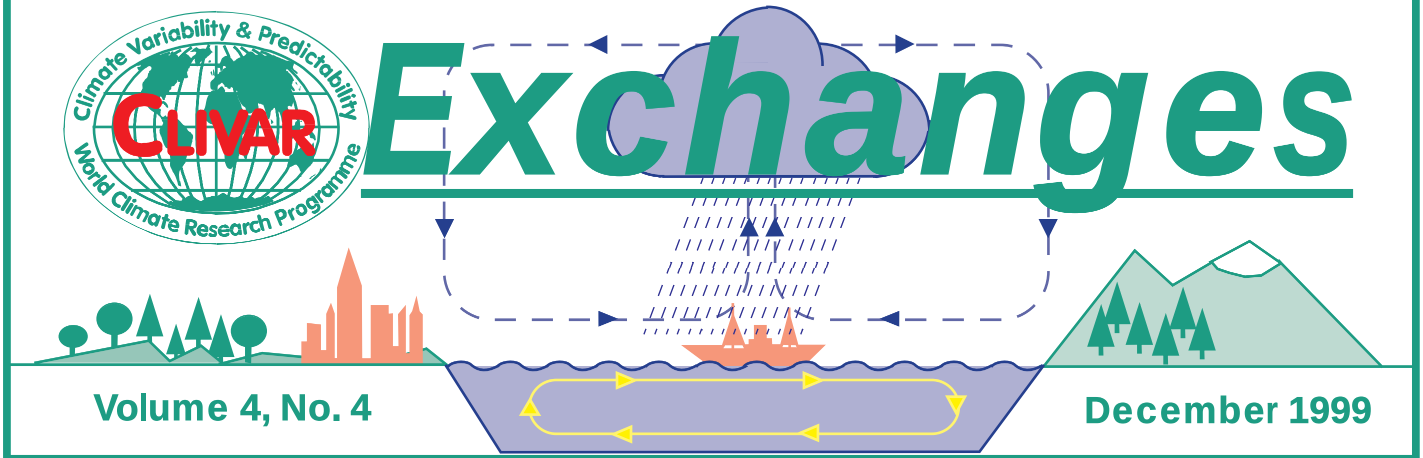
Newsletter of the Climate Variability and Predictability Programme (CLIVAR)

Exchanges



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News from the ICPO

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This issue of Exchanges

This latest issue of Exchanges contains some interesting papers on a variety of topics largely relating to the role of modelling activities in CLIVAR. As you may know, CLIVAR oversees its modelling development through two panels, one the WCRP Working Group on Coupled Modelling that is chaired by Lennart Bengtsson and the second the CLIVAR Working Group on Seasonal to Interannual Prediction chaired by Steve Zebiak. As their names imply these panels deal respectively with the long and short timescale climate processes of interest to CLIVAR (monsoons and ENSO events through to anthropogenic change). Both WGs have met recently. A report of the WGCM is included on page 37 and a report of the WGSIP will be given in the next issue.

Given the sparse nature of the observational climate data base, modelling activities are the key to better understanding the climate system and its variability. It seems likely that the requirements of climate modelling will stretch the limits of available computer capability for the foreseeable future as models move to higher resolution in both atmosphere and ocean and as long ensemble runs are required.

Second Conference on Reanalyses and 4th International Conference on Global Climate Change and Variability

This issue of Exchanges, highlighting some recent activities and findings in the field of climate modelling has also been motivated by two major meetings in late summer and fall: The Second Conference on Reanalyses held in late August in Reading, UK (please find a summary on page 38) and the 4th International Conference on Global Climate Change and Variability that took place in September at the Max-Planck-Institute for Meteorology in Hamburg, Germany. A report of this meeting is given on page 35. The papers selected for this issue provide an overview about the climate modelling efforts presented on that conference which themes and goals matched perfectly with the CLIVAR requirements in this field of climate research.

First International Conference on the Ocean Observing System for Climate (OceanObs'99)

You will remember that the last newsletter - a bumper edition - was focused on and published to coincide with the First International Conference on the Ocean Observing System for Climate in St. Raphael France. It has become known in short by most people as OceanObs'99. I, and many other CLIVAR scientists were among the approx. 350 attendees at this important meeting. Its objectives were to identify the appropriate mix of sustained global observations that would be required to address the needs of GOOS/GCOS and of CLIVAR.

A formal report of the Conference is not yet available so what follows is my own personal view. The meeting was wide-ranging and covered in detail aspects as diverse as satellite remote sensing of the ocean surface, full depth hydrography and tracer measurements, measurements from ships of opportunity and acoustic measurements of the ocean through invited papers prepared by, in many cases, large groups of co-authors. There were panel discussions that exposed a number of issues and that went on until quite late in the evenings and some excellent posters. It was hard work and was very worthwhile but in some senses the real task is still to be done – to distill an appropriate observational strategy that will exploit the strengths of each technique and that can be assembled into a sustainable observing system that will serve both research and operational activities. Details on the conference can be obtained at the conference homepage: **http://WWW.BoM.GOV.AU/OceanObs99** which includes all of the contributed papers and a draft of the conference statement. The homepage also contains a continuing dialog on the conference papers and conclusions, which encourages community participation through a comment board.

CLIVAR Data Task Team

Within the OceanObs meeting a strategy was put forward for the data systems that would be needed for ocean observations. Building on this, the CLIVAR Data Task Team held its first full meeting on the Saturday following OceanObs (incidentally the first sunny day in a week of sustained torrential rain). The sacrifice of a few hours in the sun was well worthwhile and the DTT started to formulate its view of how CLIVAR data should best be managed and made available (together with derived products) to CLIVAR researchers. CLIVAR is probably able to influence the manner in which ocean observations are dealt with in delayed-mode largely through the systems that have served so well in the World Ocean Circulation Experiment (WOCE). To this end the DTT endorsed many elements of the WOCE data system as being appropriate to fulfil some of CLIVAR's requirements. These endorsements should help to ensure the continuity of these systems. Of greater complexity are the operational (real-time) systems for both atmospheric and ocean data. Assessing the adequacy of these systems for meeting CLIVAR's needs will be major task for the DTT.

CLIVAR Panels and WGs

The OceanObs meeting was co-sponsored by the CLIVAR Upper Ocean Panel whose chairman Chet Koblinsky, (together with Neville Smith) are to be congratulated on their hard work in making OceanObs succeed. The Conference highlighted the broadened role that the CLIVAR UOP should now take (global and not solely confined to upper ocean matters) in light of the close relationship between CLIVAR and GOOS/GCOS and of the establishment by CLIVAR of sector implementation panels. Discussion is now taking place to produce revised terms of reference for UOP.

The final revisions are being made to the report of the CLIVAR African Climate Study Group. We plan that it should be available early in the New Year. This report will act as the basis for the formulation of a more concrete plan by the CLIVAR Africa Task Team (CATT) under its chairman Chris Thorncroft of the University of Reading, UK.

Other Meetings

In November the PAGES and CLIVAR again joined forces to hold a workshop on extending the instrumental record and making it useful for CLIVAR purposes in Venice, Italy. The workshop documented impressive progress on paleo data analysis, modelling and synthesis. Outstanding results include the synthesis of detailed reconstructions with annual resolution of the past climate over the last 1,000 years that have been published recently, and which are changing our views on the Little Ice Age and whether their even was a Medieval warm period (other than regionally). They provide an extremely valuable basis for advances in our understanding in natural climate variability and in the climate forcings. Fruitful exchanges between the two communities occurred and a joint research activity for the next 5 years or so has been refined. The next issue of Exchanges will be a joint one with PAGES and highlight in more detail the accomplishments of this workshop.

I am about to attend the workshop and meeting of the CLIVAR Australian-Asian Monsoon Panel in Hawaii in early December. It promises to be a lively meeting. A number of recent research papers highlight aspects of the role of the Indian Ocean in both the monsoon and in ENSO and I am looking forward to hearing more of this and of hearing how the panel plans to develop a strategy within CLIVAR to better understand the workings of the A-A Monsoon.

National programmes and information flow

It is now a year since the International CLIVAR Conference in Paris. The report has been widely circulated and contains the text of the plenary lectures and summaries of the national reports made to the conference It is essential that the CLIVAR SSG and the ICPO are kept well informed about the progress of national programmes for CLIVAR research and in light of this I will be contacting national co-ordinators for CLIVAR requesting updated statements on national plans. Information flow is a two way process and we are about to make available on the WWW a searchable information source that will enable anyone to find who is doing CLIVAR research on a particular Principal Research Area, in a geographical area or by an individual country. It will we hope include a searchable bibliography of CLIVAR-related papers and reports. The system has been developed by Christine Haas who has been working in Geneva on CLIVAR matters for the past year and I think it will prove to be an invaluable asset to CLIVAR. The value will be greatly enhanced as more information is added and kept up to date. That is where all of you CLIVAR researchers can help by feeding new information to the ICPO for inclusion.

Thank you and Happy New Year

Finally I and the SSG co-chairs Kevin Trenberth and Jürgen Willebrand want to thank all of the members of the CLIVAR Panels and WGs who have given their time and energy to the project over the past year. Your contributions are very much appreciated. I would also like to thank the ICPO staff who have supported meetings, prepared reports and particularly Andreas Villwock who has worked to ensure that CLIVAR Exchanges has appeared at the appointed times and has increasingly focused in science issues.

And of course the co-chairs and all of the ICPO staff send you best wishes for Christmas and for the year 2000.

John Gould

A Common Mode of Subseasonal and Interannual Variability of Indian Summer Monsoon

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1. Introduction

Summer monsoon rainfall is the life-blood of the agrarian societies of subtropical Asia. Dynamical seasonal forecasting of the Asian summer monsoon (ASM), if successful, would revolutionize the ability of governments of agrarian societies dependent on monsoon rainfall to deal with the prospective impacts of a weak or strong monsoon. Using ensembles of simulations with numerical weather prediction models, dynamical seasonal predictions have the potential to provide probabilistic forecasts. Based on the dispersion of the ensemble members it would be possible to establish confidence thresholds on the forecast, and to gain some insight on the potential regionality of the rainfall anomalies. However, to date, dynamical seasonal predictability of the boreal summer monsoon system has been problematic (Brankovic and Palmer, 1999), possibly due to model errors in the mean monsoon simulation which are still substantial enough that the signal being sought is smaller than the systematic bias. It has also possible that limited predictability of the monsoon may arise due to chaotic variability on subseasonal time-scales. However, it has been hypothesized that the slowly varying components of the climate system, such as sea-surface temperature and/or land-surface interactions, may predispose chaotic modes of subseasonal variability (or weather) into preferred states resulting in an increased probability of a wet or dry monsoon depending upon the sign of the forcing (Palmer, 1994). Evidence for these types of perturbations has been manifest in simulations with models of varying complexity (Palmer, 1994; Fennessy and Shukla, 1994; Ferranti et al., 1997; and Webster et al., 1998). In this paper we test this hypothesis using the NCEP/NCAR reanalysis (Kalnay et al., 1996) for June-September 1958-97. Sperber et al. (1999) present a more in-depth analysis of the dominant modes of ASM variability.

2. Interannual and Subseasonal Variability

Using daily rainfall and 850hPa winds from the reanalysis for June-September 1958-97 we have investigated the link between subseasonal and interannual variability of the Asian summer monsoon (Sperber et al., 1999). The 850hPa winds are an excellent candidate for analysis since they encapsulate both the large-scale and regional-scale structures of the monsoon circulation. Here we concentrate on the modes that are most important for Indian monsoon. We have used empirical orthogonal function (EOF) analysis to identify the dominant spatio-temporal modes of variability on (1) interannual time-scales using seasonal anomalies, and (2) subseasonal time-scales using daily anomalies (climatological daily means removed).

The most accurate estimate of rainfall available during the summer monsoon is that over India, collected through an extensive gauge network (Parthasarathy et al., 1994). Figure 1 shows the interannual variations of all-India rainfall. Associated with the interannual variation of all-India rainfall is a characteristic pattern of 850hPa wind anomalies (Fig. 2a, see page 19), comprised of cyclonic anomalies over the bulk of the Indian subcontinent, with anticyclonic anomalies located further south, and to the north in the foothills of the Himalayas. The wind pattern has been constructed from the difference of the composites based on years of above-normal versus below-normal all-India rainfall using the +/-0.5 standard deviations thresholds given in Fig. 1. The composite difference is nearly identical to the composite for 1979-95 (Annamalai et al., 1999), when the reanalysis is believed to be more reliable due to the incorporation of satellite data in the assimilation, thus indicating the robustness of this pattern of anomalies throughout the 40-year reanalysis. Similarly, relative to the observed all-India rainfall, Fig. 2b shows the regional distribution of rainfall anomalies from the reanalysis. The enhanced rainfall over India is consistent with the presence of cyclonic anomalies over the subcontinent, while the below normal rainfall to the south and west of India corresponds to the anticyclonic anomalies. This

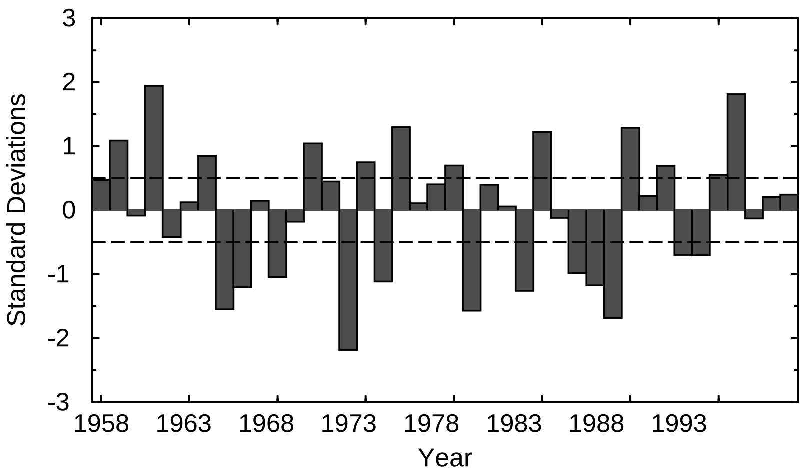

Fig. 1: Interannual variability of observed all-India rainfall for June-September 1958-97. Over this period, the average seasonal total of rainfall is 847mm, and standard deviation about the mean is 87mm. The dashed lines, corresponding to 0.5 and -0.5 standard deviations, are used to delineate years of above normal all-India rainfall from years of below normal all-India rainfall respectively.

interannual signal in the reanalysis precipitation (Fig. 2b) has been confirmed since this pattern agrees well with that obtained for the period 1979-95 (Annamalai et al., 1999) from compositing observed rainfall estimates constructed from satellite and surface gauge data (Xie and Arkin, 1996).

EOF analysis of the seasonal anomalies has successfully identified a mode which has a very similar pattern to that obtained by compositing on all-India rainfall, particularly in the vicinity of India (Fig. 2c). The anticyclonic/cyclonic/anticyclonic pattern is clearly seen in EOF-4. Similarly, the composite rainfall anomalies calculated relative to the principal component (PC) time series of EOF-4 (Fig. 2d) correspond closely to that calculated relative to observed all-India rainfall (Fig. 2b), particularly over India, and much of the Asian summer monsoon region. Importantly, the PC time series of EOF-4 has a correlation of 0.60 (significant at >1% level) with respect to the observed seasonal mean all-India rainfall. Thus, the similarity of the spatial pattern of EOF-4 and its associated rainfall anomalies (Figs. 2c, d) with that of the composites based on all-India rainfall (Figs. 2a, b), plus the high temporal correlation of the PC time series of EOF-4 with observed all-India rainfall provides confirmatory evidence that the EOF analysis has extracted a physically realistic mode of Indian summer monsoon variability.

A main tenet of the hypothesis that perturbations to subseasonal variability control the interannual variability is that the patterns of subseasonal and interannual variability should correspond (Palmer, 1994). We have found that the third mode of subseasonal variability (EOF-3; Fig. 3a, see page 19), extracted from an analysis using daily 850hPa wind anomalies, exhibits the anticyclonic/cyclonic/anticyclonic pattern in the vicinity of India obtained using the interannual anomalies (Figs. 2a, c). Time series analysis of the PC time series indicates this mode of variability to be dominated by time-scales of 7-40 days, the time-scales that are considered important for active/break cycles of the monsoon. This mode captures the main elements of the well documented pattern associated with active (wet) versus break (dry) phases of the Indian summer monsoon (Ramamurthy, 1969; Lau and Chan, 1986; Webster et al., 1998).

The composite difference of daily rainfall from the reanalysis (Fig. 3b), based on +/-1 standard deviation thresholds of the PC time series, exhibits a nearly identical pattern of rainfall anomalies as found on interannual time-scales (Fig. 2b, d). These results suggest the viability of the link between subseasonal and interannual variability. Closure of the link between the subseasonal and the interannual variability of Indian summer monsoon is established by demonstrating that the subseasonal mode projects on to the interannual variability. The link is established by demonstrating the importance of the subseasonal mode for high frequency variations of all-India rainfall. This is shown in Fig. 3c, in which the PC time series of the subseasonal mode and the variations of observed daily all-India rainfall (both subject to a 5-day running mean) are plotted for 1987. The variations of the all-India rainfall correspond closely to the changes of the PC time series, particularly during the months of June and July. The correlation of these two time series is 0.59, significant at >5% level (assuming 10 degrees of freedom or greater during the 122 day season). This level of correlation is typical of the years during which the daily all-India rainfall data are available (1971-95). Thus, this mode of variability is an important modulator of the short-term variations of Indian summer monsoon rainfall.

It should be noted that 1987 was a year of below-normal all-India rainfall, and this is clearly reflected in the bias of the PC time series and the daily all-India rainfall departures towards negative values during this summer (Fig. 3c). The seasonal average of the daily PC time series is an integrated measure of the influence of the subseasonal mode on the total seasonal anomaly. Calculating the seasonal average of PC-3 for each summer 1958-97, and correlating with observed all-India rainfall (Fig. 1) results in a coefficient of correlation of 0.67

(significant at >1% level), thus directly linking the interannual variations of observed all-India rainfall to variations of the subseasonal mode. The seasonal averages of PC-1, PC-2, and PC-4 have much weaker correlations with all-India rainfall (0.23, -0.13, and 0.04 respectively) indicating that the projection of these subseasonal modes on to interannual variations of Indian monsoon rainfall is tenuous at best. Furthermore, as suggested by the negative values of the PC during 1987, the probability distribution function (PDF; Fig. 3d) of the daily PC time series is systematically perturbed towards negative values during years of below normal all-India rainfall, whereas it is perturbed towards positive values during years of above normal all-India rainfall. These changes in the means of the PDF's are significant at >2.5% level.

