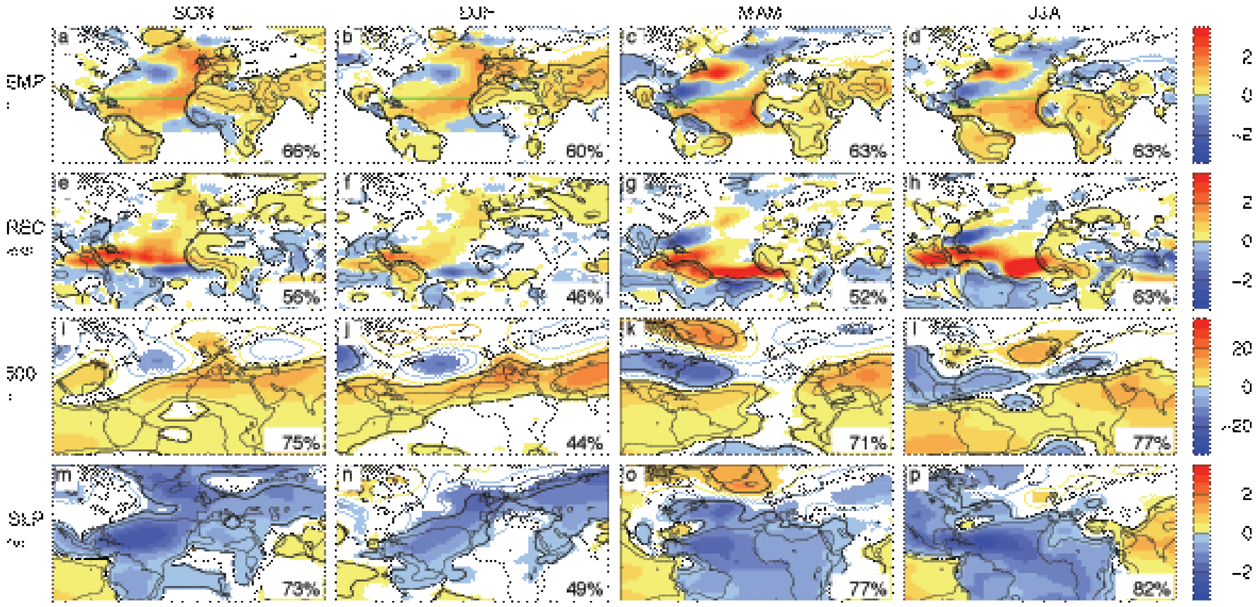

Fig. 14: Seasonal-mean results from the multi-model of six models forced with the same north Atlantic sea-surface temperature (SST) anomalies. The rows correspond to surface temperature (TEMP), total precipitation (PREC), 500hPa geopotential height (Z500) and mean sea level pressure (MDSLP), respectively. The columns refer to the seasons September-November (SON), December-February (DJF), March-May (MAM) and June-July (JJA). The SST anomalies used in the North Atlantic region can be seen in the top panels. Signals that are significant at the 10% level using a 2-sided t-test are filled in colour; other values are contoured (contours indicate values at the centre of each colour range). The quoted percentages refer to the percentage of the area shown (land area for TEMP) for which the anomaly is statistically significant at the 10% level (and therefore indicate the degree of field significance). Black contours indicate the timescale, n, (thick: 10 years, thin: 2 years) at which the response is an important component of total variability (the timescale at which the magnitude of the response is equal to the standard deviation of n-year-filtered atmospheric internal variability). The timescale is not applicable for TEMP over the sea. For clarity, the timescale for PREC is not plotted over the SST forcing region where is nearly always less than 2 years and it is smoothed for TEMP and PREC using a triangular truncation at T31. When the timescale dependence of the forcing strength is considered, the thick black contour is associated with a ~30 year timescale. From Rodwell et al. (2004).

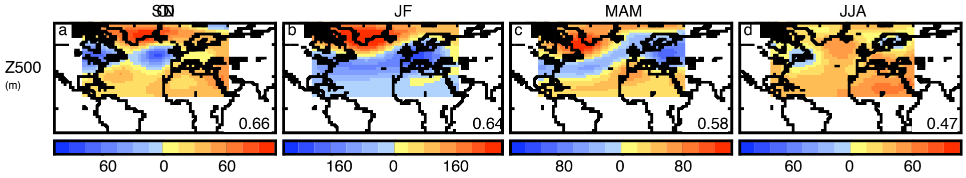

Fig. 15: The 500 hPa geopotential height (Z500) anomaly patterns that arise in the observational maximal covariance analysis used to produce the forcing sea-surface temperature anomalies shown in Fig. 14. The seasons shown are September-November (SON), December-February (DJF), March-May (MAM) and June-July (JJA). The pattern magnitudes can be compared to the multi-model mean response in Fig. 14 (row 3). Area-weighted pattern correlations with the statistically significant parts of the multi-model mean response in Fig. 14 are quoted. From Rodwell et al (2004).

Rodwell et al (2004) argued that, on the whole, the results tended to validate the model responses and also validate the application of lagged MCA to observational data. Note, however, that the multi-model responses are a factor of 2 or 3 weaker than the MCA response patterns. This may be partly associated with the optimization inherent in the MCA technique. It could also be partly associated with disagreement between models although all models individually show weaker Z500 responses than those estimated from the observations. Hence it is possible that the models may not respond strongly enough to the applied SST anomalies. If there is some truth in the latter explanation, this could imply that potential predictability is under estimated with present models.

Rodwell et al (2004) also noted some sensitivity in model responses associated with the interactions with north Atlantic storm track (see also Peng and Whitaker (1999), Peng et al. (2002), Kushnir et al. (2002)) and this may be an important topic for future research.

