Newsletter of the Climate Variability and Predictability Programme (CLIVAR)

Exchanges

Volume 6 No. 4

December 2001

Exchanges No. 22

Special issue on: Southern Ocean Climate Variability

ENSO induced variability on the Southern Hemisphere ?

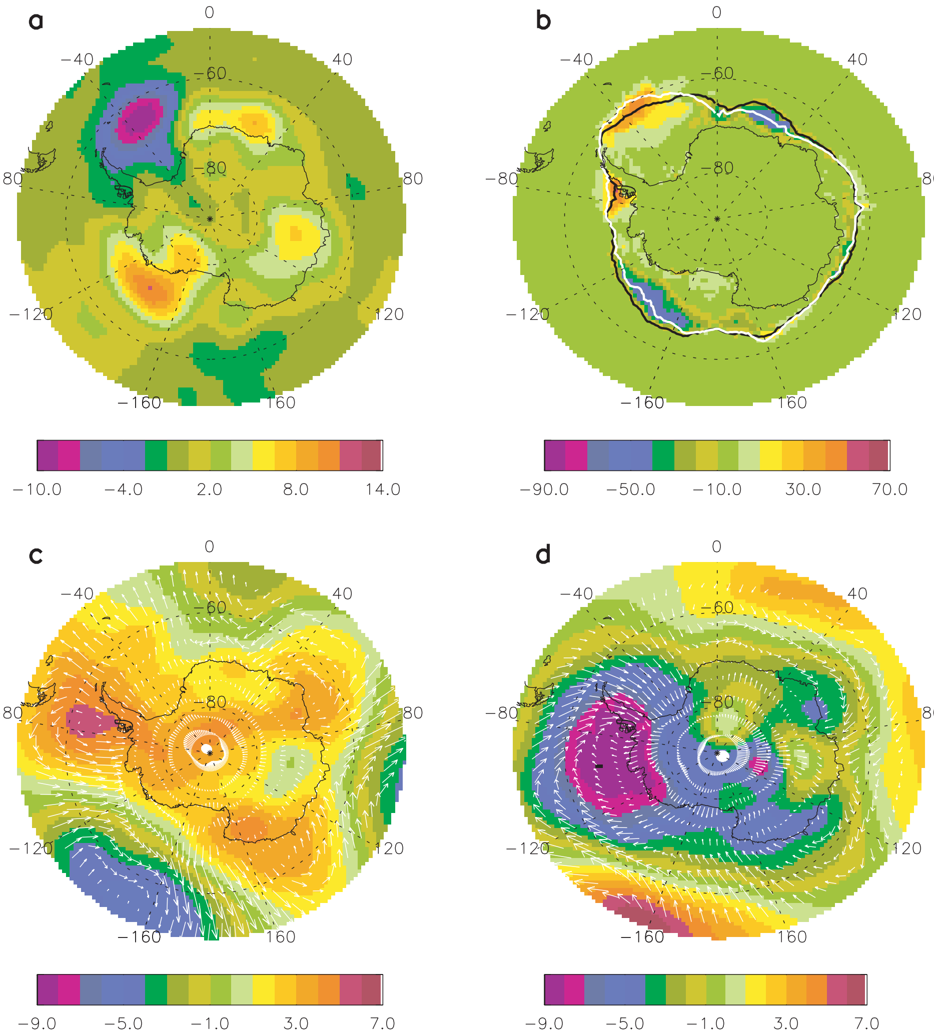


Figure 1 from paper *'An ENSO Related Climate Pattern: The Antarctic Dipole'* by X. Yuan:
ENSO impact as defined by the May composite after 4 La Niña events subtracted from the May composite after 5 El Niño events in SAT (a) and sea ice concentration (b). The white (black) line in b is the mean ice edge for El Niño (La Niña) events. The SLP anomaly (hPa) composites for El Niño (c) and La Niña (d) events in the same month indicate the atmospheric circulation that creates the Antarctic Dipole. Sea ice data were selected from NASA bootstrap ice concentration data and SAT and SLP data are selected from NCEP/NCAR reanalysis from 1978 to 1999.
The paper appears on page 3.

International CLIVAR Project Office, Southampton Oceanography Centre, Empress Dock, Southampton SO14 3ZH, United Kingdom
Tel: +44–23 80 596777, Fax: +44–23 80 596204, icpo@soc.soton.ac.uk, http://www.clivar.org/

Editorial

2001 has been a very successful year for CLIVAR science, for the International CLIVAR Project Office and for Exchanges. The implementation of an increasing number of components of the programme has accelerated, the number of national and multi-national funded CLIVAR and CLIVAR-related projects is rapidly increasing and the scientific oversight infrastructure of international CLIVAR is now almost complete. This year, we particularly made progress with our basin-wide implementation by starting panels for the Southern Ocean and for CLIVAR Pacific. Both will meet for the first time in early 2002. With the completion of observations under CLIVAR's partner programme WOCE, CLIVAR now assumes the role of being the home in WCRP for the observational oceanographic community, now addressing a wide range of issues concerning the ocean's role in global and regional climate.

In the International CLIVAR Project Office we were able to expand our staff resources quite significantly thanks to funding from the USA. Two new staff members joined the office in Southampton: Dr. Zhongwei Yan in early summer and Dr. Daniela Turk who came from Dalhousie University in September. Zhongwei's expertise in the area of monsoons and Daniela's background on ocean biogeochemistry and the Pacific Ocean will add greatly to the pool of scientific expertise in the ICPO. In addition, Dr. Mike Sparrow, the new editor of the WOCE Newsletter supports the ICPO on all issues related to the Southern Ocean. Other valuable contributions to the ICPO come from our "overseas" staff members, working part time for CLIVAR: Carlos Ereño (Argentina) for VAMOS, Roberta Boscolo (Spain) for the Atlantic panel, and Andreas Villwock (Germany) (Modelling groups, PAGES/CLIVAR, Website and Exchanges). We are all working to ensure that the ICPO deals effectively with the continuously increasing list of tasks that it is called upon to perform.