3. Conclusions and Discussion

We have isolated a mode of variability that projects strongly on to both subseasonal and interannual time-scales of Indian summer monsoon, with this mode exerting the dominant influence in the subseasonal and interannual variations of rainfall and lower tropospheric flow over this region. This supports the hypothesis that perturbations to otherwise chaotic phenomena can result in discernible influences on interannual time-scales, even though the impact does not occur to the leading (first mode, Sperber et al., 1999) and the perturbation is not manifested as bimodality, as had been suggested (Palmer, 1994). As yet, the mechanism(s) and boundary forcing(s) that cause the systematic changes in the behaviour of this linked mode of subseasonal and interannual variability have yet to be determined, but will undoubtedly have a major impact on our ability to predict all-India rainfall. If numerical weather prediction models are not able to simulate this subseasonal mode of variability, and the other dominant modes of variability that are important for the Asian summer monsoon in general (Sperber et al., 1999), this would suggest that the present limitations on seasonal predictability of ASM may imposed by our limited understanding of the complex processes that govern the ocean-atmosphere-land system rather than by nature itself. To this end, we are currently investigating the models contributed to the Seasonal Prediction Model Intercomparison Project (SMIP) initiated by the CLIVAR Working Group on Seasonal to Interannual Prediction (WGSIP). These integrations consist of ensembles of seasonal hindcasts, and the ability of the models to simulate the hierarchy of ASM modes and their interactions will be investigated to assess the state-of-the-art in seasonal forecasting.

Acknowledgments

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Interannual to Decadal Variability of the Atmospheric Circulation in Coupled and SST-forced GCM Experiments

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1. Introduction

Little is known about the role of the coupling mechanisms between atmosphere and ocean on the interannual to decadal time scales. Numerous experiments were investigated using atmosphere GCM with various lower boundary conditions reaching from climatological SST, prescribed observed SST variability, a mixed layer ocean, and various combinations to a fully interactive ocean (Bladé et al., 1999; Christoph et al., 1998; Davies, 1997; Lau et al., 1996; Moron et al., 1998; Saravanan, 1998). An investigation of the coupling mechanisms with coupled and forced GCM experiments has been performed by Selten et al. (1999). They systematically investigated the role of coupling in an atmosphere-ocean GCM by performing auxiliary experiments with the atmosphere-only and ocean-only GCM, taking fluxes and SST from the coupled simulation as boundary conditions.

The extratropical atmosphere shows widely unchanged patterns of variability, which are not depending on the lower boundary configuration (Saravanan, 1998). Merely slight changes were observed by Bladé et al. (1999). The order of variance of the single patterns and the probability function may be changed (Molteni et al., 1993). Selten et al. (1999) and Christoph et al. (1998) observed the development of spectral peaks in the amplitude spectrum of the dominant modes of variability in the coupled simulation which were absent in the SST forced simulations. Neelin et al. (1999) ascertain dominant spectral peaks within their ocean model coupled to stochastically varying atmospheric heat and momentum fluxes. The coupling was implemented by changing the mean and variance of the white noise atmospheric fluxes depending on SST.

Various conceptional models were build to analyse the role of coupling within the framework of stochastic models (Hasselmann, 1976). Barsugli and Battisti (1998) investigated a simple stochastically forced energy balance model of the atmosphere ocean system. Their model exhibits an amplification of variance in the coupled in contrast to the uncoupled system. Saravanan and Williams (1998) developed an one-dimensional stochastic model, where the atmosphere was resolved by stochastically varying coherent patterns and was coupled to an advective ocean. Their system exhibits spectral peaks in the variance spectrum. They conclude that the interaction between a stochastically varying atmosphere and an advective ocean plays a major role in the development of decal variability.

Our analysis will concentrate on the variability of various variables in different regions in coupled and SST forced GCM experiments. Chapter 2 describes the model simulations and the statistical analysis tools to analyse and compare the variance. The results are presented in chapter 3 for the euro-atlantic (chapter 3.1) and tropical (chapter 3.2) atmospheric circulation.

2. Simulations and Statistics

The analysis is based on an 800-year integration with the Hamburg ECHAM3-T21/LSG (Voss et al., 1998; Roeckner et al., 1992; Maier-Reimer et al., 1993), a coupled atmosphere ocean sea-ice GCM. A time slice of a 100-year period of integration was selected. The monthly mean SST and sea ice boundaries of the time slice coupled simulation were used to perform an ensemble of forced atmosphere-only simulations with the ECHAM3-T21. The ensemble consists of the coupled 100-year integration and four SST-forced simulations differing only in their independent initial conditions. An ensemble mean was calculated summing up the four SST-forced simulations for each time step.

The LSG ocean model is characterised by a largely underestimated tropical SST variability due to the coarse resolution of 4° x 4°, whereas the variance amplitude of the extratropical SST variability resembles observational variance.

The Northern Hemispheric winter seasonal means of the investigated atmospheric variables were pooled to one 500-year simulation by lining up the four forced simulations and the one coupled simulation. A principal component analysis was carried out for the pooled simulation, obtaining one set of empirical orthogonal functions (EOF) for each variable. A Blackman-Tukey spectrum using Bartlett smoothing was calculated for the principal components (PC) for each simulation (coupled and forced) and the ensemble mean of the forced simulations. The bandwidth and a 95% confidence interval for a stochastic process are indicated by two crossed lines. A univariate analysis of variance (ANOVA) was carried out to estimate the SST forced fraction of the total variance in the forced ensemble.

3. Results

3.1 Extratropics

Figure 1 (top) shows the first and second EOF of the euro-atlantic 500 hPa geopotential height anomalies. The EOF differ only slightly between the single simulations and there is no significant difference between the patterns of the coupled and the forced simulations. The first EOF shows a NAO-like variability with the synchronously varying pressure systems over Greenland and westward of Europe. In comparison with observations the dipole pattern is located to far to the north. The fraction of variance linearly explained by the prescribed SST in the PC of the first EOF amounts to 9% of the total variance. The second EOF shows similar structures located further to the south. The SST explained variance fraction is slightly higher with 16% of the total variance.

The variance spectra of the PC (Figure 1, bottom) of the various simulations show a wide spread at all time scales. The spectral variance of the first principal component of the coupled simulation lies within the range spanned by the spectra of the forced simulations. The ration between the spectral variance of the single forced simulations and the ensemble mean represents an estimate of the SST induced fraction of variability. The ensemble mean run shows significantly less variance on all time scales. This reflects the small fraction of SST induced variance already shown with the ANOVA of the PC.

The PC of the second EOF in the coupled simulation shows a significant spectral peak at the frequency at about 0.08/a (period of 12 years). It represents a coupled mode of variation in the coupled simulation. Here atmospheric anomalies primarily force anomalous SST through heat and momentum fluxes. The spectral peak is indeed more present in the SST than in the atmosphere. In the forced simulations the spectral peak vanishes and the variance spectra of the second PC are white. Thus there is evidence that the coupling between the two climate systems enables the development of coupled variability on preferred decadal time scales. To determine whether the coupled mode resides in the ocean or whether it needs the coupled system to develop has to be examined with auxiliary ocean only simulations. Seltan et al. (1999) did not reproduce the spectral peak in the uncoupled simulations.

3.2 Tropics

Substantial differences result from the analysis of tropical atmospheric variability. Figure 2 shows the first EOF of the zonal eddy streamfunction and the velocity potential at 200 hPa, respectively. The patterns resemble typical anomalies induced by anomalous tropical heating. They can be reproduced with a linear reduced gravity model after Matsuno (1966) and Gill (1980).

Although the variability of the tropical SST is largely underestimated by the coupled model the tropical atmospheric circulation of the forced simulations shows substantial SST forced variability. The fraction of SST induced variability amounts to 40% of the total variance of the 200 hPa streamfunction and velocity potential. The PC show significant differences between the forced and the coupled simulations. The coupled simulation has a much smaller variance that even falls below the variance of the ensemble mean simulation. Due to the large fraction of SST induced variability the ratio between the variance of the ensemble mean and the forced simulations is larger than for the euro-atlantic geopotential height.

Thus in the tropics in particular the modes of variability which are highly affected by tropical SST variability show largely overestimated variance in comparison to the coupled simulation. SST forced ensemble simulations are widely used to determine the predictability of tropical variables through SST. The present study shows that the absence of the coupling mechanisms lead to a significant enhancement of atmospheric variability in the tropics or even to an unrealistic sensitivity of the atmosphere to tropical SST and therefore to an overestimation of the predictability. Indeed over the western tropical Pacific and the Indian Ocean the variance of the precipitation is significantly enhanced in the forced simulations in contrast to the coupled simulation.

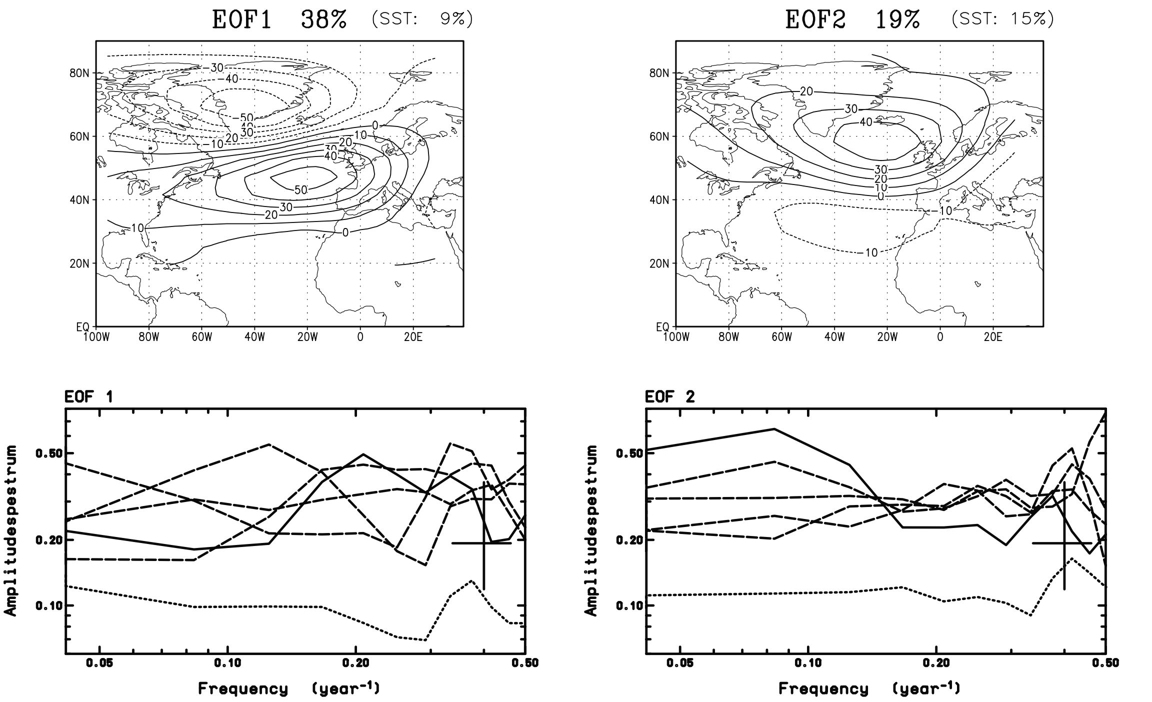

Fig. 1: First and second EOF of the euro-atlantic 500 hPa geopotential height (contour interval: 10 gpm) and spectral analysis of the principal components using a Bartlett spectrum with 22.5 degrees of freedom and a window of 12 years. The solid line represents the coupled simulation, the dashed lines the forced simulations and the dotted line the ensemble mean.

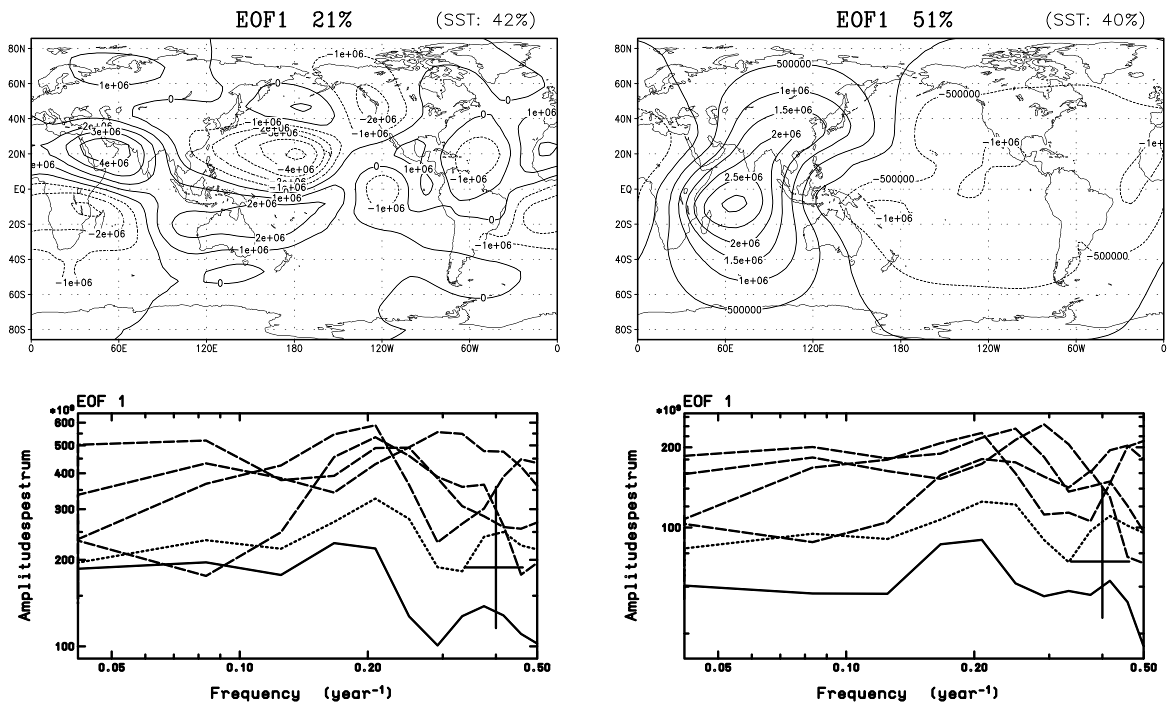

Fig. 2: First EOF of the 200 hPa zonal eddy streamfunction and the velocity potential (contour interval: 1 x 10^6 m^2s^{-1} (streamfunction, left) and 5 x 10^5 m^2s^{-1} (velocity potential, right)) and spectral analysis of the principal components using a Bartlett spectrum with 22.5 degrees of freedom and a window of 12 years. The solid line represents the coupled simulation, the dashed lines the forced simulations and the dotted line the ensemble mean.

4. Conclusions

The variability of the extratropical atmosphere is not significantly enhanced in the coupled simulation, which is in contrast to findings of Neelin et al. (1999). But there is evidence that the fully coupled system develops pronounced decadal variability as already observed by Selten et al. (1999). The findings support the hypothesis of Saravanan and Williams (1998) that the coupling plays a major role in the development of decadal variability.

A caveat of the widely used SST forced atmospheric GCM experiments resides from the large differences between the variance of the tropical atmosphere in the coupled and in the forced simulations. Particularly the modes of variability which are highly sensitive to tropical SST variability show significantly enhanced variability in the forced simulations in contrast to the coupled simulation. Thus in the forced simulations some essential feedback mechanism is missing that extenuates the SST forced tropical variability. It cannot be excluded that this phenomenon is a singularity of the ECHAM3-T21/LSG and therefore has to be verified by other GMC experiments necessarily.