While the study of the atmospheric response to given SST anomalies tell us important things about atmospheric models, the behavior within the fully coupled system could be different. For example, an atmospheric model that responds too strongly to a given SST anomaly will likely have a strong negative heat flux feedback with SST in the coupled system. This may lead to SST anomalies being damped too vigorously and thus being weaker or less persistent. The end result may not necessarily be an over estimation of the role of SST in climate variability but rather a shortening of the salient timescales. Clearly there is a need to understand and validate heat flux feedbacks in coupled models. Firstly, however, we need to determine what the feedbacks are in reality. Frankignoul and Kestenare (2002) attempted to estimate the heat flux feedback from "observational" data using (necessarily) lagged covariances of monthly-mean SST and surface heat-flux data. In general they found a strong negative feedback; particularly in the mid-latitude winter when strong mean windspeeds enhance the influence of anomalous SST on surface turbulent heat flux and lead to values in excess of -40 $Wm^{-2}K^{-1}$. (This is in agreement with AGCM results of Peng et al, 1997 and Rodwell et al, 1999 but in disagreement with the positive feedbacks in the hypothesized decadal oscillation of Latif and Barnett, 1994). However, Frankignoul and Kestenare (2002) find some sensitivity to the observational datasets they use. Radiative feedbacks were found to be generally smaller, giving less confidence in their sign, and often confined to the tropics. Frankignoul et al., (2004) went on to estimate heat flux feedbacks in several coupled models. Their results were broadly in agreement with the observational estimates but the negative midlatitude feedbacks were substantially underestimated in several models. For example, heat flux feedback estimates based on latitudinal bands over the Atlantic maximize at 26 $Wm^{-2}K^{-1}$ at around 30°N in NCEP, 22 $Wm^{-2}K^{-1}$ at 40°N in COADS but only 15 $Wm^{-2}K^{-1}$ in HadCM3 and in the CERFACS model, both at 30°N. This underestimation is certainly consistent with the indicated reduced sensitivity to prescribed SST anomalies found in Rodwell et al (2004). Frankignoul et al., (2004) also found strong model sensitivity in the tropical radiative feedback component.

While bearing in mind that the above feedback uncertainties, and other model uncertainties (e.g. associated with land-surface processes) will impact on our estimates of seasonal to decadal predictability, we now turn our attention to operational forecasting systems based on current coupled models.

Seasonal predictability from coupled GCMs integrations

As we have already seen, the potential predictability of seasonal means is low, especially for extra-tropical regions, and it is also highly model dependent. The conclusions also apply for the estimates of actual skill with state-of-the-art coupled models as shown in the experiments of the DEMETER project (Hagedorn et al., 2005). The DEMETER project (Palmer et al., 2004) evaluated seasonal to interannual prediction in a multi-model system. Seven coupled models were used to produce six-month long hindcasts, four times per year, for at least the 22-year period 1980-2001. For three of the models, more than 40 years were simulated. Nine-member ensembles were produced to sample initial condition uncertainty while the multi-model approach was used to empirically sample model uncertainty.

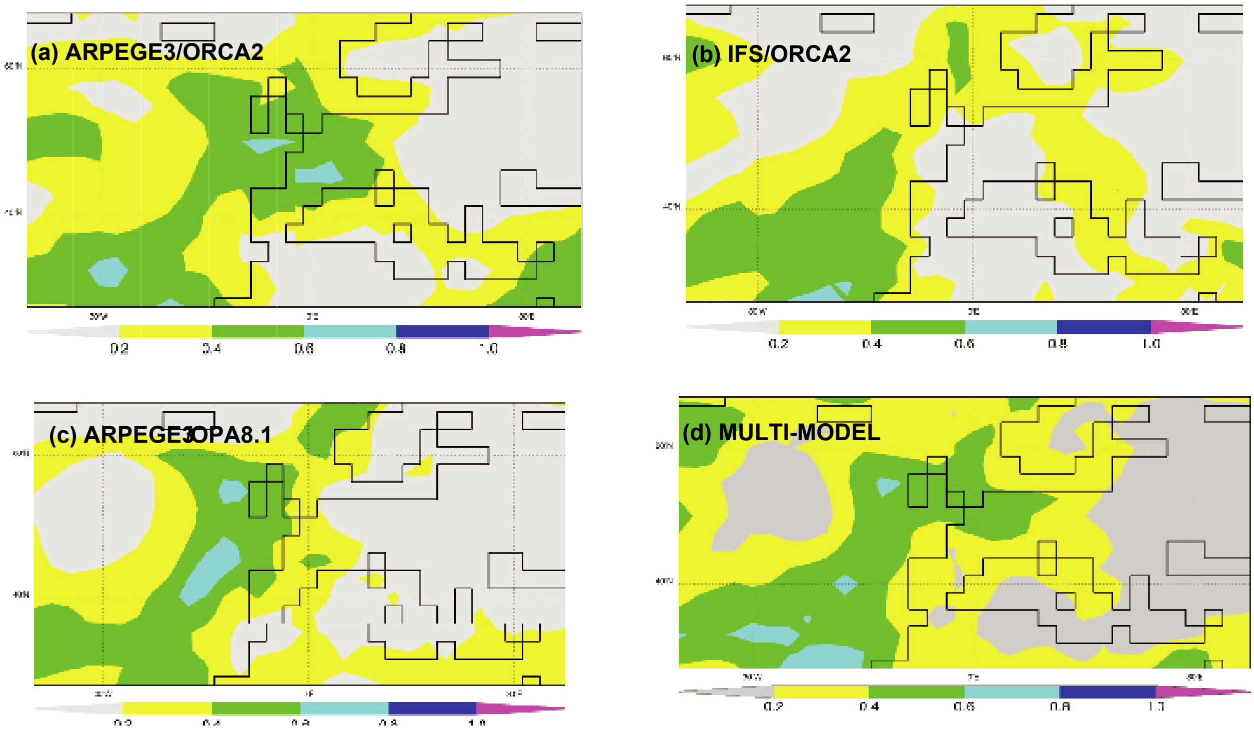

Fig. 16: Coupled-model predictive skill (anomaly correlations with ERA40) of winter (December-February) 2m temperature anomalies based on hindcasts initiated on 1 November for the years 1980-2001. (a) The ARPEGE3 atmosphere model coupled to the ORCA2 ocean model. (b) The ECMWF IFS atmosphere model coupled to the ORCA2 ocean model. (c) The ARPEGE3 atmosphere model coupled to the OPA8.1 ocean model. (d) The mean of all seven DEMETER coupled models.

Figure 16a-c show, for three individual DEMETER models, the grid-point correlation skill for wintertime (DJF) 850 hPa temperature from hindcasts initiated on 1 November over the period 1980-2001. While the models tend to agree on the levels of subtropical predictive skill, there is large uncertainty over Europe and this appears to be most sensitive to the atmospheric component of the coupled model. The range of correlation skill for Europe is from less than 0.2 to over 0.6. The significance of these differences is unclear owing to the relatively low number of years and the existence of spatial autocorrelation of the fields. In addition, part of the skill differences may be associated with relatively small spatial shifts in the predicted signals.