During this past year, the ICPO published more than a dozen reports (some only electronically), a new brochure describing the wide range of CLIVAR science and four issues of the newsletter Exchanges. Exchanges has developed to a very widely read information forum for the CLIVAR community. Its success and popularity is shown by the rapid increase in the number of articles being submitted. For this issue, we called for contributions on issues related to the Southern Ocean to highlight the recently-formed CLIVAR Southern Ocean panel, jointly chaired by Drs. Steve Rintoul (Australia) and Eberhard Fahrbach (Germany). The response to the call for papers was really overwhelming and we have been unable to fit in all the articles. This highlights a problem that we will increasingly face. We will not be able to afford (from a cost standpoint and from the point of view of the burden of editing) to publish everything we receive. We may have to be more selective in what we print and perhaps put some articles solely on the CLIVAR web site. Our market research however, tells us that virtually all of you like to have a hard copy printed newsletter.

CLIVAR science was very well represented in both the plenary talks and the poster sessions at the meeting "2001 an Ocean Odyssey" of the International Association for the Physical Sciences of the Ocean (IAPSO) that as held in late October in Mar del Plata, Argentina. Over 400 scientists had the opportunity to participate in sessions on "Decadal Variability and Predictability" and "The role of the Oceans in Climate Variability over South America" was well as many sessions on ocean circulation that were relevant to, but not specifically focused on, climate issues. It was very gratifying to see the strength of interest in these topics. There were also a number of impromptu meetings and discussions. One between George Philander and Tony Busalacchi focused on their rather different assessments of our ability to make predictions of ENSO events. It was also extremely gratifying to see such a large and enthusiastic attendance from local students.

Looking to the coming year, the first internationally co-cordinated CLIVAR activity, the Low Level Jet experiment in South America, a CLIVAR VAMOS activity, appears on the horizon. This process study, a pilot experiment for a larger project on the La Plata River basin, is planned for late 2002/early 2003.

I (JG) have just returned from a meeting in Nova Scotia of the "Partnership for Observation of the Global Oceans", POGO, (http://www.oceanpartners.org/). POGO is an alliance of many of the the major oceanographic laboratories that is working to help bring about sustained and truly global ocean observations. While this particular meeting (POGO-3) had a focus on biological measurements I indicated to the meeting the present status of CLIVAR implementation in each ocean basin, and the roles of the ocean sector panels in designing detailed implementation strategies. POGO-4 is likely to be held early in 2003 and will have a focus on the Indian Ocean. This meeting could be of considerable help to CLIVAR.

Finally, a scientific organising committee, chaired by Prof. Dr. Lennart Bengtsson has started to plan the first CLIVAR Science Conference. It will be held in late 2003 or early 2004. At the Conference CLIVAR will review the scientific progress of the first 5 years after the 1998 publication of the Initial Implementation Plan.

On behalf of the co-chairs of the CLIVAR Scientific Steering Group, Dr. Tony Busalacchi and Dr. Jürgen Willebrand, and the staff of the ICPO we wish you a Merry Christmas and a safe transition into 2002.

John Gould and Andreas Villwock

An ENSO Related Climate Pattern: The Antarctic Dipole

Xiaojun Yuan
Lamont-Doherty Earth Observatory
Palisades, NY, USA
xyuan@ldeo.columbia.edu

1. Introduction

The El Niño-Southern Oscillation (ENSO) signal has been identified in numerous studies (Simmonds and Jacka, 1995; Ledley and Huang, 1997, Harangozo, 2000). A recent study found consistent and statistically significant teleconnection patterns linking Antarctic sea ice edge (SIE) variations to those of tropical and mid-latitude climate and identified the southeast Pacific and Weddell Sea regions where the SIE is most responsive to extrapolar climate variability (Yuan and Martinson, 2000). Moreover, the tropical climate variability was linked to a high latitude climate mode that is characterized by a dipole-like pattern reflecting an out-of-phase relationship between Pacific and Atlantic polar regions. This broad-scale covarying feature was called the Antarctic Dipole (ADP). It exists strongly in the surface air temperature (SAT) and SIE fields, and moderately in sea level pressure (SLP) fields (Yuan and Martinson, 2001). Between the tropics and polar regions, a meridional teleconnection pattern exists across the South Pacific and South America, which is called the Pacific-South American (PSA) pattern, analogous to the PNA pattern in the Northern Hemisphere. The PSA is a barotropic standing wave train of alternating anomalies in the pressure/height fields that extends from the subtropical South Pacific, to subpolar region in the southeast Pacific and across the Antarctic Peninsula into the southwest Atlantic or the South America (Mo and Ghil, 1987; Farrara et al.; 1989; Karoly, 1989; Grimm and Silva Dias, 1995). This study quantifies the ENSO impacts in the Southern Ocean and reveals the relationship between the PSA and ADP.

2. ENSO impact in temperature and ice field

Although the Antarctic Dipole's variability spans from interannual to decadal time scales, its relationship with ENSO is clearly evidenced. Based on monthly Nino3.4 index (> +0.5˚C, or < -0.5˚C), we identified five warm events (1980, 1983, 1988, 1992 and 1997) and four cold events (1985, 1989, 1996 and 1999) in the period from 1978 to 1999. An ENSO impact in SAT is then calculated by subtracting a La Niña composite from an El Niño composite (Fig.1a, page 1). The largest ENSO impact occurs in the ADP region. The mean variation between warm and cold events reaches 10˚C at each center of the ADP, which is comparable to the SAT ENSO variation in the tropics. The ENSO impact in the sea ice field shows a similar pattern with less ice near the warm SAT center in the Pacific sector of the Antarctic (Fig.1b). Figure 1 gives an example of the ENSO impact in May after the ENSO events. The same calculation has been carried out for twelve months after the ENSO events, which shows that a clear ENSO impact appears in high latitudes of the Southern Ocean a couple of months after events natured in the tropics and persists 2 to 3 seasons in the polar/subpolar regions.