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A Perspective on the Ocean Component of Climate Models

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A workshop on ocean modelling for climate studies was held at NCAR in August 1998, and a full report is contained in WOCE (1999). That report is too long to summarize fully here, so this is our, shorter perspective on recent accomplishments and future challenges in ocean climate models. As with many geophysical problems, the fundamental equations governing the large-scale physical dynamics of the ocean are well known. Thus, many of the major advances in numerical modelling arise from improved parameterisation of sub-grid scale processes and surface, bottom and lateral boundary conditions. Recent accomplishments include:

a) Uncoupled ocean experiments have shown that a resolution of 0.1 deg, or finer, is required to ”resolve” the eddy-mean flow interaction in the extratropical oceans. A necessary, though perhaps not sufficient, condition is that the horizontal grid needs to be smaller than the Rossby radius of deformation at high latitudes. These eddy-resolving experiments are typically short integrations of 5-15 years, often using reanalysed wind products, and simple surface boundary conditions for heat and salt. For example, a series of experiments for the North Atlantic has been run at Los Alamos with varying horizontal resolutions of 0.4, 0.2, and 0.1 deg, forced by ECMWF winds from 1985-1998 using biharmonic horizontal dissipation in momentum and tracers, see Smith et al. (1999). The northward heat transport from these runs is shown in Fig. 1, along with a recent estimate by Trenberth (1998) of the implied ocean heat transport from a residual calculation using atmospheric reanalysis products. The hatched area in Fig. 1 is this estimate plus/minus one standard deviation. Only the 0.1 deg model experiment has a maximum transport >1 PW, and agrees with the observational estimate from 10ºN to 35ºN. Most of the change in heat transport between the experiments is due to changes in the mean flow, because the small eddy contributions in the three experiments, which are also shown on Fig. 1, are almost independent of resolution.

b) The implication of this work is that the quality of eddy parameterisations will be important in all ocean models used for climate because their horizontal resolution will be coarser than 0.1 deg. A very nice demonstration of this is the work of Roberts and Marshall (1998), which analyses the ”Veronis Effect” at a range of resolutions from 1 to 1/8 deg. Veronis (1975) showed that the buoyancy flux across the Gulf Stream resulting from horizontal mixing is largely balanced by vertical advection, thus short circuiting the thermohaline circulation in the North Atlantic and reducing the poleward heat transport. Roberts and Marshall (1998) found that the strength of this effect is close to being independent of resolution; at higher resolution the mixing coefficient is smaller, but the tracer gradients are stronger. The heat transport curves in Fig. 1 are another example of the Veronis effect in action. The final curve on Fig. 1 is from a run of the 0.4 deg resolution using the eddy parameterisation scheme of Gent and McWilliams (1990) with a constant coefficient. This scheme eliminates the Veronis effect and gives a realistic magnitude northward heat transport of >1 PW.

c) Much recent work has shown that surface boundary conditions of strong restoring of model SST and SSS to observed values produce poor surface flux fields, especially in fresh water. Hence, equilibrium temperature and salinity distributions from coarse resolution ocean models using restoring boundary conditions are poor. More realistic boundary conditions must be used, which is much easier done for heat than it is for fresh water. One reason for this is that precipitation and net E-P over the global ocean and land runoff volumes are poorly known from observations, and a second reason is that, unlike SST, SSS has no negative feedback on the surface fluxes. This means that small errors in the forcing can produce a small, but persistent, model drift that results in significant biases over very long integrations. For example, Gent et al. (1998) documents that a good equilibrium solution requires a small correction to the fresh water forcing that is supplied by a weak restoring to SSS term with a timescale on the order of a year. This term can be considered as a ”correction” to the precipitation and land runoff data used to force the model; but the fact that the ”corrected” precipitation has some areas of small negative values in the subtropics shows that model

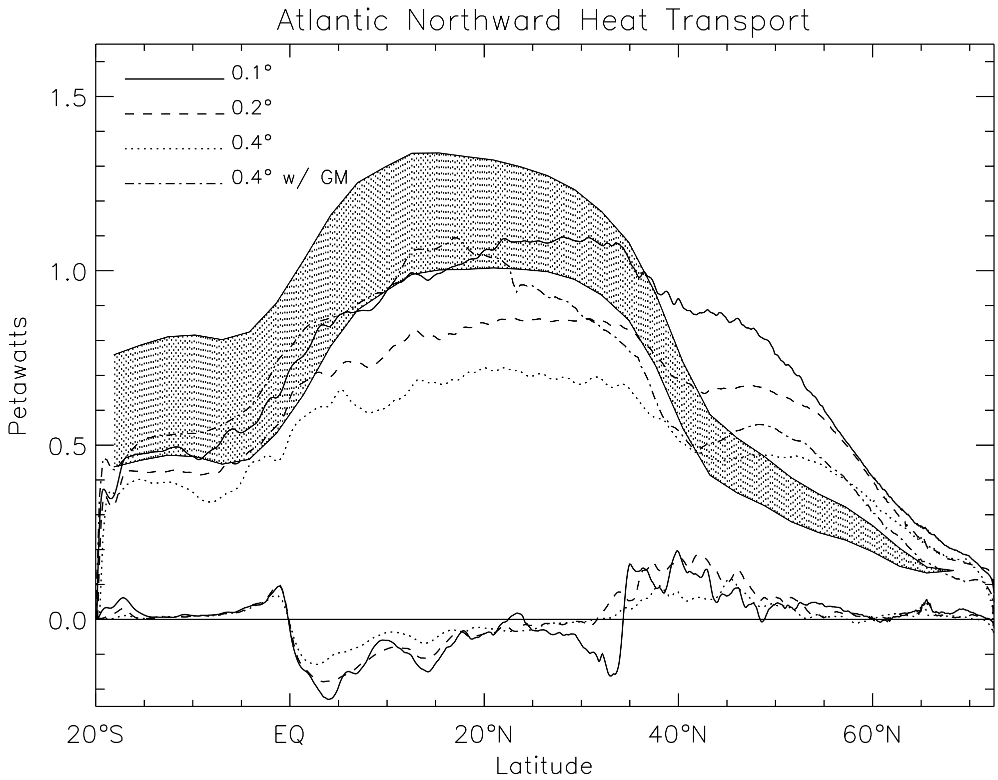

Fig. 1: Northward heat transport in the North Atlantic; the hatched area is an estimate from observations by Trenberth (1998). There are curves for the total and eddy contributions from three experiments with 0.1, 0.2, and 0.4 deg resolution. The dash-dot curve is from a 0.4 deg experiment using the eddy parameterization of Gent and McWilliams (1990).

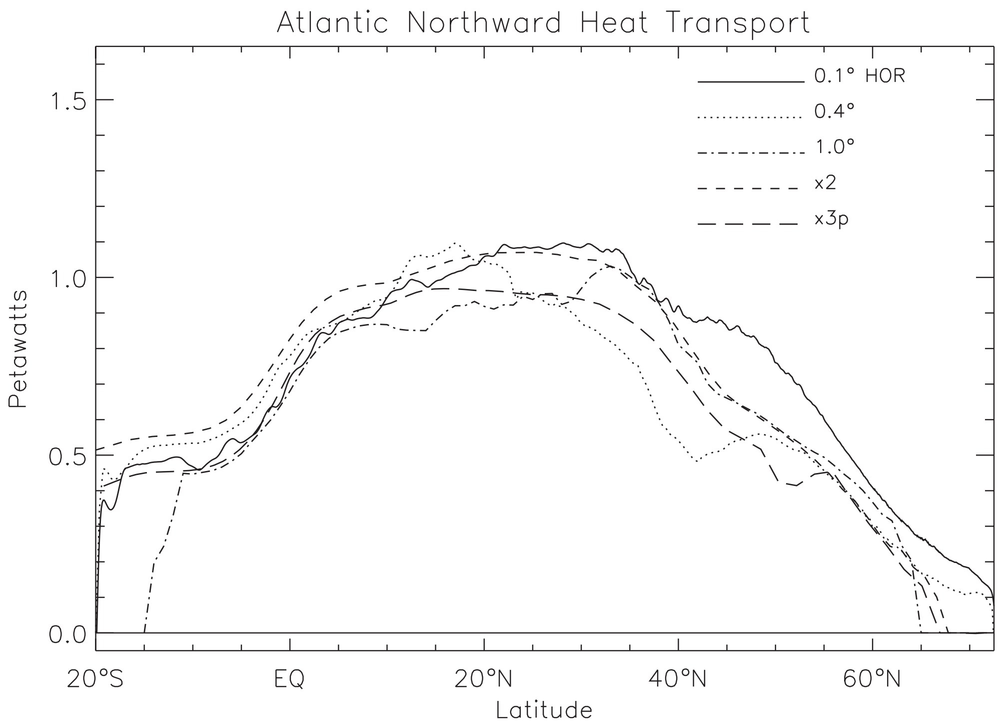

Fig. 2: Northward heat transport in the North Atlantic from five different model configurations, forced by observations. The 0.1, 0.4, and 1 deg results are from regional models of the North Atlantic, and the x2 and x3p are from the global ocean component of the CSM.

physics errors must also play a role. The bottom line is that a strong restoring boundary condition on SSS should not be used for long, equilibrium runs of ocean climate models.

d) There are two recent examples of long coupled, present-day climate model simulations that have almost no drift in SST, even though they do not use flux corrections. The first was NCAR's Climate System Model (CSM), Boville and Gent (1998), which was run for 300 years, and the second is a 1000 year run of the Hadley Centre's most recent model HadCM3, Gordon et al. (1999). The horizontal resolution in the ocean components was about 2 deg in the CSM, and 1.25 deg in HadCM3. We believe that the main reason for these successes is that the atmosphere and ocean components are compatible in their poleward heat transports, see Boville and Gent (1998). This has been achieved by improvements in both the atmosphere and ocean components. For the ocean, this requires good, global sub-grid scale parameterisations for diapycnal mixing and meso-scale eddy mixing in the non-eddy-permitting regime of these ocean components. The CSM and HadCM3 both use the Large et al. (1994) K-profile parameterisation (KPP) and the mesoscale eddy parameterisation of Gent and McWilliams (1990). However, HadCM3 uses slightly modified versions of these parameterisations; for the eddy scheme the spatially varying coefficient suggested by Visbeck et al. (1997) has been used. There is drift in SSS and in both deep temperatures and salinities in both these long, coupled integrations. However, the changes in the temperature and salinity distributions have not been large enough to significantly change the thermohaline circulations. This is the only way that SSS can cause a large feedback on the ocean solution, because excessively fresh conditions at high latitudes can cap the thermohaline circulation. Reducing these drifts in the ocean component is one of the future challenges for coupled climate modelling.

Future challenges over the next several years include:

e) Improvement to all parameterisations used in ocean climate models. For example, Polzin et al. (1997) observe much higher diapycnal mixing rates over the rough topography of the mid-Atlantic ridge than over the adjacent abyssal plain; this could be parameterised in the diapycnal mixing scheme. Visbeck et al. (1997) suggest a spatially varying isopycnal mixing coefficient that is a function of mean flow variables. Improvements are needed to bottom boundary layer schemes that are sorely needed in z-coordinate models to improve the flow over sills and other topography. Improvements are also needed to the parameterisation of the eddy effects on momentum, which most climate ocean models still parameterise as downgradient horizontal and vertical diffusion. This last question will become more important as the horizontal resolution goes from the non-eddy-permitting into the eddy-permitting regime, so that the speed of western boundary currents increases. These are just a few examples; there are many other needed parameterisation improvements.

f) To evaluate the trade-offs between potential improvements in simulations versus computational cost as the horizontal resolution in ocean climate models goes into the eddy-permitting regime. Figure 1 shows that, as the resolution gets finer, the increased northward heat transport is due to the changed mean state, so there is hope to simulate this by a good parameterisation of the effect of eddies. Figure 2 shows the northward heat transport in the North Atlantic from five models with different horizontal resolutions. The 0.1 and 0.4 deg curves are the same as in Fig. 1. The 1 deg curve is taken from a simulation described in Böning et al. (1995), that is a North Atlantic domain that stops at 15ºS, rather than 20ºS, as in the 0.1 and 0.4 simulations. The x2 and x3p curves are from global ocean alone, equilibrium simulations using the ocean component of the CSM, see Gent et al. (1998). The four coarser resolution simulations use the Gent and McWilliams (1990) eddy scheme, and figure 2 shows that with this scheme, the North Atlantic heat transport is relatively independent of horizontal resolution. It has been shown that this is not so when horizontal mixing of tracers is used. What is needed are companion experiments run in a coupled model, where the only change is the horizontal resolution and the associated mixing coefficients. This would enable a judgement to be made as to whether the potential improvements in properties important for climate are worth the substantial extra computational cost.

g) Sea-ice is a very important part of the global climate system. In the past for the CSM, we have obtained an ocean alone, equilibrium solution forced by observations before coupling to the sea-ice component, see Boville and Gent (1998). This solution uses strong restoring boundary conditions to observations in areas diagnosed from SST data as being ice covered, and the global solutions are sensitive to the time-scale used in the restoring terms. The ocean circulation then receives a large shock when it is coupled to the sea-ice component and forced by output from the atmosphere component. The only way to overcome these problems is to spin-up the ocean and sea-ice models together using observational forcing. This eliminates the restoring boundary conditions, and will reduce the shock when the ocean and sea-ice are forced by atmosphere component output. We believe this is an important step towards better global, coupled climate models.

h) Ocean climate models need to be broadened to include biogeochemistry, rather than just the physical components of most present climate models. This is needed in order that a climate model can do a complete inventory of the carbon budget, for example. Future atmospheric levels of greenhouse gases, such as CO_2, are one of the major uncertainties associated with climate predictions for the next century, see Hansen et al. (1998). Only about 40% of the carbon dioxide emitted over the past 20 years has remained in the atmosphere; the difference has been taken up by the ocean and the biosphere. Biogeochemical components in the atmosphere, land and ocean models are needed in order to predict how the oceanic and terrestrial uptake of carbon will change over the next century. These biogeochemistry components also feedback in a small, but unquantified, way on the physical properties of the atmosphere, land, and ocean. Work along these lines has been proceeding, or just started, at some centres doing global climate modelling, but this is a relatively new field that will become more important as models of the global climate system evolve over the next five to ten years.

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Coupled Climate Modelling at GFDL: Recent Accomplishments and Future Plans

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1. Introduction and description of GFDL coupled climate models

Coupled ocean-atmosphere models have been used extensively at GFDL over the past several decades for a wide variety of climate modelling studies. These include pioneering studies of the transient response of the climate system to increasing greenhouse gas concentrations, as well as studies of paleoclimate and internal variability of the coupled ocean-atmosphere-land system.

Continuing in this tradition, there are currently two distinct coupled ocean-atmosphere climate models in use at GFDL for research on global warming and other aspects of climatic sensitivity and variability. The models differ in resolution by a factor of approximately 2 but share similar physics. The R30 coupled model, which has been under development for several years, is now being used for the generation of global warming scenarios and studies of decadal-to-centennial climatic variability. This model has an atmospheric horizontal resolution of 3.75° longitude and 2.25° latitude, with 14 levels in the vertical. It is coupled to an ocean model with an approximately 2° horizontal resolution, a simple current-drift sea-ice model, and a "bucket" land model. Flux adjustments are incorporated to reduce climate drift and facilitate the simulation of a realistic mean state. The atmospheric component of this model has been studied extensively. Analyses of a large ensemble of 40-year experiments with prescribed observed sea surface temperatures (SSTs) show a highly realistic response of the model to tropical Pacific SST variations, as well as realistic representations of mid-latitude variability. Selected output from the R30 atmospheric model is available at "*http://www.cdc.noaa.gov/gfdl/index.shtml*". The R15 coupled model has similar physics but lower spatial resolution.

Several long control integrations have recently been performed, exceeding 1000 years for the R30 model and 12,000 years for the R15 model. A variety of experiments with greenhouse gas and sulphate aerosol forcings has also been conducted. The principal scientific findings from our recent modelling studies related to global warming are summarized below.

2. Simulation of the climate of the 20th and 21st centuries

A major recent activity has been the use of the R30 coupled model to study climate change over the 20th and 21st centuries. A suite of five simulations over the period 1865-2089 has been completed, in which the model is forced with estimates of the observed and projected effective greenhouse gas concentrations and sulphate aerosols. An equivalent CO_2 concentration is used to represent changes in all of the trace greenhouse gases, and changes in aerosol loading are modelled by altering the surface albedo (Mitchell et al., 1995; Haywood et al., 1997). The runs proceed until the late 21st century with equivalent CO_2 increasing at the rate of 1% per year after 1990. The ensemble members differ in their initial conditions, which are taken from widely separated points in the long control run. In addition, a suite of six integrations is currently underway using new scenarios proposed by IPCC-2000 (scenarios A2 and B2).

Shown in Fig. 1 (page 20) is the time series of observed global mean surface temperature (thick, black line), as well as the time series simulated from the five members of the R30 ensemble (various coloured lines). The observed temperature record of the 20th century is characterized by an overall warming trend, largely occurring in two distinct periods (1925-1944, and the late 1970s to the present). The ensemble members largely capture the amplitude and timing of the 20th century warming. The simulated time series form a spread around the observed record, thereby offering a perspective on the role of internal variability. Since each model starts from independent initial conditions, the internal variability realized in each of the ensemble members is independent. Closer examination of the time series for the individual realizations, however, reveals that one of the ensemble members (Experiment 3) appears to track the observed time series quite closely, including the observed warming of the 1920s and 1930s. Since the members differ only in their realizations of internal variability, this suggests that internal variability may have played an important role in the observed warming of the 1920s and 1930s.

The equilibrium response of this model to a doubling of greenhouse gas concentrations is 3.4K, approximately in the middle of the 2.1K to 4.6K range cited in IPCC (table 6.3, Kattenberg et al., 1995). The agreement between the model and observed trends suggests that this level of climate sensitivity cannot be excluded based upon the observational record.

The geographical distribution of simulated surface temperature trends has been compared with the observed trends for the period 1949-1997 (Knutson et al.,1999). The simulated and observed trends are consistent in most regions, taking into account the internal variability of the trends, as estimated from the model. There are also several areas which are inconsistent, all of which are regions where substantial cooling has been observed (primarily the midlatitude North Pacific, and parts of the Southwest Pacific and the Northwest Atlantic). These regional inconsistencies are very likely the result of deficiencies in one or more of the following: 1) the prescribed radiative forcing; 2) the simulated response to this forcing; 3) the simulation of internal climatic variability; and 4) the observed temperature record. Distinguishing between these alternatives is a high priority for future research.

The observed temperature trends in this same period have also been compared to trends generated by internal climate variability in the control integration. In nearly 50% of the areas analysed (where data was deemed adequate for this purpose), the observed warming trends exceed the 95th percentile of the simulated distribution of internally generated trends for the same location. If the model's simulation of internal climate variability is accurate, these observed trends are very unlikely to have occurred due to internal dynamics of the climate system.

Studies have also focused on changes in the large-scale extratropical atmospheric circulation under greenhouse warming. Differing responses were found in the two hemispheres. The SH tropospheric response consists of a summertime poleward shift of the westerly jet, the storm tracks, and the atmospheric and oceanic mean meridional overturning. The simulated signal emerges robustly early in the next century when compared to the control run. The signal-to-noise ratio, however, is relatively small because the signal projects strongly and positively onto the model's Antarctic Oscillation (AAO) pattern. (The AAO and its NH counterpart, the Arctic Oscillation (AO), are the principal modes of variability of the extratropical zonal-mean circulation.) The positive sign of the projection is in agreement with observed trends.

In contrast with the SH, the NH tropospheric circulation response involves an equatorward jet shift, an enhanced Aleutian Low, and a negative sea-level pressure anomaly over the Arctic. The response in the Aleutian Low and the Arctic SLP agree in sign, but not in magnitude, with recent observed trends. In particular, the observations show a much larger negative trend in Arctic SLP than is seen in the simulations. We are currently exploring the factors that underlie this discrepancy.