In spite of the low and sparse positive scores found for each individual model, the multi-model ensemble mean (Fig. 16d) displays a slightly more optimistic picture. Positive correlations are found over most of Europe and significant values appear in many areas. Figure 17 shows correlation skill for European average 500 hPa geopotential heights from each of the DEMETER models (open bars). While not particularly strong, the coupled model skill is comparable in magnitude to the skill obtained from the PROVOST atmospheric model simulations forced with observed SST (Fig. 10). The multi-model (filled bars) does as well, or better, than the best model in summer and winter but individual model inconsistencies in spring and autumn also affect the multi-model. The general improvement in skill from using the multi-model is more obvious in a probabilistic setting. It is due mainly to an increase in the “reliability” of the predictions, associated with a cancellation of errors between models and an increase in spread that samples better the forecast uncertainty. Although locally a single-model may have more skill than the multi-model, over large areas and long periods of time the multi-model is superior to any single model (Hagedorn et al., 2005).

There is also some indication that coupled models may show more predictive skill for the North Atlantic region in winter than that suggested from potential skill estimates based on PROVOST-style simulations forced with observed SST (Michel Déqué, personal communication). Similar

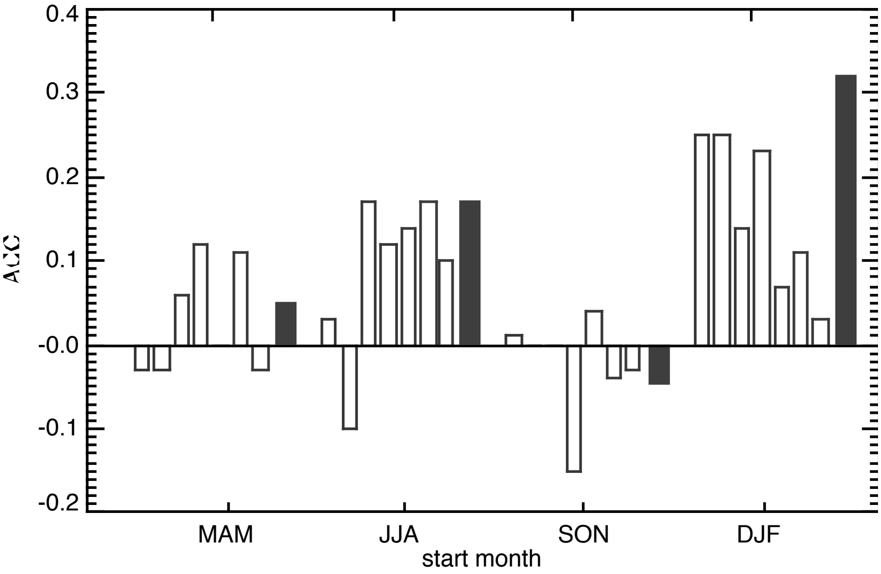

Fig. 17: Coupled-model forecast correlation skill for European 500 hPa geopotential height anomalies 1980-2001, first averaged over the box [12.5°W-42.5°E, 35°N-75°N] and over the forecast moths 2-4 from (open bars) the individual coupled models used in the EC-funded DEMETER and (filled bars) the mean of all models. The seasons shown are March-May (MAM), June-August (JJA), September-November (SON) and December-February (DJF). Verification data comes from ERA40.

conclusions have been reached with the Met Office model (Graham et al., 2005). While this result needs to be confirmed and understood physically, it does suggest the possibility for a little extra optimism for European seasonal prediction.

The success of the multi-coupled-model approach in DEMETER has motivated the creation of an operational multi-model system at ECMWF. Multi-model initiatives similar to DEMETER are envisaged by the Asian Pacific Climate Network (APCN) and the International Research Institute (IRI). These two institutions have produced operational multi-model forecasts using the “2-tier” approach (i.e. predicted SST used to force atmospheric models). However, the beneficial impact of ocean-atmosphere coupling over the tropics (Wang et al., 2004) and the indications that coupling does not degrade the skill over the extra-tropics has stirred their interest to use a set of fully coupled models.

We showed in Fig. 5 the correlation skill of 2m temperature persistence forecasts. In Fig. 18, the corresponding results from dynamical seasonal forecasts are given (the seasons shown are, unavoidably, not quite the same). Note that these plots can be readily constructed by the reader using the “KNMI Climate Explorer” at climexp.knmi.nl. Three DEMETER models have been run for the full set of years used in the observational persistence forecast (1959-2001) and these three models are used to create a “mini” multi-model. The results appear quite similar to the persistence forecasts with predictive skill for the lands surrounding the Baltic in spring and arid southern Europe in summer and with a lack of skill in winter. Generally, European skill is slightly higher in the dynamical models than for persistence. Note that the dynamical forecasts are initiated on the 1st of the month prior to the season being predicted (i.e. 1st November for DJF). The cleanest comparison (as above) is with the persistence forecast using only data up to the initiation of the dynamical forecast (Fig. 5a uses January anomalies to predict MAM although the conclusions are the same if three-month mean anomalies, i.e. NDJ, are persisted). If, instead, the persistence forecast is based on anomalies for the month (or three months) immediately prior to the season being forecast (i.e. February anomalies used to predict MAM), then persistence skill is marginally higher than the dynamical skill.