3. PSA and ADP

A composite of SLP anomalies for warm events shows a high pressure center in the southeast Pacific that results warm air blowing polward east of the center in the Pacific and cold air blowing equatorward in the Weddell Sea, vise versa for the cold events (Fig.1 c & d). The pressure pattern is consistent with warm temperature and less ice in the Pacific and cold temperature and more ice in the Weddell Sea for El Niño events. The SLP composites are also consistent with the warm/cold event composites of 500-hPa height anomalies (Kiladis and Mo, 1998) indicating the barotropic nature of the pattern. Earlier studies have suggested that the PSA pattern accompanies an increased frequency of blocking over the southeast Pacific during El Niño events (Trenberth and Mo, 1985; Kidson, 1988; Berbery et al., 1992; Renwick, 1998; Renwick and Revell, 1999). The pressure centers in Figure 1 c&d are likely the part of the PSA pattern (anomaly center in the southeast Pacific subpolar region) representing the blocking events associated with ENSO events. Apparently, the ADP is a consequence of those blocking events. Moreover, the low pressure center is more persistent throughout a year after La Niña events, which results in a more consistent response of the ADP to La Niña events than to El Niño events (Yuan and Martinson, 2001).

References

Berbery, E.H., J. Nogues-Paegle, and J.D. Horel, 1992: Wavelike southern hemisphere extratropical teleconnections. *J. Atmos. Sci.*, **49**, 155-177.

Farrara, J.D., M. Ghil, C.R. Mechoso, and K.C. Mo, 1989: Empirical orthogonal functions and multiple flow regimes in southern hemisphere winter. *J. Atmos. Sci.*, **46**, 3219-3223.

Grimm, A.M., and P.L. Silva Dias, 1995: Analysis of tropical-extratropical interactions with influence functions of a barotropic model. *J. Atmos. Sci.*, **52**, 3538-3555.

Harangozo, S.A., 2000: A search for the ENSO teleconnections in the west Antarctic Peninsula climate in austral winter. *Int. J. Clim.*, **20**, 663-679.

Karoly, D.J., 1989: Southern hemisphere circulation features associated with El Niño-Southern Oscillation events. *J. Climate*, **2**, 1239-1252.

Kidson, J.W., 1988: Indices of the Southern Hemisphere zonal wind. *J. Climate*, **1**, 183-194.

Kiladis, G.N., and K. C. Mo, 1998: Interannual and Intraseasonal Variability in the Southern Hemisphere. Meteorology of the Southern Hemisphere, D. Karoly and Vincent, Eds., American Meteorological Society, Boston, USA, 307-336.

Ledley, T. S., and Z. Huang, 1997: A Possible ENSO signal in the Ross Sea. *Geophys., Res. Lett.*, **24**, 3253-3256.

Mo, K.C., and M. Ghil, 1997: Statistics and dynamics of persistent anomalies. *J. Atmos. Sci.*, **44**, 877-901.

Renwick, J.A., 1998: ENSO-related variability in the frequency of South Pacific blocking. *Mon. Wea. Rev.*, **126**, 3117-3123.

Renwick, J.A., and M.J. Revell, 1999: Blocking over the South Pacific and Rossby wave propagation. *Mon. Wea. Rev.*, **127**, 2233-2247.

Simmonds, I. and T. H. Jacka, 1995: Relationships between the Interannual Variability of Antarctic Sea Ice and the Southern Oscillation. *J. Climate*, **8**, 637-647.

Trenberth, K.E., and K.C. Mo, 1985: Blocking in the Southern Hemisphere. *Mon. Wea. Rev.*, **113**, 3-21.

Yuan, X., and D.G. Martinson, 2000: Antarctic sea ice extent variability and its global connectivity. *J. Climate*, **13**, 1697-1717.

Yuan, X., and D.G. Martinson, 2001: The Antarctic Dipole and its Predictability. *Geophys. Res. Lett.*, **28**, 3609-3612.

Ocean and Sea Ice response to the Southern Hemisphere Annular Mode: Results from a coupled climate model

Alex Hall[1], and Martin Visbeck[2]
[1]UCLA, Department of Atmospheric Sciences
Los Angeles, CA, USA
alexhall@atmos.ucla.edu
[2]Lamont-Doherty Earth Observatory
Palisades, NY, USA

Fluctuations of the mid-latitude westerly winds characterize the primary mode of atmospheric variability in both hemispheres poleward of the equatorial belt. In the northern hemisphere (NH) zonal asymmetries in orography (and thermal response) set up the well-known wave number 2 stationary wave pattern in the NH jet stream with the most unstable parv„ concentrated over the North Atlantic and Pacific, giving rise to the NH Atlantic and Pacific storm tracks. The variability of the Atlantic storm track (the North Atlantic Oscillation, see Hurrell et al. (2001) for a recent review) dominates the zonally symmetric response. The relative zonal uniformity of southern hemisphere (SH) geography reinforces the zonal symmetry of the mean and variable flow of the southern hemisphere during all seasons. If one examines the mode of atmospheric pressure variability that accounts for the most variance one sees a clear out-of-phase relationship at all longitudes between pressure over the pole and pressure in mid-latitudes. The ring-like character of this pattern has given rise to the term Southern Annular Mode (SAM) to refer to the vacillations of the SH jet stream (Thompson and Wallace, 2000).

In this report we focus not on the internal atmospheric dynamics of the SAM (e.g. Limpasuvan and Hartmann, 1998), but on the implications of the presence of a highly zonally-symmetric and seasonally-invariant mode of atmospheric variability for the rest of the SH climate system, in particular the ocean and sea ice. While the relatively high degree of zonal symmetry of SH geography reinforces the zonally-symmetric character of the primary mode of internal atmospheric variability (i.e. the annular mode), it also facilitates hemispheric-scale resonance of ocean variability with annular mode forcing.

To study quantitatively the role of the SAM in SH sea ice and ocean variability on interannual to centennial timescales, we examined the variability in the middle 5,000 yrs of a 15,000 yr integration of a coupled ocean-atmosphere model (Manabe et al., 1991). The model exhibits energetic annular-mode-like variability with an SAM index spectrum that is white on time scales longer than a few days. The model's SAM also varies little with season (Figure 1). In these respects, the model's SAM is similar to observations (see Thompson and Wallace, 2000).