3. Continuing studies with the R15 Coupled Model

The speed of the R15 coupled model has allowed a wide range of recent studies with this model. These studies have focused on both radiatively forced climate change and internal variability of the coupled ocean-atmosphere system. Some examples of recent studies are highlighted below.

a. Large ensemble of climate change simulations

Dixon and Lanzante (1999) have recently conducted a nine member ensemble of greenhouse gas plus sulphate aerosol experiments covering the period 1765 to 2065. The study found a relatively small sensitivity of simulated surface air temperature to the year in which the model integration started (1765, 1865, or 1915). This result provided the rationale for starting the R30 experiments at year 1865. The ensemble of experiments was also used to assess uncertainties in various aspects of climate change, including global mean temperature response and the thermohaline circulation (THC). The mechanisms responsible for the simulated weakening of the THC were further investigated in Dixon et al. (1999) who showed that enhanced atmospheric water flux convergence was the primary factor leading to a reduction of the simulated THC. Additional analyses are also being conducted on the hydrologic cycle and its response to greenhouse warming, with emphasis on the near-surface continental climate (Wetherald and Manabe, 1999).

b. Sea ice and climate change

Vinnikov et al. (1999) compared the simulated decrease of Arctic sea ice in the GFDL R15 model to the observed decrease. The results (Fig. 2, page 20) demonstrate a remarkable agreement between simulated and observed trends. Further, they demonstrated that the observed decrease in sea ice extent is outside the range of internal variability of the model. Additional analyses using the R30 model provide generally similar results.

Analyses are ongoing to assess Southern Hemisphere sea ice changes, as well as changes in snow cover.

c. Multidecadal variability

Delworth and Mann (2000) have recently compared the simulated multidecadal variability in the North Atlantic of the R15 coupled model to a new multiproxy reconstruction of climate over the last several centuries. In both the model and proxy reconstructions the spectrum of climate variability has a clear peak on the multidecadal time scale (approximately 60-80 years). The simulated variability involves fluctuations in the North Atlantic THC. A comparison of the spatial structures between the model and the observations reveals relatively good agreement in the North Atlantic sector. Preliminary analyses with the R30 coupled model indicate that similar variability exists in the higher resolution model. Such detailed comparisons of model and proxy data offer a promising pathway for increasing our understanding of decadal to centennial scale variability. Delworth and Greatbatch (2000) have also used the R15 model to demonstrate that such multidecadal variability of the THC is partially attributable to stochastic forcing of the ocean through the surface heat flux.

d. Extreme event in a 12,000 year coupled run

A control integration of one version of the R15 coupled model now has been extended beyond 12,000 years, thereby offering insights into centennial to millennial scales of variability. In this extended run a highly anomalous event occurs in the high latitudes of the North Atlantic at approximately model year 3100. A large pulse of fresh water, originating in the Arctic, moves southward through the Fram Strait into the North Atlantic. This fresh water pulse is accompanied by reduced oceanic convection and cold surface air temperature (annual mean anomalies of -4 K, corresponding to 6 standard deviations below the mean). This event appears to be an extremely high amplitude realization of a prominent mode of internal variability of the coupled system (Delworth et al., 1997). Investigations of the dynamics of this variability are ongoing.

4. Simulation of the Ice Age - implications for climate sensitivity

A major source of uncertainty in climate model projections of future climate involves the sensitivity of the climate system to radiative forcing. One way to evaluate the realism of a model's climate sensitivity is to simulate climates of the distant past where sufficient evidence exists to estimate the changes in climate forcing and response. In pursuit of this goal, Broccoli (2000) used a atmosphere-mixed layer ocean model, whose atmospheric component is nearly identical to the one employed in the R30 coupled model, to examine the changes in tropical climate induced by the relatively well-documented changes in radiative forcing that occurred 21,000 years ago during the last glacial maximum. At this time, continental ice sheets were greatly expanded, atmospheric CO_2 was reduced by approximately 25%, and sea level was more than 100 m lower. When incorporated into the climate model, these changes produced a mean cooling of 2 K for the region from 30°S to 30°N.

Comparison of this simulated cooling with a variety of paleodata indicates that the overall tropical cooling is comparable to paleoceanographic reconstructions based on alkenones and species abundances of planktonic microorganisms, but smaller than the cooling inferred from noble gases in aquifers, pollen, snow line depression, and the isotopic composition of corals. The paucity of paleoclimatic evidence for tropical cooling smaller than that simulated by the model suggests that it is unlikely that the model exaggerates the actual climate sensitivity in the tropics. A more definitive evaluation of the realism of the tropical sensitivity of the model must await the resolution of the differences in the magnitude of tropical cooling reconstructed from the various paleoclimatic proxies.

5. Future plans

A major reorganization of the model development activity is underway at GFDL. The new modelling system will consist of both a software infrastructure that is shared across models and specific models that are constructed on top of this infrastructure, including fully coupled climate models. The latest version of GFDL's Modular Ocean Model will be incorporated into this system along with new land and sea-ice models under development. Two distinct atmospheric dynamical cores are included in the current realization of this system: a grid-point model on the B-grid, and a standard spectral model with the option of grid advection of water vapour and other tracers. A variety of improvements to the atmospheric physics are under active development, including a new radiative transfer code, boundary layer parameterisations, convective closures and cloud prediction schemes with prognostic cloud water. The hope is that this new structure will reduce the time required to develop new coupled models, ease the transition to new computer architectures, provide for more integrated research activities within the lab, and foster more extensive extramural collaborations. Research on seasonal-to-interannual forecasting and on the circulation of the middle atmosphere, which are currently conducted with models that are distinct in many different ways from the climate model, will be using the same modelling system and sharing most physics modules with future climate models.

The development of a new climate model for use in long control integrations, global warming scenario generation, and paleoclimatic studies is currently focused on a T42 resolution spectral atmosphere coupled to an ocean model with 2° horizontal resolution, except in the tropics where finer resolution is retained to provide a better ENSO simulation. An ice model with viscous-plastic rheology will also be incorporated. A 1° version of the ocean model is also undergoing initial testing. At present, the oceanic, land, and ice components are closer to being finalized than the atmospheric component. Plans also involve using both grid and spectral atmospheric models, at resolutions of T106 and higher, coupled to mixed layers or with fixed SSTs (or SSTs generated in lower resolution coupled model global warming scenario studies) to evaluate how alternative atmospheric physical packages affect climate sensitivity and regional climate change.

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Plate 1: Figures from Sperber et al. (see page 4)

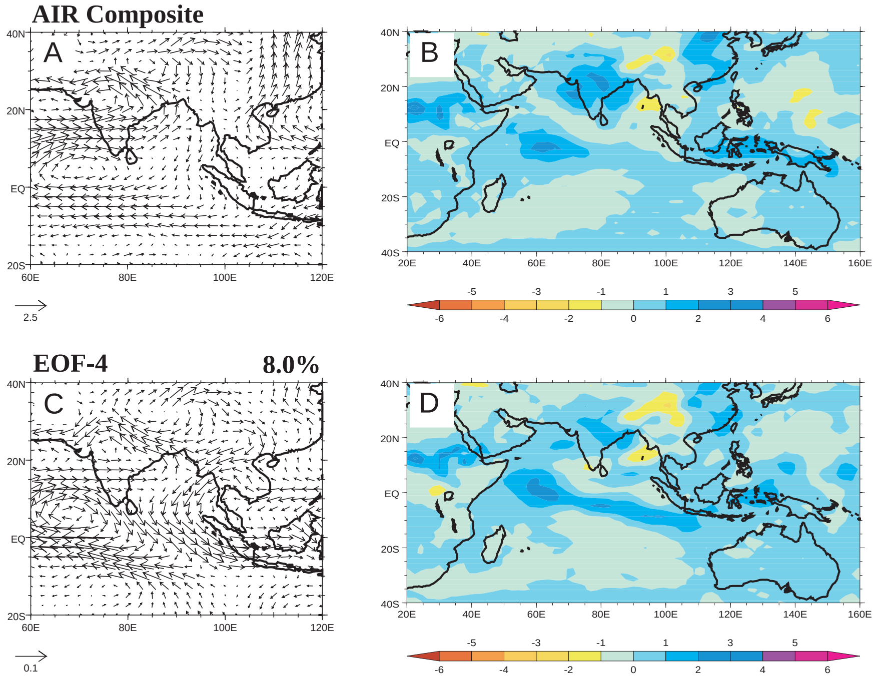

Fig. 2: The composite difference of seasonally averaged (a) 850hPa wind (unit vector=2.5ms^{-1}) and (b) precipitation anomalies (mm day^{-1}) for years of above normal all-India rainfall versus years of below normal all-India rainfall (see Fig. 1). (c) The fourth mode of variability extracted from an empirical orthogonal function analysis of seasonal anomalies of 850hPa wind. The magnitude of the wind anomalies is the product of the principal component time series and the components of the wind. Typical variations of this mode are 1-2ms^{-1}. (d) precipitation anomalies (mm day-1) constructed from the difference of composites based on years when the principal component time series of mode 4 was of above normal versus below normal using +/-0.5 standard deviations thresholds.

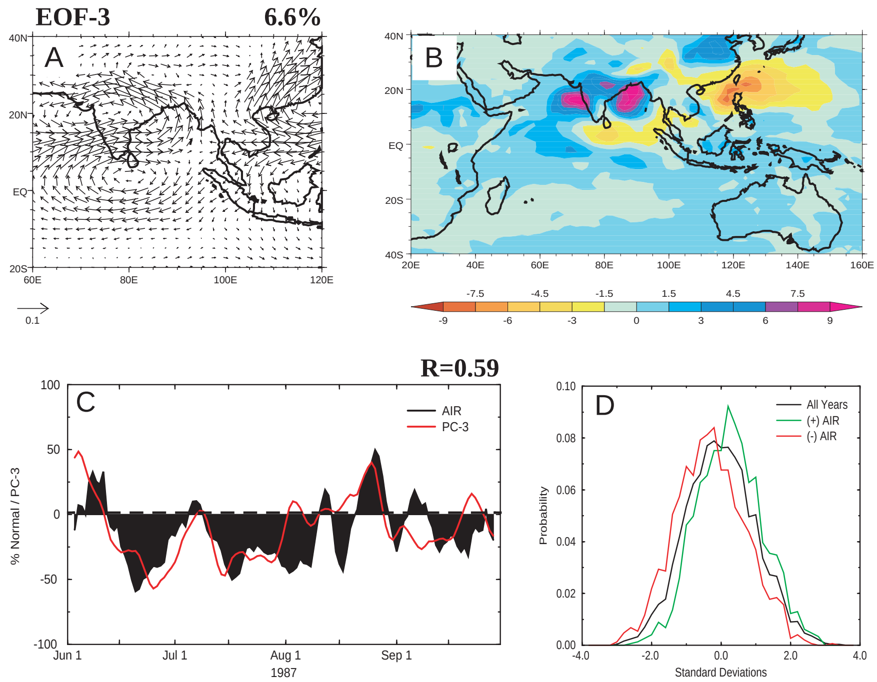

Fig. 3: (a) The third mode of variability extracted from an empirical orthogonal function analysis of daily anomalies of 850hPa wind. Typical variations of this mode are 2-4ms^{-1}. (b) precipitation anomalies (mm day^{-1}) constructed from the difference of composites based on days when the principal component of mode 3 was of above normal versus below normal using +/-1 standard deviations thresholds. (c) Observed daily all-India rainfall (filled curve, expressed as a percentage of normal) and the principal component time series of mode 3 (red line) for 1987. Both time series have been smoothed with a 5-day running mean. (d) Probability distribution functions of the principal component time series of mode 3 for all years (black line), years of above normal all-India rainfall (green line) and below normal all-India rainfall (red line). The years of above normal and below normal all-India rainfall are given in Fig. 1.

Plate 2: Figures from Delworth et al. (see page 15)

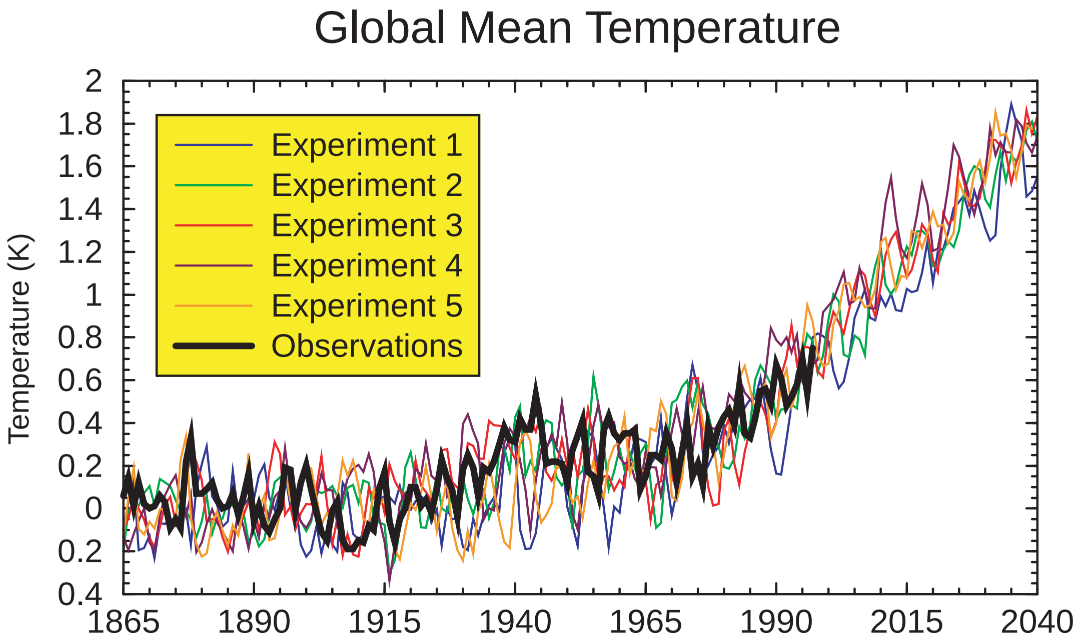

Fig. 1: Time series of observed (heavy black line) and simulated (various thin colored lines) global mean surface temperature over the period 1865 to 2040 (1997 for the observations). The simulated lines are from 5 independent realizations of the GFDL R30 coupled model forced with estimates of observed greenhouse gases and sulfate aerosols until 1990, and projections thereafter. The model output is sampled only for those locations and times at which observational data exist. For both model and observations, surface air temperature is used over the continents, while sea surface temperature is used over the oceans. The observed data are a combination of the Jones (1994) surface air temperature data and the Parker et al. (1995) sea surface temperature, updated through 1997. Anomalies are plotted relative to the 1880-1920 mean for both the model and observations.

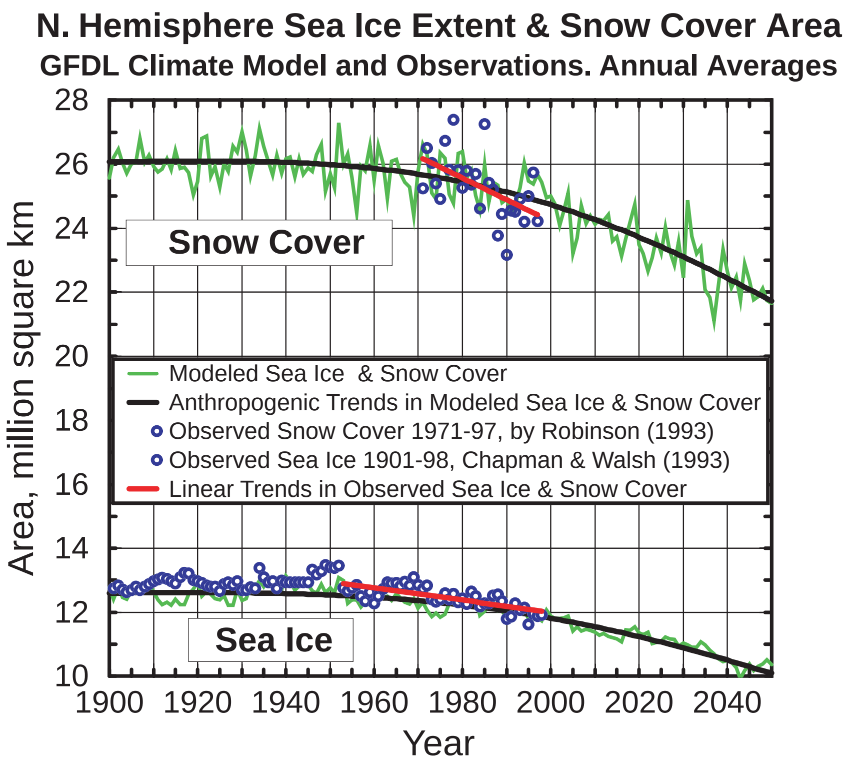

Fig. 2: Observed and simulated time series of Northern Hemisphere sea ice extent and snow cover (after Vinnikov et al.,1999).

Climate Variability at Decadal and Interdecadal Time Scales

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Only with an improved understanding of natural climate variability confident estimations of possible climatic changes due to anthropogenic influences can be given. In view of the observed increase of global mean surface air temperature since the beginning of the twentieth century (Jones et al., 1986) investigations of natural climate variability have to concentrate on time scales of decades to centuries. While the role of external factors including anthropogenic effects in causing climate changes on these time scales have been investigated widely, the knowledge of the contribution of nonlinear atmospheric processes to climate variability is rather poor. This shortcoming exists as a result of the absence of statistically sufficient long atmospheric observational data series and as a result of the limited temporal and horizontal resolution of paleoclimate proxy data. To address the problem of internal atmospheric low-frequency variability anyway long-term integrations of appropriated models are one possible way to get hints on the real atmospheric behaviour on decadal and interdecadal time scales.

The objective of this study is to quantify the natural climate variability by long-term integrations with a climate model of the atmosphere-ocean system of moderate complexity. It concentrates on the unresolved problem whether observed changes of the atmospheric circulation are generated internally and force variations of oceanic fields or whether the oceanic variability induces decadal and interdecadal atmospheric oscillations. The applied model is the three-dimensional climate model developed at the Obukhov Institute of Atmospheric Physics of Russian Academy of Sciences (IAP RAS climate model) and is described in (Petoukhov et al., 1998) and (Handorf et al., 1999). It consists of modules for atmospheric, oceanic, sea-ice and land-surface processes, linked through fluxes of energy, momentum, water, whereas no flux adjustment is necessary. In particular, the atmospheric module includes the vertical coupling of the tropo-, strato- and mesosphere. The model resolves explicitly the basic features of the large-scale and long-term atmospheric and oceanic fields, whereas all synoptic-scale processes are parameterised in terms of their statistical characteristics, regularly in a stationary manner. Recently, nonstationary parameterisations were implemented for all atmospheric horizontal temperature and moisture fluxes resulting in an increase of the temporal variability on longer time scales approximately by a factor of three. The horizontal resolution amounts to 4.5 degrees in latitude and 6 degrees in longitude. The basic primitive equations for the large-scale long-term and synoptic components were subjected to a scale analysis in dependence of latitude and height and were solved at 8 atmospheric layers and 3 oceanic layers. The used approach reduces the complexity of the model and permits fast integrations over thousands of years with low computational costs due to a much longer time step as usually used in complex general circulation models.