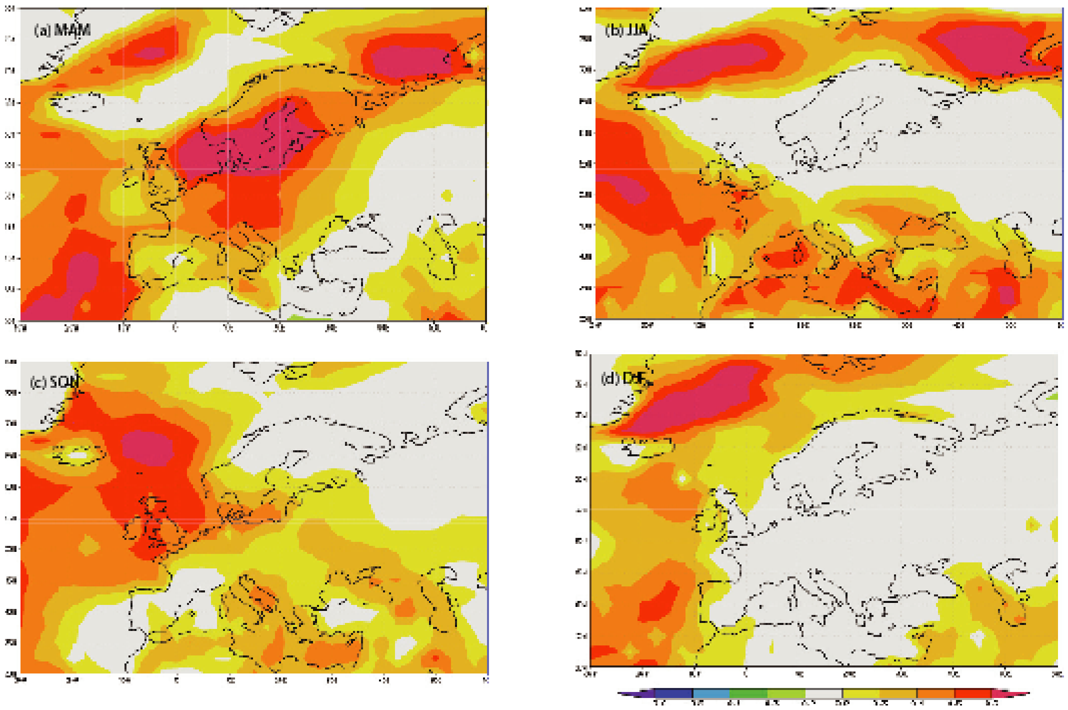

Fig. 18: Coupled model seasonal forecasts (anomaly correlation skill) for 2m temperatures based on the average of three DEMETER coupled models. (a) March-May (MAM) from February 1st. (b) June-August (JJA) from May 1st. (c) September-November (SON) from August 1st. (d) December-February (DJF) from November 1st. Verification data from ERA40 1959-2001. These plots can be readily constructed by the reader at climexp.knmi.nl

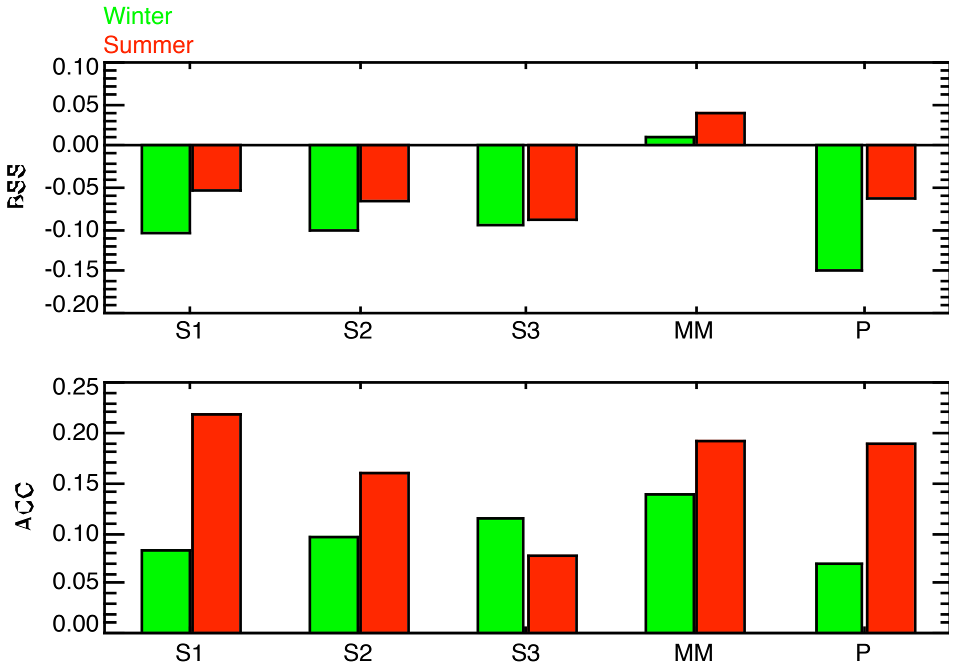

Fig. 19: Comparison of seasonal forecst skill from individual coupled models, the multi-model mean and persistence of observed anomalies. (bottom) Predictive skill of Europena 2m temperature averaged over the box [35oN-75oN, 60oW-45oW] in winter (December-February, green) and summer (June-August, red) over the years 1959-2001. The results are based on hindcasts initiated from the start of the previous month (May 1st and November 1st respectively) for three individual DEMETER coupled models (S1, S2, S3), the multi-model mean of the three models (MM) and persistence (P) of observed Europena temperature anomalies from the 3-month period prior to the initiation of the hindcasts (FMA and ASO, respectively). (top) As (bottom) but for the corresponding Brier skill socres for the event that European 2m temperature is greater than its long-term median value.

Figure 19 (bottom) confirms that dynamical multi-model has slightly higher anomaly correlation skill than a persistence forecast when forecasting mean European temperatures. However the advantage of dynamical ensemble prediction and the multi-model approach is more clearly evidenced in a probabilistic framework. For example, Fig. 19 (top) shows the “Brier skill scores”, B, for the “event” that the seasonal-mean European-mean 2m temperature anomaly is above its long-term median value. Before discussing the results, we define what we mean by the Brier skill score.

The Brier score, b, (different from the Brier *skill* score, B) is defined as $b = \frac{1}{N}\sum_{i=1}^{N}(p_i - v_i)^2$ where N is the number of ensemble forecasts, p_i the forecast probability and v_i = 1 or 0; depending on whether the event actually occurs or not. The Brier score has similarities with the conventional root-mean-square score; it is positive, and equals zero only for a perfect deterministic forecast. The Brier score from a climatological forecast, b_{clim}, can be similarly calculated by using $p_i = p_{clim}$, the climatological probability that the event occurs. The Brier *skill* score is then a measure of how good the ensemble forecast is relative to a climatological forecast: $B = 1 - \frac{b}{b_{c\lim}}$. If $B \leq 0$ then the ensemble forecast is no better, or worse, than the climatological probability forecast. $B = 1$ for a perfect deterministic forecast.

To define a Brier skill score for the persistence forecasts, the probability of the event occurring in the persistence forecast is initially 1 if the event occurs in the predictor anomalies (the three months prior to the start date of the dynamical hindcasts) and 0 otherwise. The probability is then linearly relaxed towards the climatological probability over the next 8 months of lead-time.