The positive phase of the SAM is associated with an intensification of the surface westerlies over the circumpolar ocean (around 60°S), and a weakening of the surface westerlies further north. This induces anomalous Ekman drift to the north at all longitudes of the circumpolar ocean, and anomalous Ekman drift to the south at around 30°S (Figure 2). Through mass continuity, the Ekman drift generates anomalous upwelling along the margins of the Antarctic continent, and downwelling around 45°S (Fig-

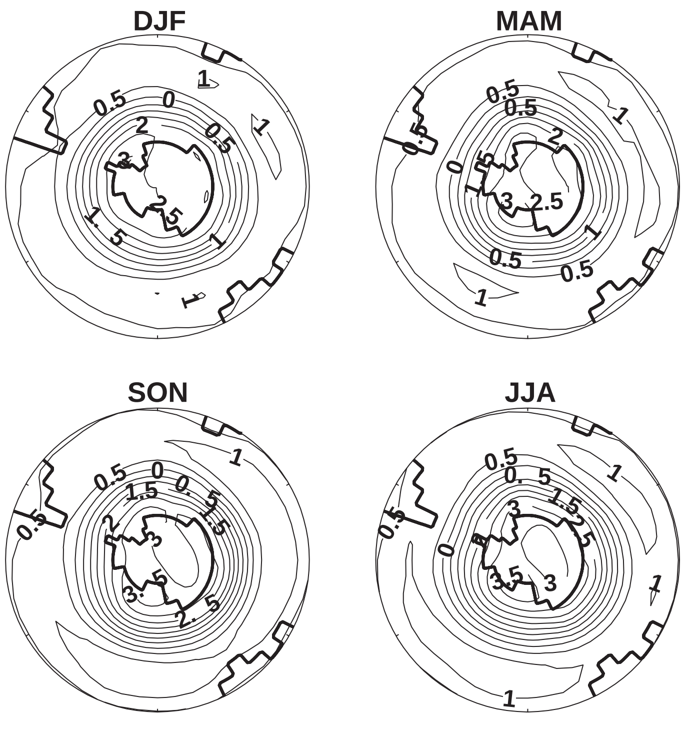


Figure 1: The patterns associated with the first EOFs of surface pressure (hPa) variability for all four seasons in the SH. All surface pressure data poleward of 9°S is included in the EOF computation. For DJF, MAM, JJA, and SON, the patterns shown account for 39%, 30%, 34%, and 24% of the variance, respectively.

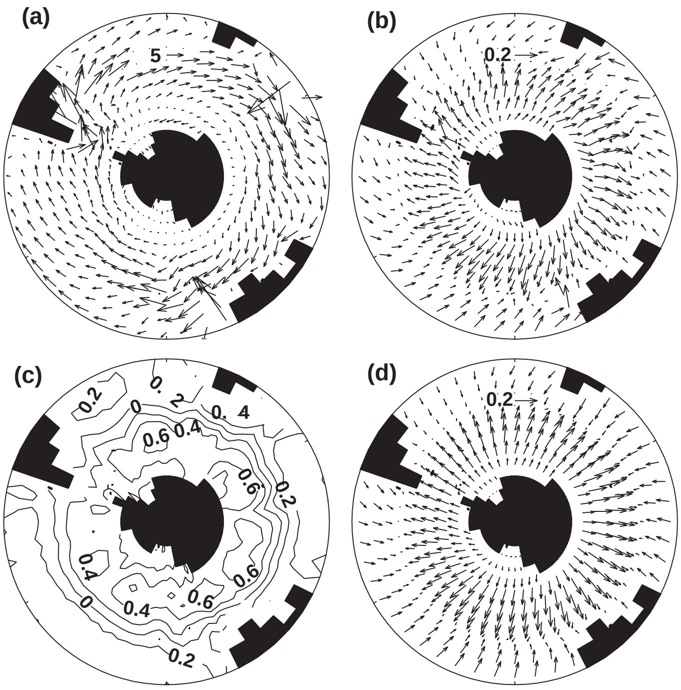


Figure 2: (a) The annual-mean climatological surface currents simulated by the ocean model. (b) The regression of annual-mean surface currents onto the annual-mean SAM index. Regressions for the zonal and meridional components of the surface currents were calculated separately. (c) The correlation between the meridional component of the annual-mean surface current and the annual-mean SAM index. (d) The Ekman drift that would result if the wind-stress pattern associated with the positive phase of the SAM were imposed on the surface layer of the ocean model. Units for (a), (b), and (d) are cm/s. Arrows illustrating the scaling of the vectors are also shown. For clarity, every other arrow is suppressed in (a), (b), and (d).

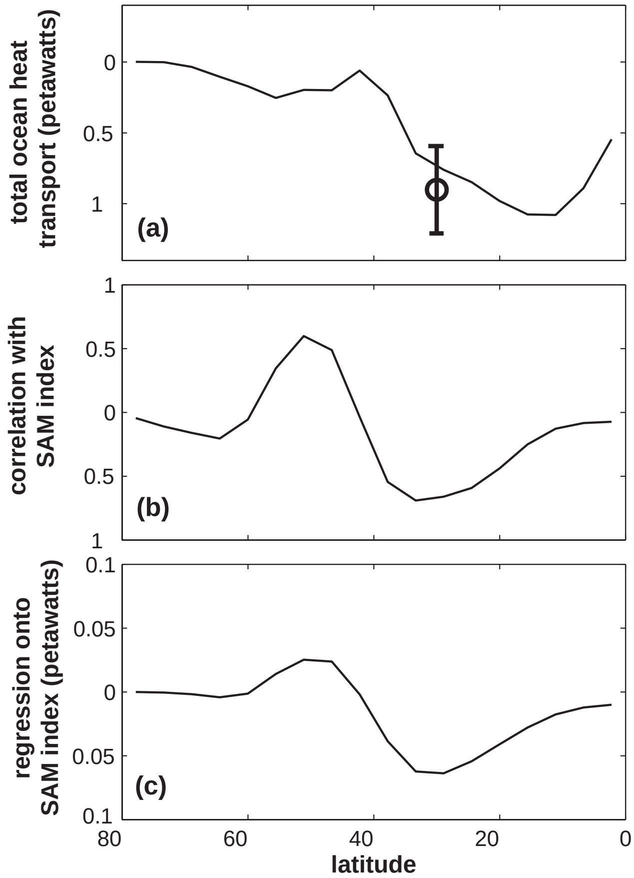


Figure 4: (a) the annual-mean, zonal-mean simulated ocean heat transport in the SH. Southward heat transport has a negative sign. Also shown, with a circle and associated error bars, is estimated observed ocean heat transport across 30°S from MacDonald and Wunsch (1996). (b) the correlation of the annual-mean, zonal-mean ocean heat transport with the annual-mean SAM index. (c) as in (b), except regression coefficients are shown.

ure 3, page 17). The anomalous flow diverging from the Antarctic continent also increases the vertical tilt of the isopycnals in the Southern Ocean, so that a slightly more intense circumpolar current is also associated with positive SAM ~ 1 Sv compared to a 80 Sv mean flow.