Despite the mentioned simplifications the model simulates the main large-scale features of atmospheric circulation in the height range of tropo-, strato- and mesosphere in good agreement with observational data. Especially, the model describes reasonably good the strength and location of the large-scale characteristic pressure patterns of the northern hemisphere. For instance, the Island low and Azores high, responsible for the North Atlantic Oscillation are reproduced. Confirmed by the results of the model validation for present-day climatic conditions the described model presents an appropriate tool for analysing the nonlinear dynamics of large-scale atmospheric patterns.

Therefore two integrations over a 1,000-year period were carried out. For both runs all external factors including the solar constant and the greenhouse gas concentration were kept unchanged, while the treatment of the ocean was different. In order to extract the internal atmospheric variability from the variability of the coupled system the first run was performed with the fully coupled model. During the second run the atmosphere has been forced by a prescribed climatological annual cycle of sea surface temperature (SST) from observations (Reynolds, 1988).
The data basis for our analyses are the model simulated

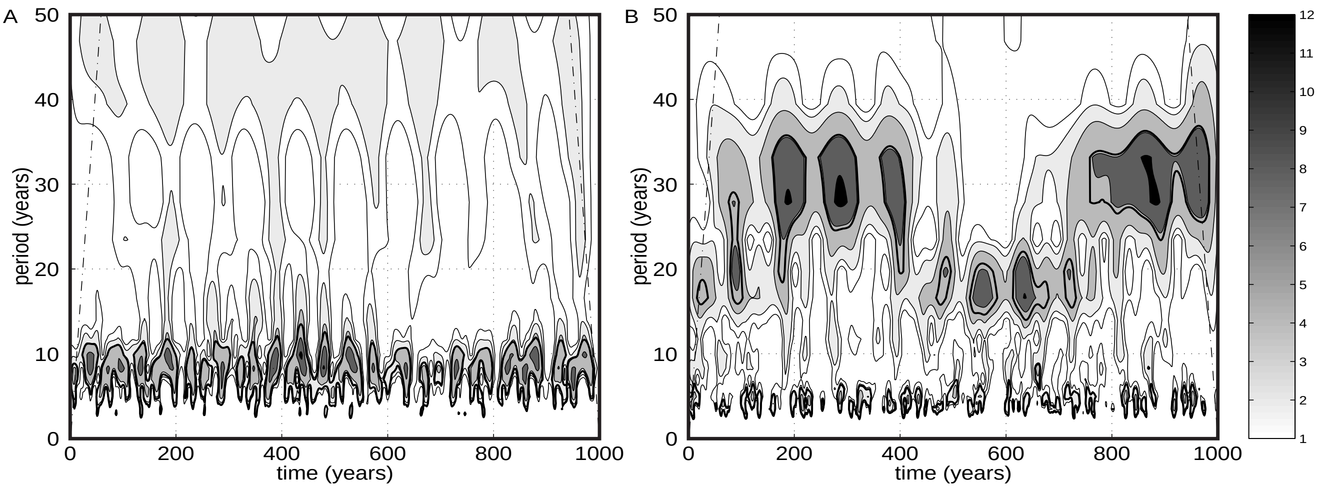

Fig. 1. Wavelet transformation, performed with the Morlet wavelet, of time series of PC1 (left panel A) and PC2 (right panel B) of SLP (13). Data obtained from 1000 year long integration of the IAP RAS climate model with an interactive ocean and were subjected to low-pass filtering with a cut-off of 1.5 years. Contour lines of squared wavelet coefficients are displayed. Thus the momentary distribution of energy in dependence of period (local power spectrum) is displayed. Large values of the local power spectrum refer to pronounced variations at the indicated time and period. At both ends dash-dotted lines separate regions where edge effects become important. The thick contour envelopes areas of greater than 95% confidence for a corresponding red-noise process with a lag-1 coefficient of 0.59 (PC1) and 0.47 (PC2). Wavelet software was provided by C. Torrence and G. Compo and is available at URL: http://paos.colorado.edu/research/wavelets/

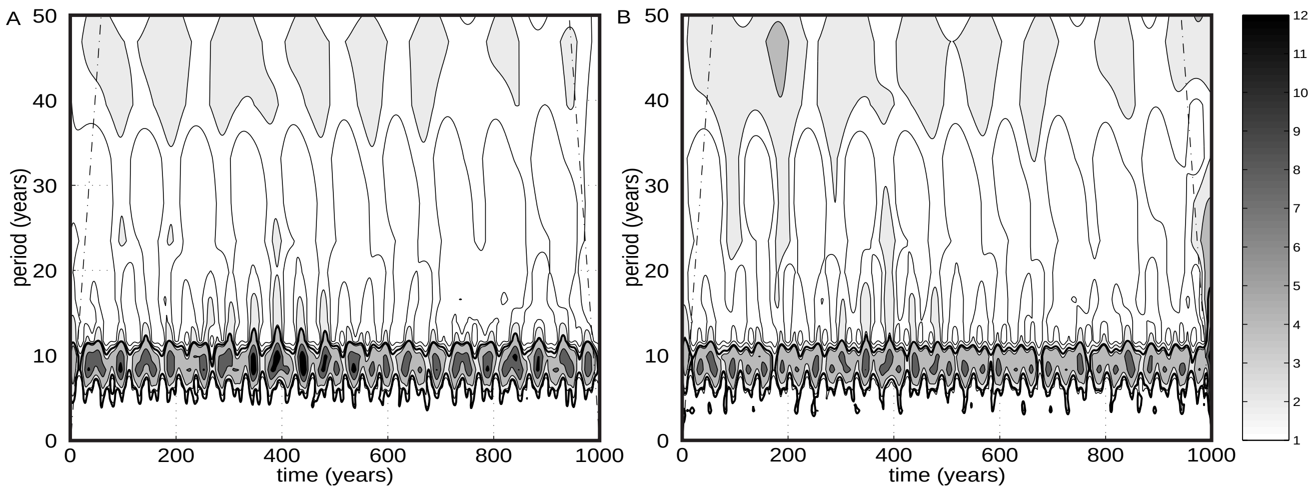

Fig. 2. Same as in Fig. 1, but SLP-data obtained from 1000 year long integration of the climate model with prescribed SST. The thick contour envelopes areas of greater than 95% confidence for a corresponding red-noise process with a lag-1 coefficient of 0.74 (PC1) and 0.71 (PC2)

northern hemispheric 5-daily averaged fields of sea level pressure (SLP), of stream function in geostrophic approximation at 5 km (~500 hPa), 18 km (~70 hPa) and 35 km (~10 hPa) and of temperature at different heights including SST. In this study we restrict ourselves to the northern hemisphere. For these multivariate data the method of empirical orthogonal function (EOF) (Preisendorfer, 1988) is a suitable tool for the determination of dominant spatial modes and their temporal behaviour. At all heights the first mode is dominated by a wavenumber 2 with a more zonal structure at stratospheric heights. This mode is closely connected with the land-sea distribution and thus with the annual cycle. The second mode contains teleconnection structures in the troposphere especially at midlatitudes whereas in the lower stratosphere mainly the long planetary waves which can propagate from tropospheric to stratospheric heights during winter are present. These large-scale spatial patterns of the atmospheric circulation remain nearly unchanged for the SST-forced run.

The temporal development of the two most dominant spatial patterns is described by the time series of the principal components PC1 and PC2. In order to quantify the low-frequency variability evident in these time series we applied a wavelet analysis. This sophisticated time-frequency analysis (Torrence and Compo, 1998) allows the investigation of nonstationary time series. The wavelet coefficients provide information about the period as well as about the time of appearance of a characteristic structure. Thus it allows to detect local temporal changes in the spectral distribution of energy. Recently developed statistical significance tests for wavelet spectra by (Torrence and Compo, 1998) enable the establishing of significance levels and confidence intervals in contrast to model spectra of corresponding white or red noise processes.

In order to illustrate features of internally generated climate variability we display the wavelet transformation of the time series of the principal components PC1 and PC2 of SLP for the coupled run (Fig. 1) and of SLP for the uncoupled run (Fig. 2). Due to our interest in low-frequency variations, all time series were subjected to low-pass filtering with a cut-off of about 1.5 years.

The wavelet analyses for the coupled atmosphere-ocean system reveal complex modes of variability. The preferred time scale of the variations of the first most dominant spatial pattern throughout the atmosphere have been found at the decadal scale at about 9 years, but shows considerable fluctuations. This is clearly indicated by the wavelet transformation of PC1 of SLP (Figs. 1A). Despite the high unsteadiness the variations at about 9 year exceed the 95% confidence level of the corresponding red noise processes during the whole integration. Analyses of the fields of other variables at heights up to 40 km confirm this result.

The second mode of variability shows a less uniform temporal behaviour throughout the atmosphere. Near the surface an interannual mode with a period about 5 years and a high degree of intermittency occurs. Additionally, interdecadal variations can be estimated. From Fig. 1B it is clearly indicated that for interdecadal variations two states exists, one is characterized by a 30 year period (model years 200-400 and 750-1000) and the other is characterized by a 18 year period (model years 0-50 and 450-750). The transition periods between these states are rather short. At upper heights we find the most dominant periods about 5 to 10 years with a maximum of spectral energy at 9 years. Furthermore time sections can be estimated, where variations at interdecadal scale between 25 to 30 years leave the 95% confidence level of the corresponding red noise processes. During some time sections (e.g. 450 to 750 years) a break down of this period has been found, which coincidences with the time of the presence of the 18 year period instead of the 30 year period in the PC2 of SLP. Nevertheless, at upper heights there is no clear distinction between two modes of interdecadal variability as described above for PC2 of SLP.

In comparison for the uncoupled run we have estimated a very strong and stable mode of decadal variability without any hint on intermittent behaviour. This mode is to be seen in the temporal variations of the first and second most dominant spatial pattern of all analysed fields throughout the atmosphere up to 35 km height without significant shifts in the distribution of spectral energy. In order to illustrate this the wavelet transformations of PC1 and PC2 of the field of SLP are shown in Fig. 2. Preferred time scales about 5 to 10 years can be inferred, which leave the 95% confidence level of the corresponding red noise processes during the whole course of integration. The maximum of the spectral energy occurs at 9 years.

To sum up, for both runs the most pronounced variations arise at the decadal scale, specifically at 9 years. These variations can be find in first as well as higher order modes for the SST-forced run. In contrast, for the fully coupled run besides the decadal periods, which show an increased intermittency, interdecadal fluctuations appear. As the interdecadal variability is only evident in the PC's connected with higher order spatial modes, the question arises whether these interdecadal fluctuations have an influence on the climatic state of the Northern Hemisphere.

This question can be answered positively, because our investigations bring out a resemblance between the temporal and spatial structure of the second mode of variability (EOF2/PC2) of SLP and of the North Atlantic Oscillation (NAO). The NAO is one of the well-known teleconnection patterns of the northern hemisphere and determines to a considerable amount the winter climate conditions in western and middle Europe. It is known from observations, that the NAO appears not only in the fields of SLP like in our model results (Wallace and Gutzler, 1981), but also in the geopotential height fields in the stratosphere (Kitoh et al., 1996) and as the leading coupled mode of variability between the tropospheric and stratospheric circulation (Perlwitz and Graf, 1995).

A wavelet analysis of the time series of the observed NAO-index, defined according to (Hurrell, 1995) shows interannual (2 to 3 years) to decadal (about 8 years) variations in coincidence with other investigations (Hurrell and van Loon, 1997). The same analysis of the NAO-index derived from results of the fully coupled run indicates preferred time scales at 3, 5 and 30 years with a breakdown of the 30 year period and a shift to a 18 year period between 450-750 years in accordance with the analyses of PC2 of SLP. The wavelet analysis of the NAO index derived from the SST-forced run reveals preferred time scales at 3.5 years and 7 to 12 years. Again, the disappearance of pronounced interdecadal variations is obvious.

On the basis of our model results and taking into account studies by other authors, we propose that a large amount of the climate variations on the decadal timescales can be understood as the result of nonlinear atmospheric dynamical processes. Modes of interdecadal variability have been identified as modes of the coupled atmosphere-ocean system which potentially can be generated by variations of horizontal gyral flows or by changes of meridional oceanic overturning. The identification of specific mechanisms that cause decadal and interdecadal variability is now our task for future studies.

Furthermore, the agreement between the preferred modes inferred from the wavelet analyses of the PCs of Northern Hemispheric SLP and stream functions at upper heights with that of the NAO index supports the view that the model atmosphere fluctuates between a preferred high-index state with strong zonal flow and weak planetary waves and a low-index state with pronounced planetary waves and weak zonal flow. Such a view is confirmed in the framework of nonlinear dynamics in the sense that climate fluctuations on longer timescales are caused by changes of the probability density functions of nonlinear weather regimes. Some specific mechanisms leading to interdecadal variations of the climate system have been already detected, but especially the contribution of atmospheric nonlinear processes to changes of regime frequency has not been understood. The latter has to be determined by future studies in order to assess the influence of anthropogenic changes on the climate system.

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Wavelet software was provided by C. Torrence and G. Compo and is available at URL: *http://paos.colorado.edu/research/wavelets/*

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Climate change signals in the North Atlantic Oscillation

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1. Introduction

The North Atlantic Oscillation (NAO) describes an atmospheric phenomenon in the North Atlantic sector as an organized motion of the Icelandic Low (IL) and the Azores High (AH) (Defant, 1924). For largely unknown reasons these pressure systems exhibit a synchronous meridional shifting where a northward shifting is accompanied by a strengthening of both centres of action. This results in an enhanced meridional pressure gradient with a mainly zonal circulation over the North Atlantic. In winter this zonalisation extends to Western Europe with a typical warm air mass advection from the Atlantic over Europe and cold air advection north-west of the IL centre. The southward shifting is accordingly combined with weakening of IL and AH and more meridional circulation. Explaining locally up to 50% of the near surface variance, the influence of the NAO on the interannual low tropospheric temperature variability cannot be neglected. Therefore, interdecadal changes in the NAO are relevant for regional climate variability over Europe and North America (Hurrell, 1995).

The issue of this study is whether this important atmospheric phenomenon is subject to a change in view of the expected anthropogenic influence on the global climate system.

2. Data and Method

We study the NAO in an observational data set from the German Meteorological Service (DWD) derived from time series of gridded sea level pressure spanning the period 1880 to 1995 as well as in several model data sets with different forcing scenarios, periods and initial conditions mostly derived from the coupled atmosphere-ocean general circulation model (AO-GCM) ECHAM-3/LSG in Hamburg with spectral T21 resolution (Roeckner et al., 1992). In particular, we concentrate on an ensemble of four model runs with increasing greenhouse gases according to the observed CO_2 concentrations until 1985 and then to IPCC scenario A ("business as usual") (Houghton et al., 1990).

The usual NAO index ("standard index") employed by Hurrell and van Loon, 1997 and many others (cf. Maechel et al., 1998) is the pressure difference between two fixed locations near Iceland and the Azores. We define the NAO index by the first principal component (PC) derived from four time series of central pressure and mean latitudinal position of IL and AH. This index is advantageous compared to other NAO indices based on pressure differences at fixed locations because it always follows the main centres of action and thereby represents the full meridional pressure gradient. In addition, our method of obtaining the NAO index is appropriate for assessing a seasonally-varying signal since the pressure systems are subject to a seasonally-induced shifting. Thus, the evident time-dependent shifting of the centres of action (Ulbrich and Christoph, 1998) is taken into account. The sign convention is such that a positive value signifies the northward shifting with zonal circulation regime and vice versa (Glowienka-Hense, 1985, 1990).

3. Results

In Figure 1 the individual annual means and 11 years lowpass filtered running means of the NAO index are shown for the four ECHAM-3/LSG scenario A model simulations with external CO_2 forcing as well as the running means of the DWD observational data respectively. On the interannual time scale a strong variability can be observed implying the near unpredictability of the year-to-year changes of the NAO. However, the magnitude of interannual NAO variability is realistically simulated by the model compared to the observed NAO. On the other hand, the smoothed curves reveal a low frequency signal on time scales of about 50 years.

Additionally, the scenario runs predict the continuation of the recent positive NAO state for the future until the middle of the 21th century.

In spite of some specific differences in details such as an occasionally breaking of the future positive phase in run 2 and 4, the climate signal in the form of the recent positive NAO tendency occurs in each ensemble simulation - especially in the ensemble mean. In this context, it is not essential that the general positive tendency is transiently interrupted since the interannual variability is quite large. Rather we want to focus on the interdecadal time scale where a clear positive trend of the NAO mean state is revealed. Particularly, this is expressed in the ensemble mean.