The Figure 19 (top) depicts the Brier skill scores for the predictions of seasonal, European-mean anomalies above their median value for each season. While the coupled models and persistence have a negative Brier skill score (implying that their skill is lower than the reference climatological forecast), the multi-model outperforms all the predictions in the probabilistic case and gives skilful forecasts. It has been found that this is due to an increase in both reliability (a measure of how well the forecast probability matches the verification frequency) and resolution (the ability to issue reliable forecasts with probabilities different from the climatological frequency) of the multi-model predictions. The comparison of the multi-model and persistence forecasts illustrates the importance of formulating predictions that include a measure of the uncertainty, such as probabilistic forecasts, instead of ensemble mean or deterministic predictions. Part of the increased skill of the multi-model over the individual models in Fig. 19 can be attributed to its larger ensemble size. However, Palmer et al (2004) showed that 54-members taken from the seven-model multi-model ensemble give better Brier skill scores than a 54-member ensemble created with just the best-performing individual model.

Figure 20 shows the potential predictive skill for four individual coupled models. Here the word “potential” refers to the assumption that the model is perfect and the initial conditions are known (almost) perfectly. The anomaly correlation is calculated, as in Collins (2002), by taking each ensemble member in turn, assuming it represents the truth and the other ensemble members are compared to it. The results are given for four different DEMETER models. The similarity between coupled models with the same atmospheric component implies that differences are truly sensitive to the atmospheric component and not simply due to sampling uncertainties. It is not necessarily the case that the atmospheric model component with highest potential predictive skill (in this case, ARPEGE3) is the most “perfect”. The important result is that potential predictive skill is strongly model dependent. This means that we cannot at present give a good estimate of an upper-bound for attainable predictive skill.

While bearing in mind this last point, we now look at potential predictive skill from a single model used to make decadal forecasts.

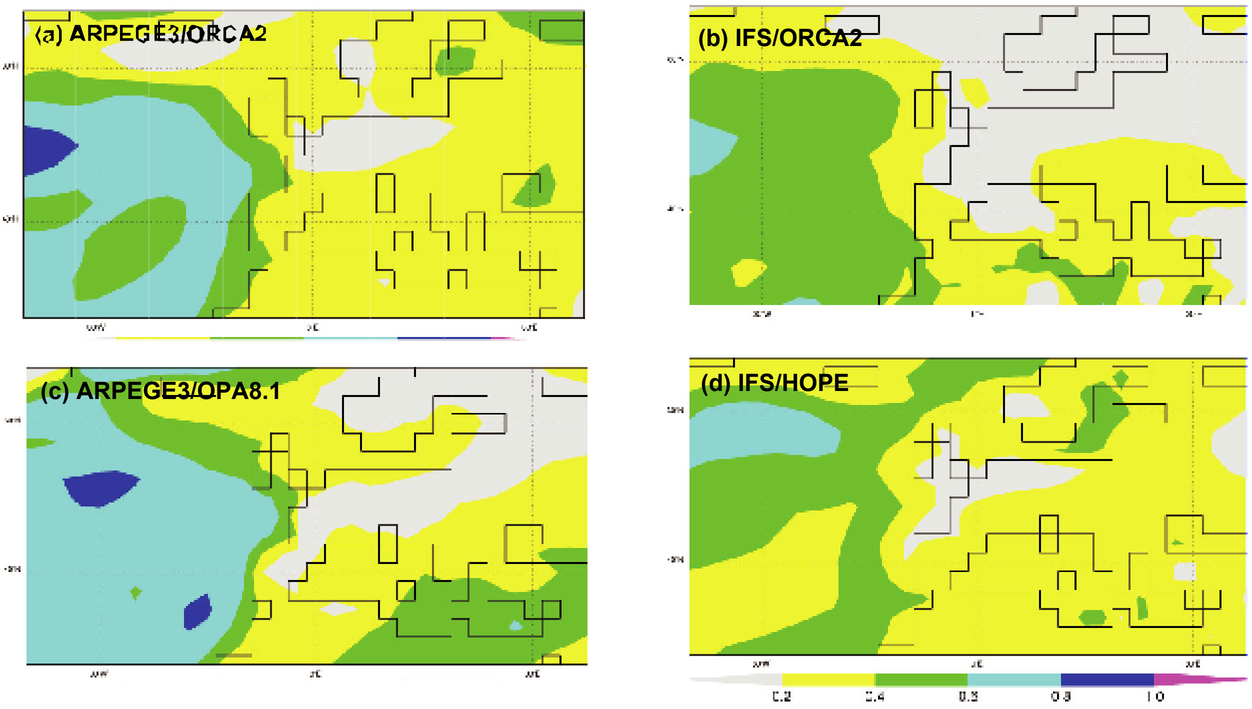

Fig. 20: Coupled model potential predictive skill (anomaly correlations assuming a perfect model) of winter (Decmber-February) 2m temperature anomalies based on coupled model hindcasts for the winters 1980-2001 using four different coupled models as indicated.

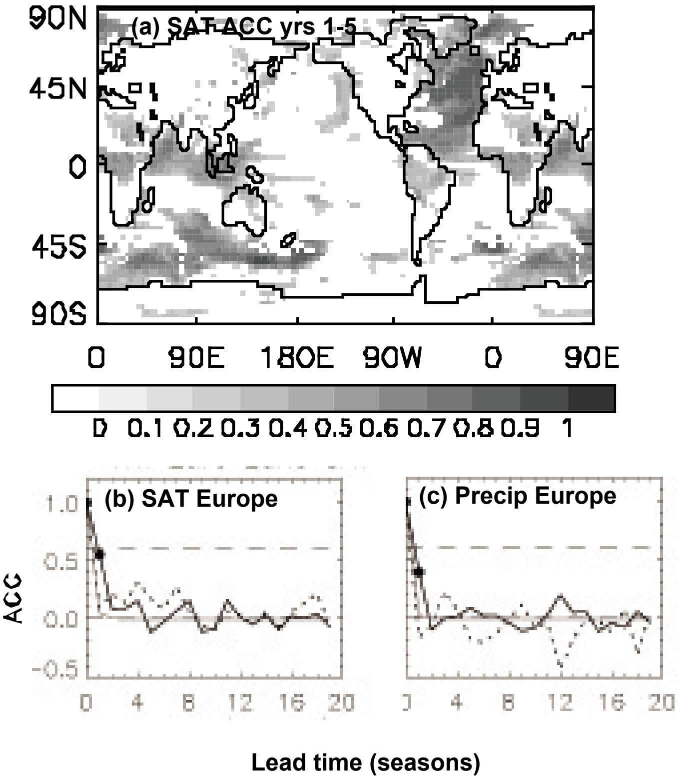

Fig. 21: Coupled model potential predictive skill (anomaly correlations assuming a perfect model). The model is the UK Met Office's HadCM3 coupled ocean-atmosphere model. Results are based on 12 ensembles with 5 members each. The atmosphere only is perturbed. (a) Surface air temperature averaged over the first 5 years, (b) European land surface air temperature and (c) European land surface precipitation. From Collins (2002).