In addition, the anomalous divergent flow advects sea ice further north, resulting in an increase in sea ice coverage by about 5%. Finally, positive SAM drives anomalies in meridional heat transport; increases in poleward heat transport of about 15% occur at about 30°S, while decreases of 20% occur in the circumpolar region (Figure 4, page 18). These sea ice and heat transport anomalies can be traced to the SAM-induced ocean circulation anomalies noted above.

The ocean and sea ice fluctuations associated with the SAM constitute a significant fraction of simulated ocean variability poleward of 30°S all year round. The zonally-symmetric atmospheric and oceanic changes during a positive index phase can be summarized in a schematic (Figure 5).

The coupled model simulation suggests that the SAM is likely an important source of large-scale internal variability in the real SH ocean. The SAM may also pro-

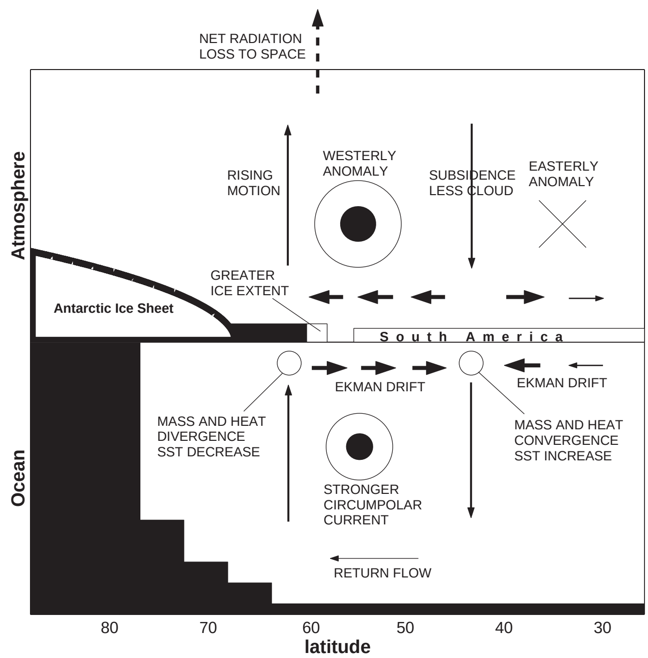


Figure 5: Schematic drawing of the changes in the atmosphere and ocean that occur when the SAM index is positive.

vide a framework for understanding how the SH ocean responds to external forcing. For example, SAM-like changes in the SH atmosphere have been found in global climate change model projections (e.g. Kushner et al., 2001). Our results indicate that changes in the southern ocean due to external forcing may be understood in terms of a forced response to the SAM.

References

Hurrell, J.W., Y. Kushnir, and M. Visbeck, 2001: The North Atlantic Oscillation. *Science*, **291**, 603-605.

Kushner P., I. Held, and T. Delworth, 2001: Southern hemisphere atmospheric circulation response to global warming. *J. Climate*, in press.Limpasuvan V., D.L. Hartmann, 2000: Wave-maintained annular modes of climate variability. *J. Climate*, **13**, 4414-4429.

MacDonald A.M., C. Wunsch, 1996: An estimate of global ocean circulation and heat fluxes. *Nature*, **382**, 436-439.

Manabe S., R.J. Stouffer, M. Spelman, K. Bryan, 1991: Transient responses of a coupled ocean-atmosphere model to gradual changes of atmospheric CO_2. Part I: annual-mean response. *J. Climate*, **4**, 785-817.

Thompson D.W.J., J.M. Wallace, 2000: Annular modes in the extratropical circulation. Part I: Month-to-month variability. *J. Climate*, **13**, 1000-1016.

Interannual winter rainfall variability in SW South Africa and potential influences from the Southern Ocean region

C.J.C. Reason, M. Rouault and J-L. Melice
EGS and Oceanography Depts., University of Cape Town
Rondebosch, South Africa
cjr@egs.uct.ac.za

Introduction

Historically, most South African research into climate variability has tended to focus on the summer rainfall region that covers the eastern and northern parts of the country and where most of the population and agricultural activities are located. Relatively little attention has been paid to the SW Cape region which not only contains the second largest city in the country (Cape Town), but is also a major tourist and agricultural area. This region is one of winter rainfall, largely via cold fronts with lesser (though still significant) contributions from other systems like cut-off lows. Winter 2001 was particularly wet with July recording about 2.5 times climatological rainfall for that month. Reason (2001) argued that SST anomalies in the midlatitude South Atlantic and significant shifts in the atmospheric planetary wave distributions over the mid- to high latitudes of the Southern Hemisphere during JAS 2001 may have led to the anomalously wet winter in the SW Cape. Here, we extend these ideas further by looking at potential relationships between winter rainfall in this region and SST and atmospheric circulation anomalies in the mid- to high latitudes.

Data and results

A rainfall index formed by averaging May-September rainfall over the region 17-21E, 32-24S from the New et al. (2000) dataset (Fig. 1) indicates substantial interannual rainfall variability. The premise is that this variability is driven by factors that influence the track and intensity of the midlatitude depressions and associated cold fronts that climatologically are responsible for almost all this region's rainfall. The factors that are considered here are SST upstream in the midlatitude South Atlantic, the location and strength of the winter jet and planetary wave distributions in the Southern Ocean region. Correlations of this index for 1950-1998 with UKMO GISST2.2 SST data and NCEP re-analyses together with composites for wet (1954, 1957, 1974, 1977, 1991, 1996) and dry (1969, 1972, 1973, 1978, 1980, 1982, 1998) winters suggest the following scenario.