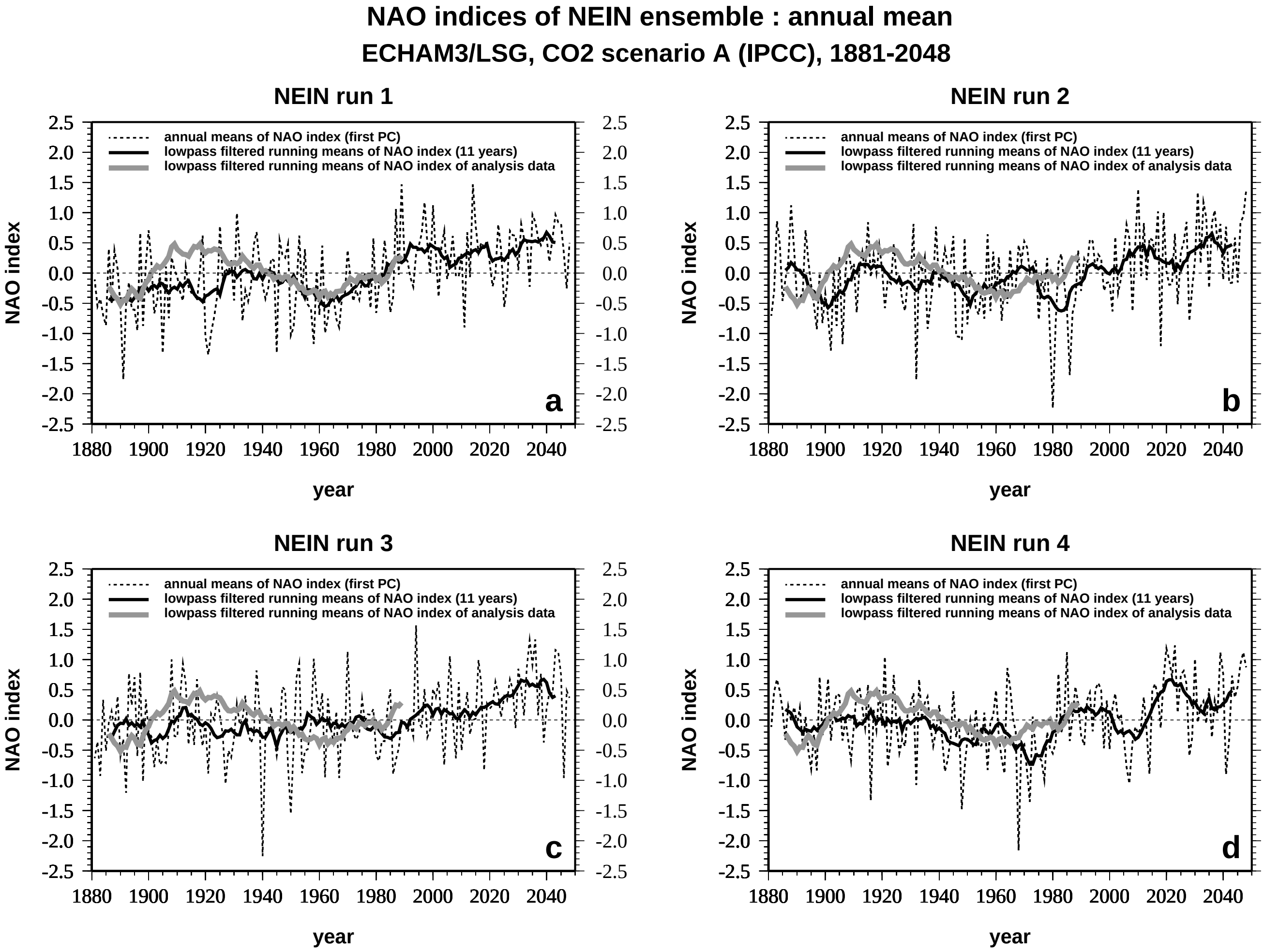

Fig. 1: NAO index of the four ensemble runs with greenhouse gas scenario A of the IPCC: annual means (thin dashed line), lowpass filtered running means of 11 years (black solid line) and lowpass filtered running means of the DWD observational data set (grey solid line). Compared with the original simulation (Fig. 1a), the additional runs (Fig. 1b-d) are based on identical model physics and external forcing parameters (only CO_2) but varying starting conditions derived from three states of the corresponding control run each 200 years apart.

There should be no doubt that the NAO in the ECHAM-3/LSG is characterized by a climate signal probably due to the greenhouse forcing that takes effect in the model from the 1970's onward.

Such a positive phase of the NAO indicates a predominantly zonal circulation over the North Atlantic and a characteristic pattern of winter temperature anomalies over the surrounding land masses with warming over Eurasia and cooling over North-East America. Incidentally, this temperature pattern is also expected in connection with the potential greenhouse induced global warming (Paeth and Hense, 1998) and has been termed COWL by Wallace et al. (1995).

The correlation to the standard index based on pressure gradients at fixed stations is relatively strong reaching nearly 0.9 even on the interannual time scale.

To assess the dependence of the NAO development on model version several model simulations performed with the recent version ECHAM-4/OPYC in Hamburg (Roeckner et al., 1996,1998) including different forcings by greenhouse gases and sulphate aerosols.

In this context, we observe the same trend to a strong and continuously positive NAO phase from 1980 onward. Thus, it seems likely that a greenhouse gas climate signal of the NAO can be defined which is independent of the considered ECHAM model version and the initial conditions.

To handle the NAO signal in a statistically more precise way an analysis of variance (ANOVA) (Morrison, 1990) has been carried out based on the four ensemble runs. By means of the ANOVA the influence of the common external forcing parameter CO_2 on the total variance of the ensemble simulations can be quantified and its statistical significance determined. First the test has been performed for 20 year running means.

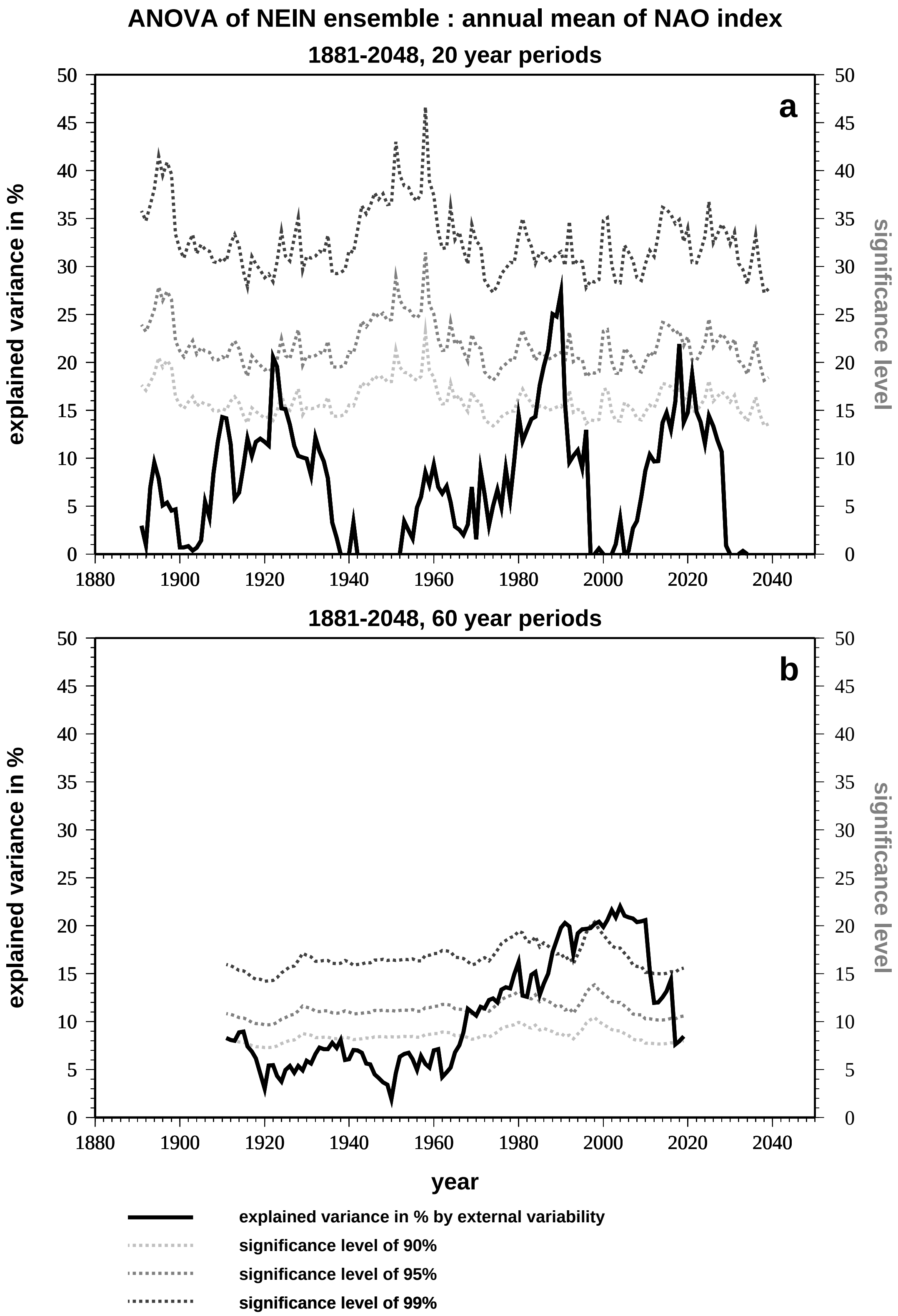

Fig. 2: Analysis of variance of the annual means of NAO indices based on the 4 realizations of the ECHAM-3/LSG ensemble: explained variance in % by the external forcing parameter (black solid line), significance level of 90/95/99% (dotted lines with greyscale). The ANOVA relates the variance of the ensemble mean to the single variances of each ensemble run in order to separate the external forcing from the internal model induced variability. Here, ANOVA refers to 20 year periods (a) and 60 year periods (b) shifted through the whole data set. Therefore, the significance levels are also varying. The x-axis' legend corresponds to the middle year of each period.

On this time scale (Fig. 2a) significant values of the external influence on total variance only appear sporadically and internal variability clearly dominates. In consequence climate prediction on the base of a greenhouse induced NAO change should be difficult even on this climatological time scale. On the other hand, if the ANOVA is focused on periods of 60 years (Fig. 2b), which correspond to the characteristic multidecadal time scales of the NAO low frequency variability, the greenhouse forcing emerges from behind the model internal variability after 1970. With explained variances of almost 25% the null-hypothesis that there is no influence of the external CO_2 forcing on the total NAO variability of the ensemble has to be rejected with an error level of 5% or less between 1970 and 2020 as middle years of 60 year-long periods, with some deterioration at the end of this simulation period. This deterioration is up to now subject to speculations: it might be caused by long term effects of the oceanic circulation. Further investigations have to be carried out. Before 1970 the null-hypothesis cannot be rejected indicating that the low frequency variability is induced by internal dynamics.

Generally, the dynamics of IL - deepening as well as northward shifting - contribute more to the NAO signal than AH does. The seasonal response is strongest in late summer and winter. The interannual variability of the North Atlantic Oscillation states on time scales less than 10 years decreases synchronously with the positive trend of its decadal-mean state implying a stabilisation of its present and future zonal state.

A model intercomparison study referring to ensemble simulations of the Canadian CGCM and the English HadCM2 with similar climate change scenarios leads to missing NAO signals in these models! However, if the whole Northern Hemisphere pressure field is taken into consideration instead of the North Atlantic sector as a priori assumption, the tendency to a strong circum-global zonalisation can be revealed from 1980 onward probably due to the common greenhouse forcing. The effected circum-global circulation mode is mostly called the Arctic Oscillation (AO) which is very similar to the more regional NAO but of hemispheric extent. It is likely that NAO and AO are two representations of the same atmospheric circulation mode. This zonalisation trend is persistent in all considered greenhouse gas-induced model runs.

4. Summary and Conclusions

The ANOVA clearly indicates a statistically significant influence of the greenhouse forcing on the NAO in the ECHAM-3/LSG model confirming the existence of a climate signal within the simulated field of sea level pressure. The signal consists of a trend to a positive and continuing phase of the NAO implicating a typical pattern of temperature anomalies with warming over Eurasia and cooling over North-East America in winter, which proves to be persistent with regard to varying initial conditions as well as different model versions.

Other coupled models show a climate change signal in the more hemispheric AO which is in sign and relevance very similar to the NAO signal predicting a zonalisation trend over the whole Northern Hemisphere.

Finally, the most interesting question is whether these results might be transmitted to the real NAO with strong implications for the ongoing discussion of anthropogenic climate change. According to our study the observed state transitions of the real NAO since 1880 are unlikely due to the greenhouse forcing. However, the recent positive trend since 1965 might indicate the beginning of the climate signal as it occurs in the scenario A model runs. But in view of the observed strong positive phase at the beginning of the 20th century, which is most likely based on natural climate variability, the recent 30 year-long trend to be compared to the multidecadal variability of the NAO has to be considered to be too short to lead to reliable statements.

Statistical evidence whether or not the real NAO is subject to a greenhouse induced change, might arise in 10 to 30 years, when the NAO signal would really emerge from behind the background noise of natural variability, if it remains in the recent predominantly positive state.

Nevertheless, there are two important methodological implications by our results: since the simulated greenhouse-gas induced NAO based on the field of sea level pressure reveals a recognizable climate change signal, it seems that pressure is actually appropriate to detecting climate change although it has been considered to be too noisy up to now. On the other hand, this study shows, that it is very useful to consider ensemble simulations when addressing the question of climate change signals since this represents a way to extract the externally induced variability. E.g. in Figure 1 the first ECHAM-3/LSG run originally provided by the DKRZ would have been misleading by reproducing astonishing analogies to the observed NAO index already from 1930 onward which obviously was due to pure chance.

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Natural and Anthropogenic Causes of Twentieth-Century Temperature Change

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A paper recently appeared in Nature (Tett et al., 1999) in which we analysed the causes of twentieth century near-surface temperature change. Here we describe our analysis in a less formal manner and also present some additional results using seasonal data that are analysed in more detail in a paper recently submitted to Climate Dynamics (Stott et al., 1999).

Optimal detection

Optimal detection is in principle just ordinary least-squares regression (Allen and Tett, 1999) in which we estimate the amplitude in observed data of pre-specified patterns of climate change. It is “optimal” in giving more weight to patterns in which there is less variability. Here we specify patterns in space and time of climate response to various forcings derived from the HadCM2 coupled ocean atmosphere general circulation model (Johns et al., 1997). The analysis makes no assumption about the size of a signal, just its shape. Consequently uncertainty in climate sensitivity is not a problem, nor are missing feedbacks, providing they primarily alter the size of the response rather than its shape. A signal is detected if the likely range of its amplitude in the observations is entirely positive, i.e. the data tell us to reject, at some pre-specified significance level, the null hypothesis that it is not present. In our analysis we also check whether the residual of regression after we have fitted the signals under consideration is consistent with internal variability as simulated by a control run of HadCM2 (in which external climate forcings, except for the diurnal and seasonal cycle, are kept constant).

The analysis

We have a 1700 year control run for statistics of internal variability and simulations with what IPCC (Dickinson et al., 1995) indicate are the two most important anthropogenic forcings and the two most important natural forcings. These are:

- **G**: well mixed greenhouse gases, represented by equivalent CO_2.
- **GS**: well-mixed greenhouse gases plus sulphate aerosol from burning fossil fuels. Only a direct radiative effect is explicitly represented, but on large scales the indirect effects should look similar.
- **Vol**: stratospheric aerosol of volcanic origin. We use the updated reconstruction of Sato et al. (1993).
- **Sol**: solar irradiance variations. We consider variations in total solar irradiance using the reconstruction of Hoyt and Schatten (1993) extended with satellite data (Willson, 1997).

For each forcing we have an ensemble of four simulations covering the twentieth century so as to increase the signal-to-noise. The modelled response to these forcings is compared with an observed data set of near-surface temperatures from (Parker, et al., 1994). Since previous work (Stott and Tett, 1998) has found that modelled climate change projects most strongly onto large space and time scales, we filter the data by decadally averaging annual or seasonal data and by projecting all spatial fields onto spherical harmonics to retain only scales greater than 5000 km. Each spatio-temporal pattern consists of five decades of decadally-averaged spatially-smoothed data. 50 years is long enough to give good signal-to-noise but short enough that we can estimate the statistics of natural internal variability from the control run. We analyse five 50-year periods; 1906-56, 1916-66, 1926-76, 1936-86 and 1946-96.

For more information about the analysis procedure used and to see an animation of the signals and the observations see *http://www.met-office.gov.uk/sec5/CR_div/sfbtett/c20tc_si_top.html*.

Results

Analyses have been carried out using annual data and seasonal data in the decadal averages (Stott et al., 1999). In both cases we find that internal variability alone is not consistent with observed climate change in 3 out of the 5 periods we consider (1906-56, 1916-66, 1946-96), even though the consistency test we apply on the residuals of regression is a weak test in that it uses no information about the shape of the modelled signals. In the most recent 50-year period (1946-96) it rules out all combinations without an anthropogenic signal. Therefore we do not find a satisfactory explanation of twentieth century temperature change that excludes anthropogenic influence.

Using annual data Tett et al. (1999) found that signals are prone to degeneracy, that is, different patterns resemble each other, or resemble linear combinations of each other. With decadal seasonal means the degeneracy is lost and we may legitimately consider results from regressing up to all four signals at once.

Greenhouse gases, sulphate aerosols and solar changes are all detected during at least one of the 50-year periods. Volcanoes however, are not detected in any of the five 50-year periods considered here, although they are detected on annual scales and are sometimes detected using decadal averages for 50 year periods with different starting years (Stott et al., 1999). Since our aim is to provide a necessary but sufficient explanation of recent climate change we exclude volcanos from our explanation and consider anthropogenic and solar factors only.

The best-estimate pattern amplitudes, β, for the three signals and their likely ranges are shown in Fig 1. The **GHG**&**SUL** ellipse for 1946-96 is above both the β_{GHG}=0 and the β_{SUL}=0 axes, indicating that both greenhouse gases and sulphate aerosols are detected in this period. The **GHG**&**SUL** ellipse for 1906-56 lies below the $\beta_{GHG}=\beta_{SUL}$ line, indicating that here we need to reduce the ratio of the sulphate to greenhouse gas signal amplitudes below that specified in the **GS** experiment to remain consistent with the observations. The 1-D confidence interval for the solar signal amplitude is above the β_{Sol}=0 axis in 1906-56 indicating that solar changes are detected early in the century. In their analysis using annual data, Tett et al. (1999) showed that detection of solar changes is dependent on the relative amplitude of the anthropogenic signals being approximately the same as in the **GS** experiment. When they reduced the amplitude of sulphates by 33% or more, they no longer detected the solar signal in 1906-56. By analysing seasonal data however, we find that detection of a solar influence is not conditional on assuming the relative amplitudes of the anthropogenic factors to be similar to that prescribed in the **GS** simulation.

The contributions of greenhouse gases, sulphate aerosols and changes in total solar irradiance to the trends in global-mean temperatures for each of the 50-year periods considered in the seasonal analysis are shown in Fig. 2. The overall pattern is of steadily increasing contributions from the anthropogenic components with warming due to greenhouse gases balanced by sulphate cooling in the mid century and greenhouse warming dominating later in the century. Early in the century, there is a relatively small but statistically significant contribution from solar changes.