Interannual-to-decadal predictability from coupled GCMs integrations

Collins (2002) used 12 five-member ensembles of 10-year coupled model (HadCM3) simulations to investigate potential predictability at interannual to decadal timescales. He did find some decadal predictability of surface air temperature anomalies, particularly over the north Atlantic, Fig. 21a. A working assumption in the study by Collins is that the model is perfect and anomaly correlations were made against each ensemble member in turn. Whether the model does capture well enough features such as the variability of the thermohaline circulation, its relationship with SST and the atmospheric response to SST forcing is not straightforward to validate against observations. Assuming, however, that the model does capture these features adequately enough then Fig. 21b and c suggest that potential predictive skill for European temperatures and precipitation decreases sharply with lead-time and may be of little use beyond a season.

Seasonal forecast skill for the United States increased during the 1990s and this may have been due in part to the use of the climate "trend". Indeed, this trend effect is thought to be yielding seasonal skill equal to or larger than the ENSO effect. Presumably, such trends may be associated with global or local man-made climate change, or with low-frequency natural variability. Clearly it is possible that enhanced decadal predictability for Europe may also be obtained from observed trends or the inclusion of anthropogenic forcing in climate models.

Mitigating actions and financial benefits

We argued in the introduction that a forecast is only useful if it can have a positive impact on decision making. A weather forecast for tomorrow that it will be showery may well make you decide to take an umbrella. A forecast for the next few days that there will be strong winds may make you decide to go on a sailing holiday rather than play golf. More seriously, we have noted that a medium-range weather forecast may help you decide whether to shut-down a nuclear power plant or not. It is clear that no further cost benefit analysis is required to justify making medium-range weather forecasts. We argued that the same is true for climate change forecasts. Although the uncertainties in climate change forecasts are difficult to quantify, the potential consequences of sustained greenhouse gas emissions are severe enough for such forecasts to have an impact on policy decisions. For seasonal to decadal forecasts, the benefits are less clear-cut (with the possible exception of seasonal forecasts for selected tropical locations). For such forecasts, it may be that the user must be included in the assessment of predictability (for example, quantifying the predictability of “growing days” rather than simply 2m temperatures) and that an integrated and optimized forecast-decision making process is required to produce a benefit from such forecasts (Pielke and Carbone, 2002).

In relation to the example in the introduction, there may have been more value to a user from the forecast of 75% probability that $T_{8June}>T_{clim}+3$ than the forecast of 100% probability that $T_{8June}>T_{clim}$. This is because the value also depends on the (financial) loss to a user if the event occurs and the cost to the user of taking mitigating action. A big potential loss could warrant taking mitigating action even if the event is not completely certain (see, *e.g.*, Palmer et al. 2000). The identification of mitigating actions is a key issue for forecasting. Possible mitigating actions will clearly depend on the event. As an example we identify two distinct categories: a physical action: ‘tie it down so it does not blow away’ and a financial action: ‘take out insurance in case it blows away’. Below, we work through a simple example that demonstrates the usefulness, or otherwise, of these two categories of mitigating actions.

A farmer may be keen to know if there will be any frost days during the period March - May. On average half the years have a frost day during this period. Suppose that the farmer can sell the crop for a profit $P=1$ unit if it is not damaged by frost but it would cost the farmer 1 unit to plow-up a frost-damaged crop so that the potential loss (including the loss of profit) is $L=2$ units. Here, we will assess the effects of different mitigation strategies if only the climatological probability, $p_{c\lim}(=0.5)$, is known or if a probabilistic forecast is available.

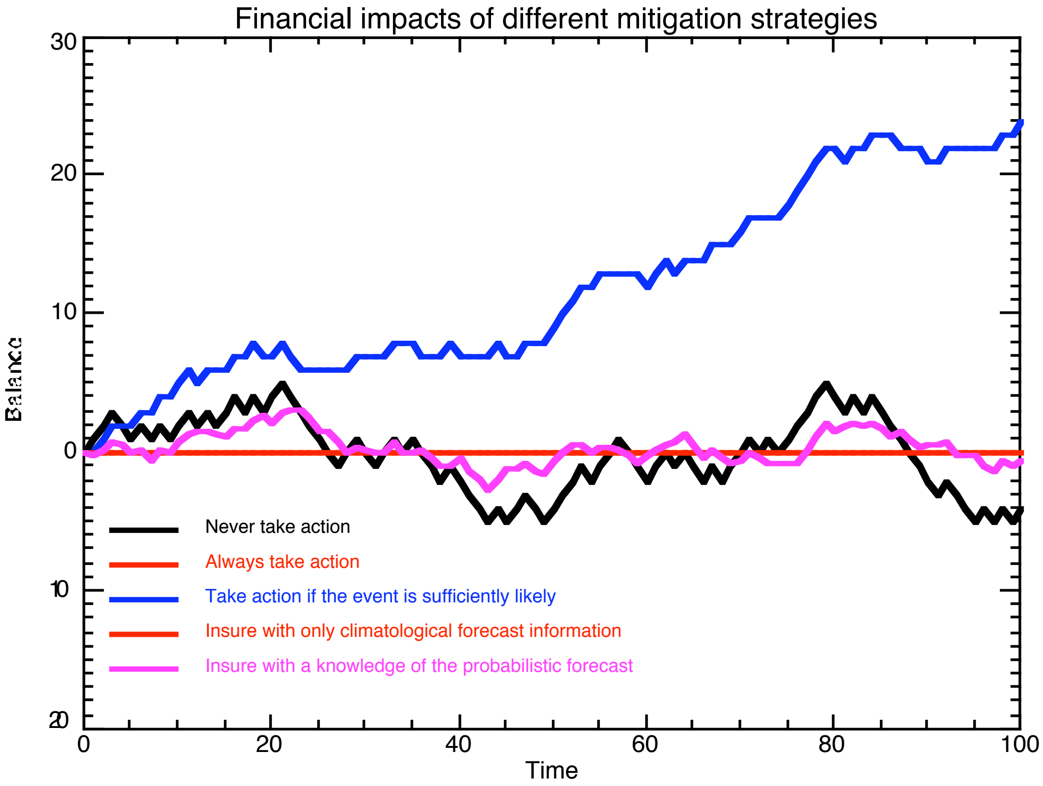

Fig. 22: The effects of a hypothetical climate event on a forecast user's bank balance using different mitigation strategies. Black curve: no mitigating action is taken so that the user makes a profit (1 unit) in a good year and an overall loss (1 unit) in a bad year. Blue curve: a (physical) action with fixed cost (1 unit) is taken if the forecast probability, p, exceeds a critical value p_{crit} *(0.5). Red curve: the user insures against the event, assuming only the climatological probability* p_{clim} *(0.5), is known. Magenta curve: the user insures against the event, assuming a probabilistic forecast is available. Please see the text for further details.*