During wet winters, negative geopotential height anomalies (Fig. 2) extending from the SW Atlantic (climatologically, an area of strong cyclogenesis in the Southern Hemisphere - Jones and Simmonds (1993)) over southern South Africa and a stronger jet immediately upstream of Cape Town (Fig. 3) favour increased midlatitude depressions and more active fronts crossing the region. Warm SST anomalies in the SW Atlantic (favourable for cyclogenesis) and immediately south and southwest of Cape Town together with cool anomalies over the subtropical - midlatitude South Atlantic Ocean tend to be associ-

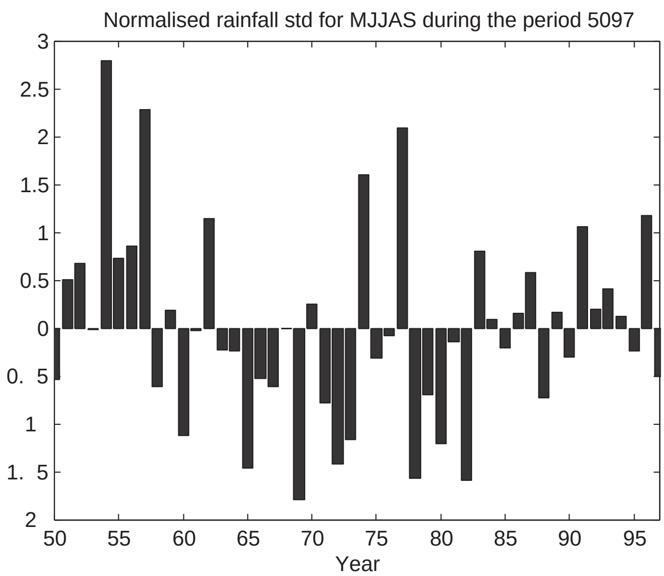


Fig. 1. Normalized May-September rainfall anomalies (1950-1997) for SW South Africa

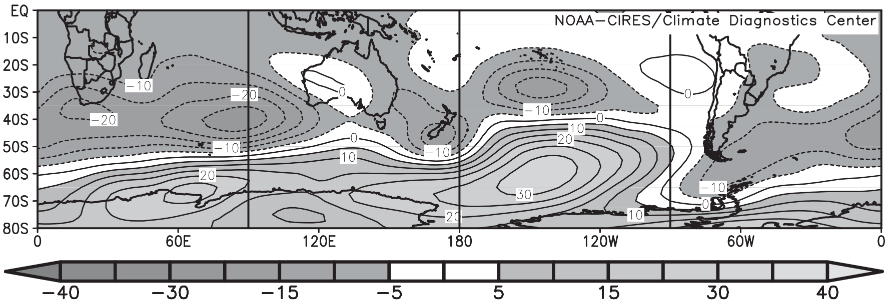


Fig. 2. 500hPa geopotential height anomalies for wet composites, May to Sept. 1954, 1957, 1962, 1974, 1977, 1991, 1996 (from NCEP/NCAR Reanalysis)

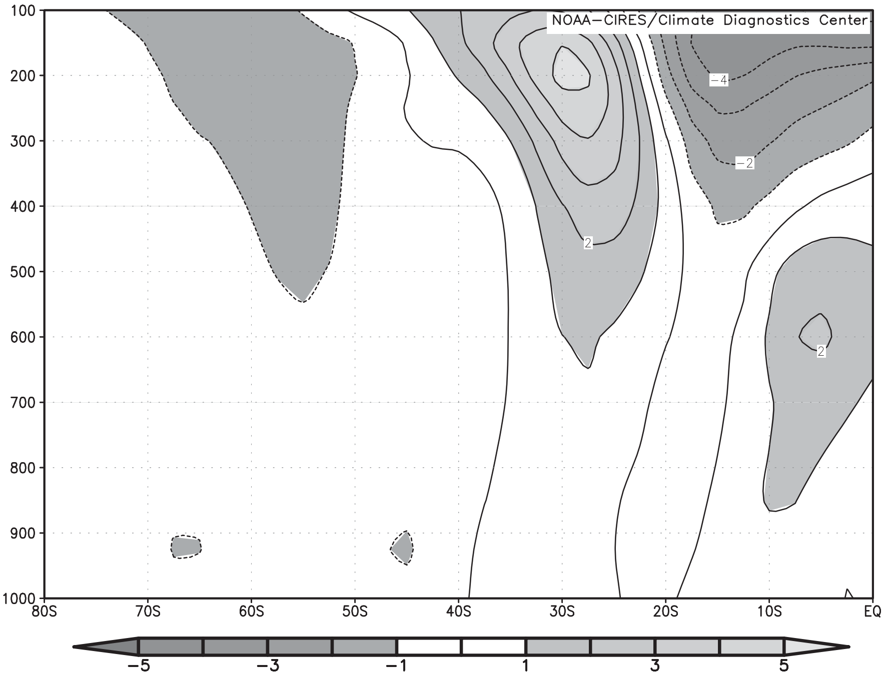


Fig. 3. Zonal wind anomalies at 15E for wet composite anomalies for wet composites, May to Sept. 1954, 1957, 1962, 1974, 1977, 1991, 1996 (from NCEP/NCAR Reanalysis)

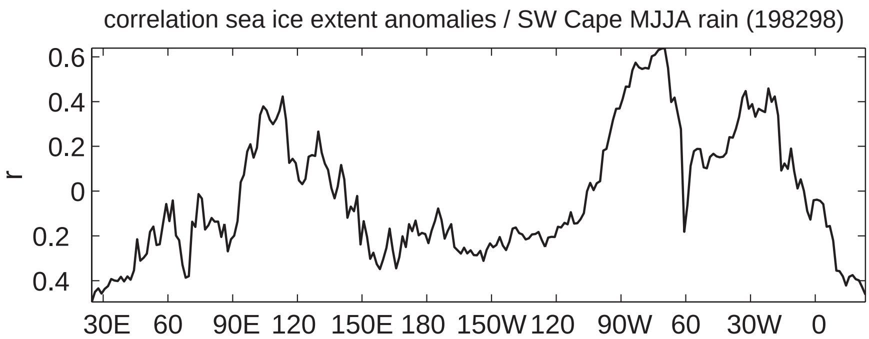


Fig. 5 Correlation of sea ice extenr anomalies around the Southernn Hemisphere with rainfall in South Africa (MJJA) for the period 1982-98.

ated with wet winters (Fig. 4, page 18). The cool SST anomalies act like positive orography so to conserve potential vorticity, the zone of strong winter westerlies shifts north and storm tracks are more equatorward than usual. Finally, the warm anomalies near Cape Town help to intensify the systems as they approach, hence increasing rainfall further. Roughly the reverse scenario and SST patterns occur during dry winters.