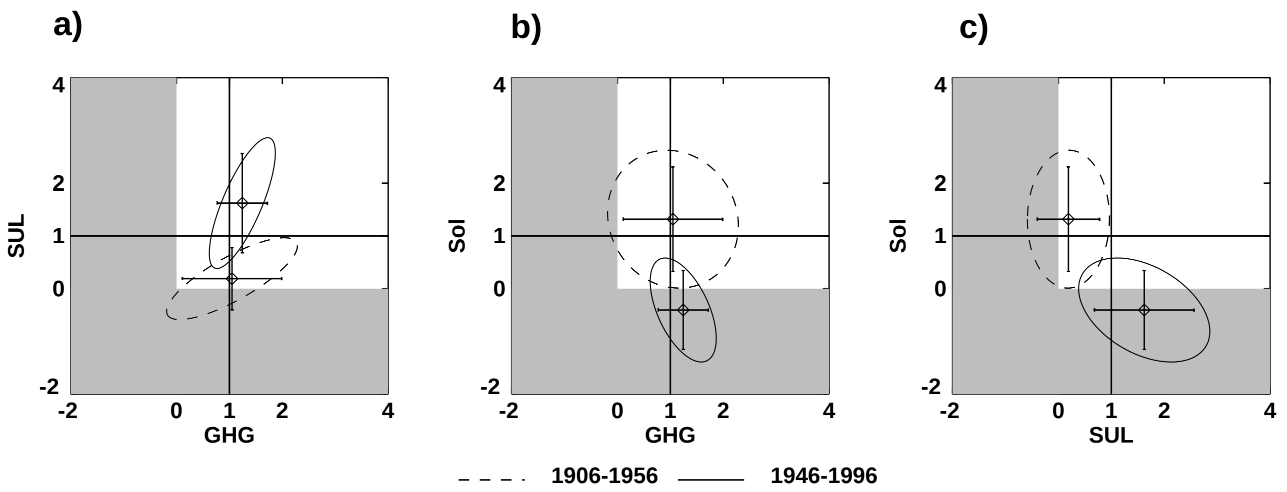

Fig. 1: Ellipses containing 90% of the estimated joint distribution of signal amplitudes for a) GHG&SUL, b) GHG&Sol and c) SUL&Sol. Each ellipse is centred on its best estimate (shown with a cross) and its size reflects the uncertainty in the amplitudes of the signals. Solid horizontal and vertical lines: 1-D confidence intervals for the amplitudes of each signal separately.

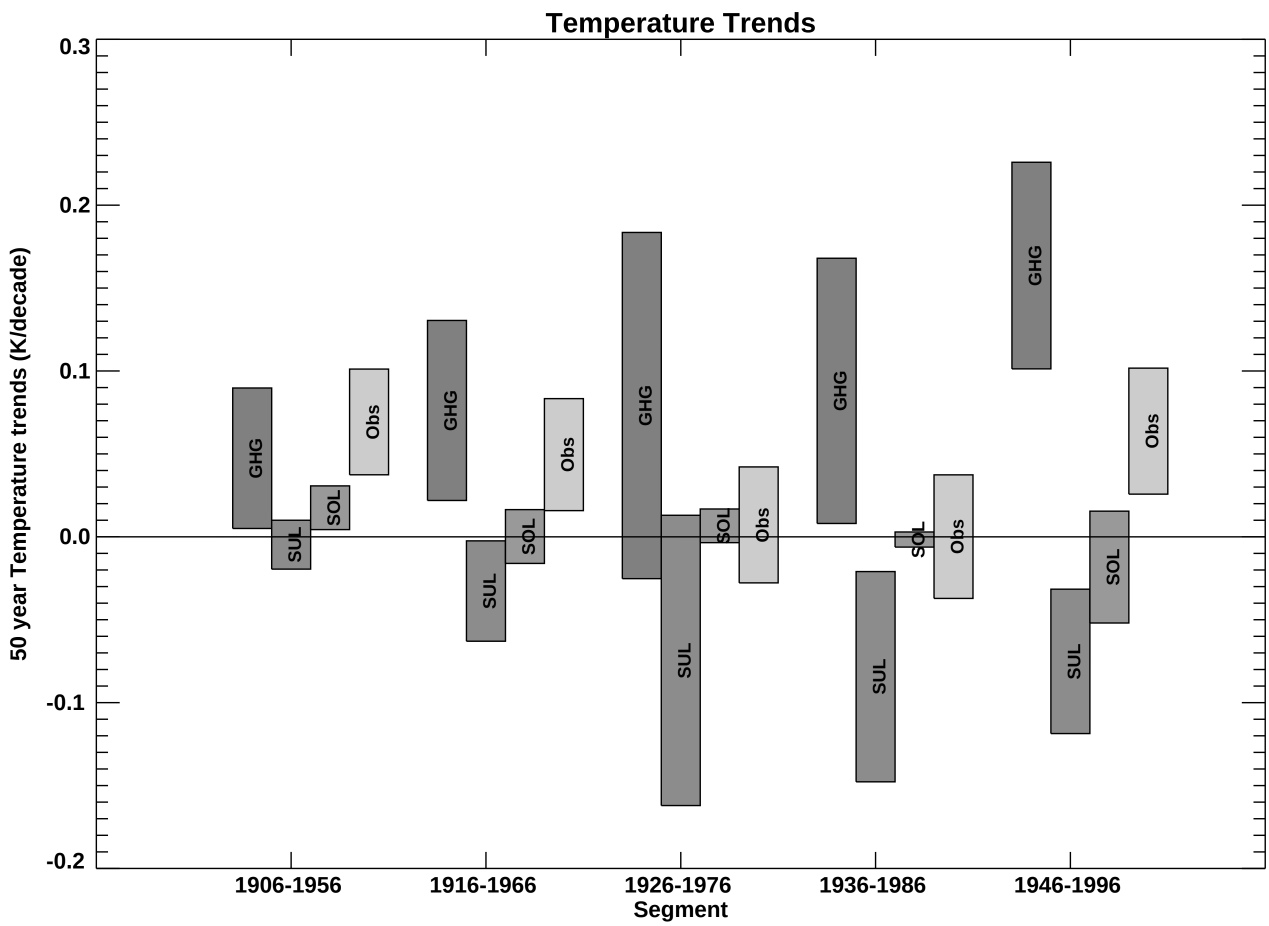

Fig. 2: 50-year temperature trends and their uncertainties due to GHG, SUL and Sol.

Conclusions

Our results indicate that the warming observed in the latter half of the twentieth century was caused by anthropogenic increases in greenhouse gases partly balanced by some cooling due to tropospheric sulphate aerosols, rather than by natural variability either internally or externally forced. By optimising over seasons and using one particular reconstruction of total solar irradiance, we have found evidence that solar effects contributed significantly to the warming observed in the first half of the century. However, a seasonal analysis using an alternative reconstruction of total solar irradiance (Stott et al., 1999), does not find a detectable solar influence in combination with greenhouse gases and sulphate aerosols.

The modelling simulations we used have a number of limitations; in particular we did not consider changes in the spectral distribution of solar irradiance or possible associated changes in ozone (Haigh et al., 1999). Future work addresses these limitations in a model that unlike HadCM2 does not need flux adjustments to maintain a stable climate. A limitation of our analysis procedure is that we use standard regression which may lead to a low-bias in pattern amplitudes that is likely to be more serious for weak signals. This is currently under investigation and future work will report on the implications of taking account of noise in model-predicted signals for the results reported here.

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U.S. CLIVAR Defines Objectives and Approach

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Beginning with their first meeting in September 1998, the U.S. CLIVAR Science Steering Committee (SSC) has been concerned with defining its goals over the next decade, establishing expert panels to implement the U.S. contributions to meet the goals of the international CLIVAR science and implementation plans, and advising U.S. agencies on high priority activities that are needed to begin an effective U.S. programme.

Looking over the broad range of CLIVAR goals the SSC is defining those of highest U.S. priority. While this process is still in progress, the SSC implementation strategy is strongly shaped by the following goals:

- *Expand understanding of seasonal-to-interannual variability.* This includes improving understanding and the ability to predict ENSO and expanding study to variability modes other than ENSO.

- *Explain the recent multi-decadal trend in the Arctic Oscillation/North Atlantic Oscillation.* The special nature of this remarkable phenomenon suggests this may be an opportunity to attribute observed climate variability to natural or anthropogenic mechanisms.

- *Develop an hypothesis for rapid climate change that is consistent with the paleo evidence*. Because rapid and global changes in the past may serve as analogies for possible future change understanding their causes are important despite the relatively low probability of occurrence in the near future.

- *Understand the mechanisms for decadal climate variability and assess its predictability.* Observations, modelling and empirical studies should be accelerated to understand the mechanisms and assess the potential predictability of decadal variability, particularly over the Atlantic, North America and the Pacific from the tropics north. Use present and past seasonal-to-decadal climate variability to test and validate comprehensive models used for assessing anthropogenic climate change. Because the impact of assessments of anthropogenic climate change depend so directly on the ability of the underlying models to explain observed climate variability, great importance is placed on improving those model's ability to reproduce the relatively well-observed variability of the recent past.

- *Develop methods for connecting regional climate descriptions to large- scale climate variability.* Because climate models of necessity have relatively low resolution, their ability to describe regional climate patterns is limited. The value of climate predictions can be significantly improved through better "down scaling."

The approaches to these problems will span the full spectrum including continued empirical studies of instrumental and proxy climate records, analytical theory, sustained observations as well as model experimentation and development. While much of this work can effectively proceed without a high degree of coordination, there are some areas that are particularly promising but require a coherent national contribution to an international effort. Among these are:

- *The global climate observing system.* A high U.S. priority is to define the needs for an integrated global climate observing system and begin to establish the highest priority parts.

- *Comprehensive Climate Models*. While computing capabilities limit the ability to exploit these models for climate study so does the manpower within the supporting institutions. U.S. CLIVAR will work to establish infrastructure to develop model diagnosis and development teams to help improve comprehensive climate models. These teams will be comprehensive in scope and will draw heavily from the expertise in the academic community.

- *Ocean State Estimation.* The combination of broadly distributed observations and assimilating modelling will be able to produce analysed fields of ocean data over the last 50 years, with high resolution products available for the period from 1988 on. These will be invaluable in the study the mechanisms of climate variability and potentially can improve climate prediction.

- *Basin-scale Extended Climate Studies (BECS).* In order to fully exploit the power of ocean state estimation to understand future climate variability, coherent U.S. contributions to international efforts to measure and analyse oceanic and atmospheric climate variability of the Pacific (Pacific BECS) and Atlantic (Atlantic Climate Variability Experiment) sectors are being developed.

- *Pan-American Studies.* As part of the international Variability of the American Monsoon System (VAMOS) programme, the U.S. plans to continue studies, begun under the Pan-American Climate Study (PACS), of the American monsoon, to expand those studies to the north, and to establish meaningful coordination with the Global Energy and Water Cycle Experiment (GEWEX) to better understand the hydrological cycle and land-surface processes.

While the U.S. approach to CLIVAR is organised somewhat differently than the PRAs of the international organization, it can be mapped onto those research areas. The best developed U.S. plans are in the GOALS PRAs G1 (ENSO) and G3 (American Monsoon), in decadal modulation of ENSO (bridging G1 and D4), and in seasonal-to-decadal variability in the Atlantic sector spanning PRAs D1 (North Atlantic Oscillation), D2 (Tropical Atlantic) and D3 (Atlantic Thermohaline). Efforts in G1 include global modelling and empirical studies coupled with enhanced observations in the Pacific Ocean. Efforts in G3 are integrated with VAMOS and based on new tropical ocean and atmosphere observations. Modest expansions of the modelling, empirical and observational studies needed for these efforts will support studies of decadal variability (under D1, D2, D3 and D4). A majority of the U.S. work in the anthropogenic PRAs A1 (Prediction) and A2 (Detection and Attribution) will be based mainly on coordinated modelling efforts. Planning and pilot studies for G2 (Asian-Australian Monsoon) will be initiated. Other areas, such as G4 (African Climate Variability), extending D3 to study Arctic changes, and D5 (Southern Ocean), are of interest, but the U.S. hopes other nations will take the lead in developing and implementing a strategy to satisfy CLIVAR objectives in these areas.

Many ingredients of research in the individual PRAs are common to them all. The U.S. will support integrating efforts such as development of models and data assimilation techniques, design and implementation of improved observing systems, and continuation of present satellite and in-situ observations. The U.S. also recognises the interdisciplinary nature of the climate research - close cooperation is required with operational activity in the World Weather Watch (WWW), the Global Climate Observing System (GCOS), the Global Ocean Observing System (GOOS), and the Global Ocean Data Assimilation Experiment (GODAE), and with complementary research programmes such as GEWEX and Past Global Changes (PAGES). In particular, the U.S. CLIVAR programme is predicated on continuation and evolutionary improvement of (a) satellite and in situ measurements that support operational analyses of the atmosphere, (b) satellite measurements of sea surface topography and surface winds over the ocean, and (c) the Tropical Atmosphere Ocean (TAO) array.

Consistent with the above objectives and general approach, the SSC has established an implementation team consisting of four expert panels to review, motivate and implement plans for U.S. activities. The present panels address CLIVAR activities in the Atlantic, Pan-American and Pacific sectors and one concerned with seasonal and interannual modelling and prediction. Other panels may be added in the future but it is hoped that the collection of panels will continue to function as a single implementation team that frequently meets together to fashion a coherent programme.

Based on advice from the implementation team and the SSC, the U.S. agencies contributing to CLIVAR have identified six high priority research areas they will support in 2000. These are:

- Empirical studies, diagnosis and modelling of the coupled ocean-atmosphere-land system, with emphasis on decadal climate variability. This reaffirms the efficacy of analyses of available observations and model experiments to help understand climate variability and the importance of understanding all three elements of the climate system. Phenomena of interest include (but are not limited to): decadal variability and predictability of ENSO; tropical Atlantic variability; mid-latitude phenomena like the Pacific Decadal Oscillation; and the North Atlantic Oscillation (NAO)/ Arctic Oscillation (AO).

- Diagnosis and modelling of the impact of sea ice and midlatitude SST anomalies on the circulation of the atmosphere. The climate impact of extratropical boundary conditions is almost certainly weak but perhaps the key to decadal variability. In particular, the role of transient atmospheric eddies, convection and boundary layer processes must be elucidated.

- Enhanced observation, modelling and analysis and of coupled ocean-atmosphere-land phenomena in the Atlantic and Pan American sectors, with emphasis seasonal-to-interannual climate variability. Of specific interest are, in the Americas and tropical Atlantic, feedbacks in the land-ocean- atmosphere system in the Pan American monsoon, the effects of Pacific SST, and the interaction with extratropical variability (the NAO and warm season rain in North America).

- Design studies for ocean observations in support of CLIVAR objectives. In support the objective of producing improved analysed ocean fields through data assimilation, methods for efficient sustained observations of various parts of the ocean climate system must be designed. Design studies of the following are sought: A. Low-latitude western boundary currents of the Atlantic and Pacific; B. Meridional overturning circulation in the Atlantic; and C. Complete observing systems over significant portions of the tropical and subtropical Pacific and/or Atlantic.

- The design of a process experiment for Pacific equatorial upwelling. Upwelling is central to ENSO and a key link in the shallow meridional overturning cells joining the subtropical gyres to the equator. Studies are sought that explore the possibility of measuring the transport and the depth and properties of the source waters.

- A design study and proof of concept of a strategy for developing surface flux products. Surface fluxes over the ocean are particularly valuable for diagnosing climate dynamics and validating coupled models, yet operational flux products are inadequate for climate studies. A strategy for combining routine and research-quality in-situ observations and satellite measurements with, or to improve, operational analyses to produce accurate flux fields is needed.

More complete descriptions of the items, and the background behind them, can be found at http://www.usgcrp.gov/usgcrp/usclivar along with links to the sites of the agencies supporting each item.

An important element of the U.S. approach to CLIVAR is the concept of in-situ observations of the upper ocean and surface fluxes coupled with remote sensing of surface elevation, sea surface winds and temperature all integrated within dynamically based data assimilation techniques. Central elements of these efforts will be the Global Ocean Data Assimilation Experiment and the Argo profiling float array which are being planned outside CLIVAR but with climate research needs in mind. U.S. scientists have met to elucidate the goals and basic implementation strategy for a Pacific Basin Extended Climate Study (PBECS) and an Atlantic Climate Variability Experiment (ACVE) and updated implementation plans should be available for review in the Spring of 2000. The ACVE plan will have the benefit of international meetings and will include responses to suggestions from scientists around the Atlantic. International discussion of PBECS has yet to take place.

Address for U.S. CLIVAR home page:
http://www.usgcrp.gov/usgcrp/usclivar/

4th International Conference on Modelling of Global Climate Change and Variability

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The 4th International Conference on Modelling of Global Climate Change and Variability was held at the Max-Planck-Institut für Meteorologie in Hamburg from September 13-16, 1999. More than 300 participants from 34 different nations attended this meeting that highlighted the recent accomplishments and future challenges in global climate modelling. It also described the growing practical applications of such models in seasonal forecasting and the estimation of climate impacts. Furthermore, results from models of the chemical and biological components of the climate system were shown. Four major sessions focused on:

- Development and Validation of Comprehensive Climate Models and Emerging Issues
- Modelling of Seasonal to Interannual Climate Variability
- Modelling Decadal to Centennial Climate Variability
- Prediction and Detection of Anthropogenic Climate Change

The conference summarised in a very comprehensive way the major accomplishments in climate modelling and prediction over the last decade.

Dr. Guy Brasseur, the successor of Prof. Hasselmann at the Max-Planck-Institut für Meteorologie, highlighted the emerging role of atmospheric chemistry in global climate modelling. He pointed out that the changes in the physical climate system and in the bio-geochemical system are connected by a two-way relationship. Global climate modelling will therefore increasingly involve various interactions between the different components of the climate system. Recent climate change scenarios already incorporate refined atmospheric chemistry and their feedbacks to the physical climate system.