The forecast probability of frost occurring, p, depends on the initial and boundary conditions. Hence p will vary from year to year. Suppose that we can model p as a random variable, uniformly distributed over the interval [0,1]. Whether the event actually occurs in a particular year also depends on chaos. Chaos is introduced with a second random variable, q. The event occurs if $q < p$ where q is independent of p and also uniformly distributed over the interval [0,1]. Notice that the event does indeed occur with probability p (so the forecast is perfectly reliable) and on average it occurs half the time. There are several mitigation strategies that the farmer may be able to adopt.

a) Suppose that the farmer's strategy is to never take mitigating action. The change in the farmer's bank balance is given by $\Delta B = P - EL$, where $E = 1$ if the event occurs (*i.e.* $q < p$) and $E = 0$ if not. The black curve in Fig. 22 shows the effect of this strategy on the farmer's bank balance. The balance resembles a random walk (but the expected long-term change in the balance is zero by design of the example).

b) Suppose that the farmer takes action (at a cost $C = 1$ unit) to insulate the crop if the forecast gives a probability greater than some "critical probability" ($p > p_{crit}$). Here p_{crit} is chosen to be 0.5. The change in the bank balance is then given by $\Delta B = P - AC - (1 - A)EL$ where $A = 1$ if action is taken (*i.e.* $p > p_{crit}$) and $A = 0$ if not. The blue curve in Fig. 22 shows the effect of this strategy on the farmer's bank balance. Occasionally $\Delta B < 0$ and the farmer suffers a loss in that particular year. This happens when $q < p < p_{crit}$ (*i.e.* no action is taken but the event does occur). However, more often than not $\Delta B > 0$ and so, *with the 'tie-it-down' mitigation strategy, predictability is of benefit to the user*.

c) Suppose, instead, that the farmer decides to take out insurance against the event of frost. Traditionally the objective of taking out insurance is to reduce the user's financial volatility. A small premium is paid each year to prevent the occasional big loss when the event occurs. Initially assume that no forecast is available. The insurance premium will, under some idealized assumptions, simply reflect the climatological probability of the event: $\text{PREMIUM} = p_{c\text{lim}}L$ and the change in the bank balance is given by $\Delta B = P - p_{c\text{lim}}L$. The red curve in Fig. 22 demonstrates that insurance, without the knowledge of a forecast (other than climatology), perfectly reduces the user's financial volatility. (Incidentally, this curve also represents, for this particular example, the strategy of always taking mitigating action at the cost $C = 1$ unit).

d) Suppose, again, that the farmer decides to take out insurance against the event of frost but this time there is a probabilistic forecast available. We make the reasonable assumption that the insurance broker also has access to this forecast. The insurance premium for a given year is therefore given by $\text{PREMIUM} = pL$ and the change in the bank balance is given by $\Delta B = P - pL$. The magenta curve in Fig. 22 demonstrates that the presence of a forecast means that the user's financial volatility is *not* completely removed. Variability does not come directly from the variability in E but from the variability in the insurance premium. It is clear, therefore, that *predictability has a detrimental impact on the usefulness of taking out insurance*.

The above example is, admittedly, a simple one although the general conclusions do not depend on the precise values used. It is clear that predictability has different impacts on the user depending on which class of mitigation strategy the user adopts.

Palmer et al (2000) demonstrated a real benefit for strategy (b), above, for a user exposed to the event that winter European temperatures are colder than 1^{o}C below normal. Real probabilistic seasonal forecasts were used although admittedly these were forced with observed SST. The maximum "value" of such a probabilistic forecast was found to be around 20% of that achievable with a perfectly deterministic forecast (perfect determinism). Since a perfectly deterministic forecast is not a possibility, Rodwell (2003) showed that this corresponded to a reduction of ≈12% in expected expense compared to if only climatological probabilities are known. The recent DEMETER coupled model seasonal hindcasts give a value of ≈15% for winter and summer for the event that European 2m temperature is greater than normal. About half this value is achieved for the event that seasonal-mean precipitation is greater than normal. Although these numbers are relatively small, they are not insignificant and there would appear to be real value in seasonal forecasts for a company, say a utility company, which is exposed to, and can take mitigating action against, European-wide climate anomalies.

On the other hand, forecast information is of no use to the "user" if their only mitigating strategy is to insure. This is because the insurance premium (or cost of a weather derivative) is likely to factor-in the probability of the event occurring. While insurance may still be useful for reducing volatility, it will not be as effective as when no forecast information was available. Insurers themselves are often cited as major potential customers for long-range forecasts, partly because of their familiarity with working with probabilistic information. However, one could argue that predictability does not favor the insurance industry *as a whole* either. Although the use of forecast information in insurance and other weather derivatives may be inevitable in the long term, the only long-term "winners" may be the forecast providers themselves!

There are other issues not addressed in our example above. For example, we have assumed that all parties have access to the same forecast information and have assumed that the user is not concerned about bankruptcy. However the main point we wish to convey, which is not affected by these assumptions, is that the forecast community should consider carefully which user communities to target when developing long-term plans for integrated forecasting systems.

Conclusions and key issues for the future.

We started with the example of the predictability of the extreme European summer heatwave of 2003. Medium-range forecasts were shown to be quite accurate and clearly had an impact on decision-making. Weekly-mean *probabilistic* forecasts with lead-times up to a month in advance also appeared to show real skill for this event. Seasonal predictability and the *utility* of seasonal forecasts for European applications (Cantelaube and Terres, 2005) have received considerable attention lately (*e.g.* through the EC-funded DEMETER project). However, the seasonal forecasts for the summer heatwave did not show great skill (although we have highlighted issues, such as soil moisture initialization and a possibly too weak response to Atlantic SST anomalies, that could have improved these forecasts).