Summary

There is evidence that interannual winter rainfall variability in SW South Africa may be influenced by SST upstream in the midlatitude South Atlantic and by large scale circulation anomalies in the Southern Hemisphere midlatitudes. While the scenario presented above appears plausible, it needs to be confirmed with more sophisticated analyses including modelling. Ongoing work is considering the possible influence of the Antarctic Circumpolar Wave (White and Peterson, 1996), Antarctic sea-ice anomalies (e.g., Fig. 5 using model data from Fichefet et al. (2001)) and experiments with the UKMO HADAM3 GCM. The latter is part of a South African government funded project into seasonal forecasting for southern Africa (http://www.egs.uct.ac.za/csag/dacst) and includes runs with observed SST forcing from 1985-2001 as well as prescribed SST anomaly experiments.

Acknowledgements

We thank NOAA-CIRES Climate Diagnostics Center, Boulder Colorado for usage of their Web site http://www.cdc.noaa.gov/ where Figs. 2-4 were plotted.

References

Jones, D.A., and I.H. Simmonds, 1993: A climatology of Southern Hemisphere extra-tropical cyclones. *Climate Dynamics*, **9**, 131-145.

Fichefet, T., B. Tartinville, and H. Gosse, 2001: A numerical simulation of the Antartic sea ice variability, 1958-1999. *J. Geophys. Res.*, submitted.

New, M., M. Hulme, and P.D. Jones, 2000: Representing twentieth century space-time climate Variability. Part II: Development of 1901-1998 monthly grids of terrestrial surface climate. *J. Climate.*, **13**, 2217-2238.

Reason, C.J.C., 2001: The wet 2001 winter over the SW Cape: potential large scale influences. *S. Afr. J. Sci.*, submitted.

White, W.B., and R.G. Peterson, 1996: An Antarctic circumpolar wave in surface pressure, wind, temperature and sea-ice extent. *Nature*, **380**, 699-702.

Variability of Water Mass Transformation and Formation in the Southern Hemisphere

Johannes Karstensen[1], and Detlef Quadfasel[2]
[1]Lamont-Doherty Earth Observatory
Palisades, NY, USA
jkarsten@ldeo.columbia.edu

Niels Bohr Institutet for Astronomi, Fysik og Geofysik, Københavns Universitet
Copenhagen, Denmark.

Introduction

The meridional overturning circulation of the Southern Ocean - the Deacon Cell - couples the deep thermohaline conveyor originating in the North Atlantic with the wind driven thermocline circulation of the southern hemisphere subtropical gyres (Speer et al., 2000). Westerly winds in the circumpolar belt drive an equatorward Ekman transport in the upper layer, which is supplied by upwelling of deep waters. This upwelling is further enforced by bottom water formation on the shelves of Antarctica that is being fed by southward near surface transports closer to the continent (Rintoul et al., 2001). Both branches of this double-upwelling cell undergo intense air-sea interaction processes. The southern part looses buoyancy and bottom water is formed, the northern branch gains buoyancy and feeds the thermoclines of the subtropical gyres. Eventually these waters return to the northern convection sites and close the conveyor (Gordon 1986; Sloyan and Rintoul, 2001a).

In a recent manuscript (Karstensen and Quadfasel submitted) we have used climatological and synoptic hydrographic and transient tracer data to quantify the ventilation rates of the southern subtropical gyres, and compared those with estimates derived from air-sea fluxes. For all three oceans together the southern subduction is around 100 Sv (1 Sv=10^6 m^3/s), variations from using different methods do not exceed 30%. In this note we report the results from the air-sea flux derived estimates and explore the variability and trends in the water mass formation over the past decades.

Method and data

Walin (1982) and Tziperman (1986) developed an elegant theoretical frame to analyse the annual mean water mass formation rates from heat and freshwater fluxes at the ocean's surface. Here we follow their approach. Air-sea exchanges of heat and freshwater continuously transform the characteristics of the surface waters and remove them from one density class and accumulate them in others. The divergence of the transformation then is a formation of a water mass, which can only be compensated for through fluxes into the interior of the ocean, the subduction.

Surface water mass transformation combines density fluxes derived from heat and freshwater fluxes at the air-sea interface with a mass budget on individual outcropping density layers (Walin, 1982; Tziperman 1986; Speer and Tziperman, 1992). The density flux at the sea surface is

$$F_\rho = -\alpha H / c_W + \rho(T,S)\, \beta\, (E - P)\, S/(1-S)$$

Here, c_W is the heat capacity of water, H is the surface net heat flux, E-P is the net freshwater flux, α is the coefficient of thermal expansion of sea water and β the haline contraction coefficient, S is the salinity, ρ(T,S) the surface density. In general all variables are functions of location and time. Using monthly data the mass budget in discrete density bins of ($\Pi(\rho-\rho')$), over an 1x1° area ΔA can be diagnosed using

$$F_m = 1/\Delta\rho\, \Sigma_{1\ \mathrm{to}\ 12}\, \Delta t\, \Sigma_{i,j}\, \Delta A_{i,j}\, F_\rho\, (\Pi(\rho-\rho'))$$

The convergence/divergence of the so calculated transformation corresponds to the formation / destruction of water masses.

A crucial point for the calculation of water mass formation rates is the quality of the surface flux data and their compatibility with the oceanic surface density field. Older climatologies, such as the Comprehensive Ocean Atmosphere Data Set (COADS) are usually based on a number of individual observations, such as from ships or drifting buoys, distributed irregularly in space and time. Gridding of such data makes sense when enough samples are available for the averaging, but becomes problematic where only few observations have been made, such as south of 45°S. Consequently this region has often been excluded from analysis of water mass transformation in the past. Gridded data sets often do not close the global heat and freshwater cycle and as a zero order approximation a global bias is then assumed (daSilva et al., 1994).

During the last few decades, however, air-sea flux estimates improved significantly with the introduction of satellite-based remote sensing technologies. Now atmospheric data sets are produced routinely by assimilating all available observations into atmospheric general circulation models. The NCEP/NCAR (Kistler et al., 2001) and the ECMWF reanalysis projects provide dynamically consistent global data sets.