Dr. J. Shukla (COLA, USA), highlighted the accomplishments as well as the challenges in seasonal prediction. He started his scientific review in the early 80s when the first seasonal predictions were proposed. Although the predictability achieved from coupled model integrations shows a strong model dependence (through simulated convection and diabatic heating processes), there are encouraging indications for seasonal predictability. Furthermore Dr. Shukla pointed out that regional models driven by the results obtained from global coupled models could provide reliable regional information on the seasonal time-scale in the near future. In summary, he stated 'We have come a long way - but we have miles to go'.

In a special session the PROVOST (Predictability of Climate Variations on Seasonal to Interannual Timescale) project was featured. This EU-funded study comprises an intercomparison of a number of atmospheric general circulation models run for a 15year period between 1979 and 1993 to assess predictability. It was pointed out that the highest predictive skill could be found in the tropics but that there were also indications for potential predictability in the extratropics.

Shifting to longer time-scales in the session on "Modelling Decadal to Centennial Climate Variability" Dr. G.J. Boer (CCC, Canada) presented two different methods to investigate the predictability of the coupled ocean-atmosphere system on timescales of months to decades. The main questions discussed in this session are whether there is any potential for predictability on decadal timescales at all and which processes could generate such predictability. The latter question needs to be addressed differently for different regions of the globe.

A number of papers dealt with the variability of the North Atlantic Oscillation and its relationship to other tropical and extra-tropical modes of variability, e.g. to the thermohaline circulation and the tropical Atlantic variability as well as its predictability. In the scientific discussions the different theories about the coupled or uncoupled nature of these phenomena and their various time-scales were highlighted. Further investigation of historical data as well as modelling efforts are required to get more insight into the natural climate variability on decadal time-scales.

In the last session of the conference the issues of prediction and detection of anthropogenic climate changes were discussed. Two invited papers given by Prof. Dr. Lennart Bengtsson, MPI, Hamburg and Dr. Maurice Blackmon, NCAR, Boulder, USA, summarized the major recent accomplishments with regard to climate change prediction. Prof. Bengtsson focused on the question whether the frequency and intensity of extreme events have changed during the last century and whether they will change in the future.

An analysis for the 20th century does not provide a conclusive indication of an increase of extreme events. Although assessments of the damage costs caused by extreme events seem to indicated an increase, this is not a good measure, e.g. because of the increase of population in coastal zones, changes in living standards, etc. Nevertheless there are some indications that extreme rainfall events tend to increase in parts of the globe. This can also be shown through high resolution model simulations of climate change. The modelling results presented by Prof. Bengtsson indicate changes in the rainfall patterns as well as in the intensity of the rainfall. There is a tendency for an increase in rainfall in tropical regions, in the monsoon regions and in high latitudes, in contrast to a decrease in the subtropics. Overall the probability for extreme rainfall events is increasing in the model results.

In the second talk Dr. Blackmon gave an overview about the coupled model experiments performed at NCAR and future plans. The experiments carried out so far indicate a global warming of 1.7 to 2.5^{o}C, depending on the scenario, for the end of the next century. He pointed out that even with a substantial reduction in the emission of the greenhouse gases a warming of 1.5-1.7^{o}C will be expected which is about twice the current temperature increase in comparison with pre-industrial conditions. Although most of the model results agree about the range of global warming there is still a need for model improvements to better understand and simulate the past and future climate. For example most models fail to simulate the warming between 1920 to 1940 and the subsequent cooling until the early 60s.

Other papers in this session focused on specific climate phenomena and their projected changes for the next century. An important question for the Northern Hemisphere and especially for Europe is whether the thermohaline circulation in the North Atlantic might change substantially or even break down completely. Although it was stated that a complete shut-down of the thermohaline circulation is unlikely to occur within the next century, a number of model simulations show a tendency for a weakening response to global warming.

A number of presentations focused on climate change detection and attribution. Dr. P. Stott, Hadley Centre, Bracknell, UK showed that the warming in the beginning of the century can partly be attributed to solar activity. Dr. U. Cubasch, DKRZ, Hamburg, Germany, presented an intercomparison of a number of coupled climate change experiments archived in the IPCC data distribution centre in Hamburg. The temperature trends of those simulations are very similar, whereas the precipitation anomalies show a wider range. Additional experiments are required to reduce this uncertainty. This was also stated by Dr. M. Allen, Rutherford Appleton Lab., UK. Only very large ensembles of climate change experiments with coupled models will enable us to reduce the uncertainty in climate change prediction, detection and attribution.

In summary, we have seen a rapid progress in climate modelling and prediction in the decade since the first climate conference in 1989. However, in spite of this progress, the present achievements only constitute the very first steps towards the building of a robust capability for climate monitoring and prediction. The results presented on the conference have shown that the modelling of the individual climate sub-systems, atmosphere, ocean, land surfaces, bio-geochemical cycles etc. is getting more advanced and sophisticated thanks to the availability of better data and powerful computers. Modelling of atmospheric processes in particular, has benefited from the synergy with numerical weather prediction and atmospheric models now extending from the surface up into the mesosphere.

The coupling of the different components of the climate system is proceeding rapidly with the integration not only of the dynamical and thermodynamical processes of the physical system - atmosphere, ocean and land surfaces, but also of atmospheric chemistry and bio-geochemical cycles.

A new exciting area of the numerical experimentations is decadal prediction where there now at least are indications that useful predictive skill may be possible to achieve.

The conference has shown again that numerical modelling is of central importance for the large international programmes such as WCRP and IGBP. In the CLIVAR programme for example, numerical modelling is now playing a leading part. Modelling experiments and simulation studies are integral parts of observational studies and field experiments by pointing to interesting phenomena and identifying areas where special measurement efforts are needed. Modelling in combination with data assimilation further helps to optimise the observing systems.

In this sense we hope that we will again be impressed by the progress being made in the field of climate modelling when the community reconvenes to the 5th Conference on Global Climate Modelling in Hamburg in three to four years.

Third session of the JSC/CLIVAR Working Group On Coupled Modelling

Roger Newson, JPS, WMO, Geneva, Switzerland

At the kind invitation of the Max Planck Institute for Meteorology, the third session of the JSC/CLIVAR Working Group on Coupled Modelling (WGCM) was held in Hamburg, Germany, 20-22 September 1999. An excellent introduction to the work of the group had been provided by the Fourth International Conference on Modelling Global Climate Change and Variability (organized by the Max Planck Institute of Meteorology) the preceding week (13-17 September 1999) which included focused sessions on the development and validation of comprehensive climate models, modelling seasonal to interannual variability, modelling decadal to centennial climate variability, and the prediction and detection of anthropogenic climate change.

With this background, WGCM duly reviewed the range of activities being carried out under its auspices, some of which are described in the following text. One of the most important of these is the Coupled Model Intercomparison Project (CMIP) with two components: CMIP1 examining global coupled model simulations of present day climate; and CMIP2, concerned with climate sensitivity experiments with CO_2 increasing at a rate of 1% per year. A paper with a detailed description of CMIP is being published in the Bulletin of the American Meteorological Society. A range of diagnostic subprojects has been undertaken, drawing on the CMIP1 and CMIP2 data bases that have been assembled at the Programme for Climate Model Diagnosis and Intercomparison (PCMDI) at the USA Lawrence Livermore National Laboratory, Livermore, CA. CMIP, particularly the results of certain of the CMIP diagnostic projects, is also providing important input for the IPCC Third Assessment Report which is currently in the course of preparation. WGCM considered carefully how CMIP should be further developed. It was recommended firstly that the range of data collected in CMIP1 and CMIP2 should be extended so that additional processes as simulated by models, especially such aspects as feedback mechanisms and ocean mixing, could be investigated in more detail. At the same time, updated or new CMIP1 or CMIP2 integrations would be accepted. Secondly, initiation of a third phase of CMIP (CMIP3) will be explored, focusing specifically on twentieth and twenty-first century coupled model simulations, but the exact approach to be followed is complicated by the numerous scenarios employed and lack of agreement on forcing data sets. The activity would be linked to that of IPCC Data Distribution Centres which are also archiving data from these runs. The possibility of agreeing on a single forcing data set and collection of just single integrations from each modelling group will be followed up by CMIP.

With respect to the intercomparison of idealized model doubled CO_2 equilibrium experiments, specific further studies of cloud feedback and its sensitivity to details of parameterisation are now being planned. These will be an extension of the perturbation techniques employed by Cess et al. a few years ago. Interested modelling groups will be invited to perform ten-year integrations using AMIP sea surface temperature and sea-ice distributions with an atmospheric concentration of 345 ppmv CO_2 as a ”control” and the sea surface temperature and sea ice distribution from a doubled CO_2 (690 ppmv) simulation in which the cloud optical properties would be the ”best estimate” of each group. A further pair of experiments should then be carried out with a perturbation in the water-ice transition (via a change in key internal parameter or combination of parameters). The ten annual means of cloud forcing for the doubled CO_2 simulation minus control, separated into long- and short-wave components (both global means and zonal averages), will then be computed, and analysed and compared. It is hoped that details can be finalized at the European Geophysical Society Annual Assembly in Nice, 25-29 April (a symposium on ”feedback” is planned as part of this event).

WGCM was also given a comprehensive update on the latest work in detection and attribution of climate change. It was particularly noted that the typical results from optimal detection methods (which estimate the amplitude of model simulated climate change signals in observations) continue to indicate that the time-space evolution of surface temperature observations over the recent five decades is inconsistent with internal climate variability (as inferred from coupled model simulations) and is evidence of a significant and detectable anthropogenic influence on climate. However, this remains subject to the caveat of our limited knowledge of intrinsic internal climate variability and that which is naturally forced, and the simulation of these variabilities by models. There is additionally a need to understand why different coupled models react differently to similar forcing, and a comparison of model simulations of the past would be valuable to assess the range of forcings and inconsistencies in model simulations. This may be an activity that could be taken up by CMIP.

In respect to the informal co-operative investigation of features of decadal climate variability that might be predictable based on experimentation with global climate models, WGCM recommended that a workshop should be held later in 2000 (probably in October in conjunction with the fourth session of WGCM). The main topic of the workshop will essentially be the evidence of decadal variability that can be detected in long-term climate integrations with atmospheric or coupled ocean-atmosphere models, particularly indications of low-frequency variations in mid-latitudes driven by observed sea surface temperatures and sea-ice that appear to be reproducible. It has been shown that observed decadal variations in the North Atlantic Oscillation can be simulated. Other studies (e.g. initial states from long control integrations with coupled models, restarted with small perturbations superimposed: some results have suggested that the patterns of at least some sub-surface (oceanic) variables may be predictable several years ahead) will be reviewed. Examples of real forecasts/hindcasts on the same sort of time-scale will also be examined.

Other important topics taken up by WGCM included consideration of the problems associated with the initialization of coupled model integrations, the specification of forcing scenarios, progress in ocean model development, and the latest experimentation and analyses in the Palaeoclimate Modelling Intercomparison Project (PMIP) (which was reviewed in detail at the second session of WGCM in Melbourne, October 1998: see Exchanges, Vol. 3, No 4, November 1998). Space prevents a description of these topics here, but the full report of the WGCM session is expected to appear in the International CLIVAR Project Office Publication series early in 1999.

Second International WCRP Conference on Reanalyses

Reading, UK, 23-27 August 1999

Roger Newson, JPS, WMO, Geneva, Switzerland

The practical arrangements for the Second WCRP International Conference on Reanalyses, 23-27 August 1999, were undertaken by the European Centre for Medium-range Forecasts (ECMWF). All participants (190 from over 30 different countries) appreciated the excellent arrangements made, the facilities offered at the Conference site (the Wokefield Executive Centre, Wokefield Park, near Reading, Berkshire, UK), and the memorable accompanying hospitality.

The present event was a follow-up to the First WCRP International Conference on Reanalyses held in Silver Spring, Maryland, USA, 27-31 October 1997. That Conference had already identified several of the numerous benefits from the major reanalysis efforts that had been carried out by ECMWF, the USA NOAA National Centers for Environmental Prediction (NCEP) in collaboration with the National Center for Atmospheric Research (NCAR), and the USA NASA Goddard Space Flight Center Data Assimilation Office (DAO). The Second WCRP International Conference on Reanalyses was arranged with the purpose of reviewing the continuing progress in validation and exploitation of the reanalysis data sets. It was already clear that there would be many successes to report across the entire spectrum of WCRP interest and beyond and this conference focused far more on applications of reanalyses rather than their validation and intercomparison as had the first conference. In this regard, research requirements in the climate area and other domains, were placing increasing demands on the quality of the reanalysed data sets. Accordingly, the Conference was expected to be a forum for setting out the requirements, assessing the extent to which they could be addressed in a new round of longer and more complex reanalyses, and providing comments or guidance to the reanalysis producers. The Conference was lively and productive including over 80 oral and 100 poster presentations.

The value of reanalyses for an impressive range of scientific studies and applications was demonstrated. Interesting and striking new results were shown of diagnostics of atmospheric behaviour and interactions with the ocean, land and cryosphere, the behaviour of El Niño, the occurrence of the Madden-Julian Oscillation, the polar circulation and stratospheric-tropospheric exchange, as well as in areas such as seasonal forecasting, the ocean circulation, ocean waves, hydrology, synoptic events, and geophysics. One novel application was in the determination of propagation loss of telecommunication signals. Examples were also given of the use of the reanalyses as a teaching tool.

The quality of the reanalyses was highly appreciated and, generally, the differences between the different reanalyses are approaching the level where they cannot be resolved by existing reference data sets. Nevertheless, there continues to be uncertainties in various aspects of the reanalyses, especially in terms of surface fields and fluxes. Improvements are needed in observations, data assimilation methods and models themselves to meet the requirements for a sufficiently accurate documentation of interactions between the different components of the climate system. The importance of having two or more state-of-the-art reanalyses as a basis for cross-comparison (e.g., of diagnostic results) and for indicating possible areas of shortcomings was strongly reaffirmed. The Conference duly encouraged the production of long reanalyses every 5-10 years, taking advantage of advances in operational systems, new data sets (e.g. from the continuing recovery of historical data) and the overall accumulated experience.

Despite their strengths, reanalyses can only be interpolations of the input observational data which have many gaps in time and space. Repeatedly during the Conference, the high priority to be attached to improving data quality, to filling in gaps in the observational data base, and to continuing efforts to obtain past data sets was emphasized. Because of the changes in observing systems and the available observational data base over the period of the reanalyses, the varying and often unknown biases in observing systems (which are not eliminated by reanalysis), it was noted that, although present reanalyses provide a good basis for studying interannual variability, they are not generally suitable for detection and assessment of long-term trends in climate variables, a key issue for CLIVAR. For trend analysis, it would be necessary to identify and document all the changing characteristics of data. This would require a major investment of resources whose availability is not apparent.

New reanalyses are now being planned and will form the basis for new studies. These include:

- **NCEP**: a second reanalysis for a limited period 1979-1998 is being undertaken using an updated forecast model and data assimilation, improved diagnostic outputs, and including corrections for the known problems in the first NCEP/NCAR reanalysis. This will also provide the bridge to a much more advanced next generation reanalysis planned for about 2003 or later. A regional USA reanalysis is also being prepared.
- **ECMWF**: an ambitious and comprehensive 40-year reanalysis project (ERA-40) is in preparation for the period 1958-present. A much wider selection of data sources will be used in the ERA-40 reanalyses, but the reanalyses will then inevitably reflect the changes in the observing system since 1958. ERA-40 will employ a 3DVAR scheme, and a 60-level T159 forecast-model coupled with an ocean-wave model.
- **NASA/DAO**: major upgrades have been made to the data assimilation system (the Goddard Earth Observing System, GEOS) employed in NASA's first reanalysis, with a physical-space three dimensional variational analysis algorithm having been included and a revised scheme has the capability of assimilating TRMM and SSM/I precipitation observations, as well as GPS data. The possibility of a new reanalysis is being examined taking into account the expected quality of the analysis system, the availability of computing resources, and the need for multiple reanalysed data sets.

The Conference further underlined that the reanalysis output needed to be made as widely available as possible, with access through the internet if possible. Availability of data sets on CD-ROMs was also very useful, especially for countries where the internet is not as yet fully developed, as well as for educational purposes. Reanalysis data sets needed to be supported by comprehensive documentation detailing the model used, the physical parameterisations, the input data, etc.

Grateful acknowledgement is expressed to the sponsors of the Conference, which as well as the WCRP itself, included:

- the European Centre for Medium-range Weather Forecasts
- the USA National Aeronautics and Space Agency
- the USA National Oceanic and Atmospheric Administration
- the USA National Science Foundation
- the American Meteorological Society
- International Business Machines, Ltd.
- Fujitsu Systems (Europe) Ltd.

(The full proceedings of the Reanalysis Conference will be published in the WCRP report series early in 2000).

CLIVAR Calendar

2000	Meeting	Location	Attendance
January 8 - 15	80th AMS Annual Meeting	Long Beach, USA	Open
January 24 - 28	AGU Ocean Sciences Meeting	St. Antonio, USA	Open
February 20 - 24	SOLAS Open Science Conference	Damp, Germany	Open
March 13 - 17	Joint Scientific Committee of WCRP, 22nd Session	Tokyo, Japan	Invitation
April 3 - 7	6th International Conference on Southern Hemi-sphere Meteorology and Oceanography	Santiago, Chile	Open
April 5 - 7	WOCE/CLIVAR Data Products Committee	College Station, USA	Invitation
April 8 - 10	CLIVAR VAMOS Panel 3rd Session	Santiago, Chile	Invitation
April 13 - 14	CLIVAR Atlantic Panel, 1st Session	Natal, Brazil	Invitation
April 25 - 29	European Geophysical Society, XXV Assembly	Nice, France	Open
May 1 - 5	CLIVAR SSG - 9th Session	Honolulu Hawaii	Invitation
May 30 - June 3	AGU Spring Meeting	Washington , USA	Open
July 10 - 14	Meteorology at the Millennium	Cambridge, UK	Open
October 2 - 6	WGCM Workshop on Decadal Predictability	La Jolla, USA	Limited
October 9 - 11	JSC/CLIVAR Working Group on Coupled Modelling - 3rd Session	La Jolla, USA	Invitation

For more information, please contact the ICPO or check out our web-page: **http://www.dkrz.de/clivar/latest.html**

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