It is possible that there may be “windows of opportunity” where European predictability is enhanced by the existence of particular (extreme) patterns of Atlantic, El-Niño or tropical Indian Ocean SST anomalies, or because European land surface properties such as soil moisture or snow-cover are rather extreme. More generally, however, present models show rather little seasonal to decadal potential predictability or predictive skill for Europe.

There is considerable variability amongst models in their estimates of potential predictability. This means that we cannot make precise estimates of the ultimate levels of predictability based on our present models: “there is no such thing as a perfect model”. This may imply that the true level of predictability *could* be higher than the present potential predictability estimates.

One thing seems certain however, the ultimate levels of seasonal to decadal predictability will be rather low for Europe and the utility or otherwise of seasonal to decadal forecasts may rely on careful optimization of the whole “end-to-end” forecast-to-user decision-making process.

We have highlighted two categories of possible mitigating actions that users can make. For fixed mitigating costs, there may already be forecast value for a user interested in rather large-scale anomalies. If the cost of taking mitigating action is a function of the probability of an event occurring then (as in the case of insurance) there may be little benefit to the user arising from predictability.

Finally, we highlight in list-form particular topics that could form the basis of future research and which could lead to improvements in seasonal to decadal prediction for Europe.

a) Initial Data
   - Improved ocean data assimilation
   - Improved land surface initialization (e.g. soil moisture, snow cover etc)
   - Improved techniques for the generation of coupled-model ensemble perturbations

b) Model Improvements
   - Improved representation of land surface processes
   - Reduction in model systematic error
   - Improved representation of key physical processes (air-sea interaction, aerosols etc)
   - Improved numerical or statistical downscaling to user-specific areas

c) Users
   - Improved communication and education about the use of probabilistic forecasts and access to feedback from users.
   - Use of user-specific variables (such as “growing days”, “frost days”, “cold-windy days” etc) in predictability studies
   - Concentration on demonstrating general skill and utility of forecasts out to a month ahead.
   - More use of seamless forecasting systems (combining short-range, medium-range, monthly, seasonal and decadal forecasts).

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APPENDIX II. Programme

Day 1. Monday 19 April 2004

9.00	Coffee & Registration	
10.00	Opening of the Workshop	
	Welcomes, local arrangements, aims & program	Rowan Sutton
	WCRP JSC perspective on the importance of predictability	Brian Hoskins
10.25	**Session 1: Ongoing prediction activities** (Chair: Y. Kushnir) (reports from operational centres and climate forums including the communication with communities of users. 25 minutes including discussion per presentation.)	
	LR forecasting of Atlantic Sector Climate at IRI	Andrew Robertson
	Seasonal forecasting of Atlantic Sector Climate at MeteoFrance	Michel Deque
11.15	Coffee	
11.45	Operational seasonal forecasting at the S. African Weather Service	Willem Landman
	Dynamical and statistical seasonal forecasting at CPTEC	Jose Marengo
	LR forecasting at ACMAD and the African Climate Outlook Forums	Nassor Abdallah
13.00	Lunch (with opportunity for putting up posters)	
14.30	**Session 1 continues** (Chair: P. Nobre)	
	LR forecasting of Atlantic Sector Climate at ECMWF	David Anderson
	Climate Prediction at CPC	Huug van den Dool
15.45	Tea	
16.15	**Guest Lecture:** "Developments and future prospects in understanding predictability" Tim Palmer, ECMWF; Introduced by Tony Busalacchi	
17.15	Drinks reception and poster viewing in Department of Meteorology	
19.00	Close of Day	

Day 2. Tuesday 20 April 2004

9.00	**Session 1 continues** (Chair: T. Stockdale)	
	LR forecasting of Atlantic Sector Climate at UK Met Office	Matt Huddlestone
	LR forecasting at the Drought Monitoring Centre, Nairobi	Charles Mutai
	Statistical forecasting for the tropical Atlantic region at CDC	Ludmila Matrosova
10.40	Coffee	
11.10	**Session 1 continues** (Chair: T. Stockdale)	
	Dynamical downscaling for Nordeste climate at FUNCEME	Nilson Campos
	A decadal climate prediction system at the UK Met Office	Doug Smith
12.00	**Session 2: Presentation of White Papers** (Chair: R. Sutton) 45 mins, including discussion, for each White Paper, except papers 3 and 4 (Busalacchi and Stockdale) which are allocated 1 hour	
	The physical basis for prediction of Atlantic sector climate on seasonal-to-interannual timescales	Yochanan Kushnir

12.45	Lunch	
14.00	**Session 2 continues** (Chair: D. Marshall)	
	The physical basis for prediction of Atlantic sector climate on decadal timescales	Mojib Latif
14.45	The climate observing system for the Atlantic sector	Tony Busalacchi
15.45	Tea	
16.15	Coupled prediction systems for Atlantic sector climate	Tim Stockdale
17.15	Opportunity for discussion	
17.30	Close of Day	

Day3. Wednesday 21 April 2004

9.00	**Session 2 continues** (Chair: P. Nobre)	
	Seasonal-to-decadal predictability and prediction of West African climate	Neil Ward
	Seasonal-to-decadal predictability and prediction of Southern African climate	Chris Reason
10.30	Coffee	
11.00	**Session 2 continues** (Chair: C. Reason)	
	Seasonal-to-decadal predictability and prediction of North American climate	Huug van den Dool
	Seasonal-to-decadal predictability and prediction of South American climate	Paulo Nobre
12.30pm	Lunch	
13.45	**Session 2 continues** (Chair: C. Reason)	
	Seasonal-to-decadal predictability and prediction of European climate	Mark Rodwell
	Opportunity for discussion	
15.45	Tea	
16.15	**Guest Lecture:** "Merging forecasts with applications" Neil Ward, IRI; Introduced by Y. Kushnir	
17.15	Close of Day	
19.30	**Dinner**	

Day 4. Thursday 22 April 2004

9.00	**Introduction to Session 3:** Break out groups Groups to address recommendations for future priorities in a) research b) the observing system c) development of prediction systems.	Rowan Sutton
9.15	Break out groups	
10.30	Coffee	
11.00	Continutation of break out groups	
12.30	Lunch	
13.30	**Reports from break out groups**	
14.30	Tea	
15.00	**Plenary discussion**	
16.00	Close of the Workshop	

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