In the analysis presented in this note we use heat and freshwater fluxes derived from the NCEP/NCAR reanalysis output for the time span 1950 to 1999. For the oceanic fields we use reconstructed monthly sea surface temperatures from 1950 to 1999 (Reynolds and Smith, 1994) to account for the ocean's response on changes in the heat flux field. As no high-resolution salinity data set is avail-

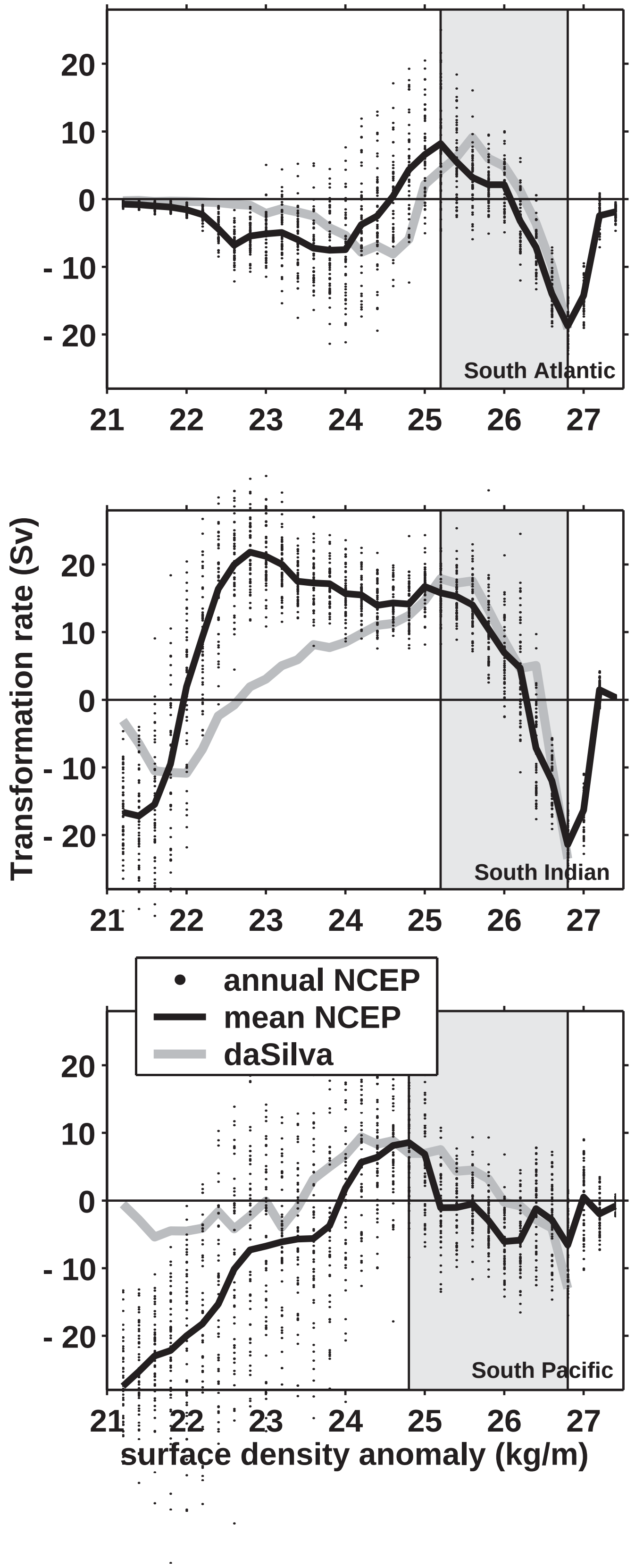


Figure 1: Southern Hemisphere water mass transformation. NCEP/NCAR reanalysis data between 1950 and 1999, mean (black line); individual years (dots) and daSilva et al. (gray line), The gray shaded area indicate the density anomaly range of water mass formation.

able, we simply use the World Ocean Atlas 1998 (based on Conkright et al., 1998) salinity climatolgy to calculate the surface density field. Water mass transformations were estimated over relatively large density bins of 0.2 kg/m^3. We further calculated annual mean water mass transformation rates based on monthly data from January to December of each year.

Results

Mean Fluxes

Comparing the COADS based water mass transformation rates (daSilva et al., 1994) with those using the NCEP/NCAR reanalysis shows similar overall patterns, but also large differences in certain density anomaly ranges (Figure 1). Ship and buoy based observational data is sparse in the Southern Ocean and the daSilva et al., (1994) climatology excludes most of the dense waters, limiting the comparison to the lower density anomaly range. The annual mean values of the transformation rates from NCEP/NCAR show a large scatter and thus the differences between climatology and mean reanalysis are probably not surprising. Largest differences occur in the Indian Ocean at densities <24.6 kg/m^3 and in the Pacific at densities <23 kg/m^3, but in general the COADS estimates are within the scatter of annual NCEP values. Looking into the thermal and haline components we find the thermal component to be responsible for these differences, but we do not know why this occurs. In the following we will only discuss the NCEP derived transformation rates.

There are large similarities between the three oceans: A maximum in transformation occurs at around 25 kg/m^3 (left bound of grey area in Figure 1). The formation is the derivative of the transformation and this maximum separates formation of denser water from its destruction, or the formation of less dense waters. It may thus be interpreted as the boundary between the permanent thermocline and the seasonal or tropical thermocline outcrop (Speer and Tziperman, 1992). At higher densities the minimum in the transformation around 27 kg/m^3 indicates the upper limit of the density anomaly interval where water mass formation occurs. In the South Atlantic and South Indian Oceans it is a rather sharp peak, while in the South Pacific it is much broader. The density at this peak is the highest density at the base of the permanent thermocline in the gyres.

The transformation rates can be translated into water mass formation rates by taking the difference between the minima and maxima (Figure 1). In the South Atlantic (70°W to 20°E) we see about three times larger formation from dense water into less dense water (grey area in Figure 1) then vice versa, with an overall of 26 Sv. For the Southern Indian Ocean (20 to 120°E) we find a formation of about 40 Sv with a similar ratio for the transformation towards dense and towards less dense water. For the South Pacific only about 18 Sv are formed. This is surprising, since the Pacific is the widest of the three oceans.

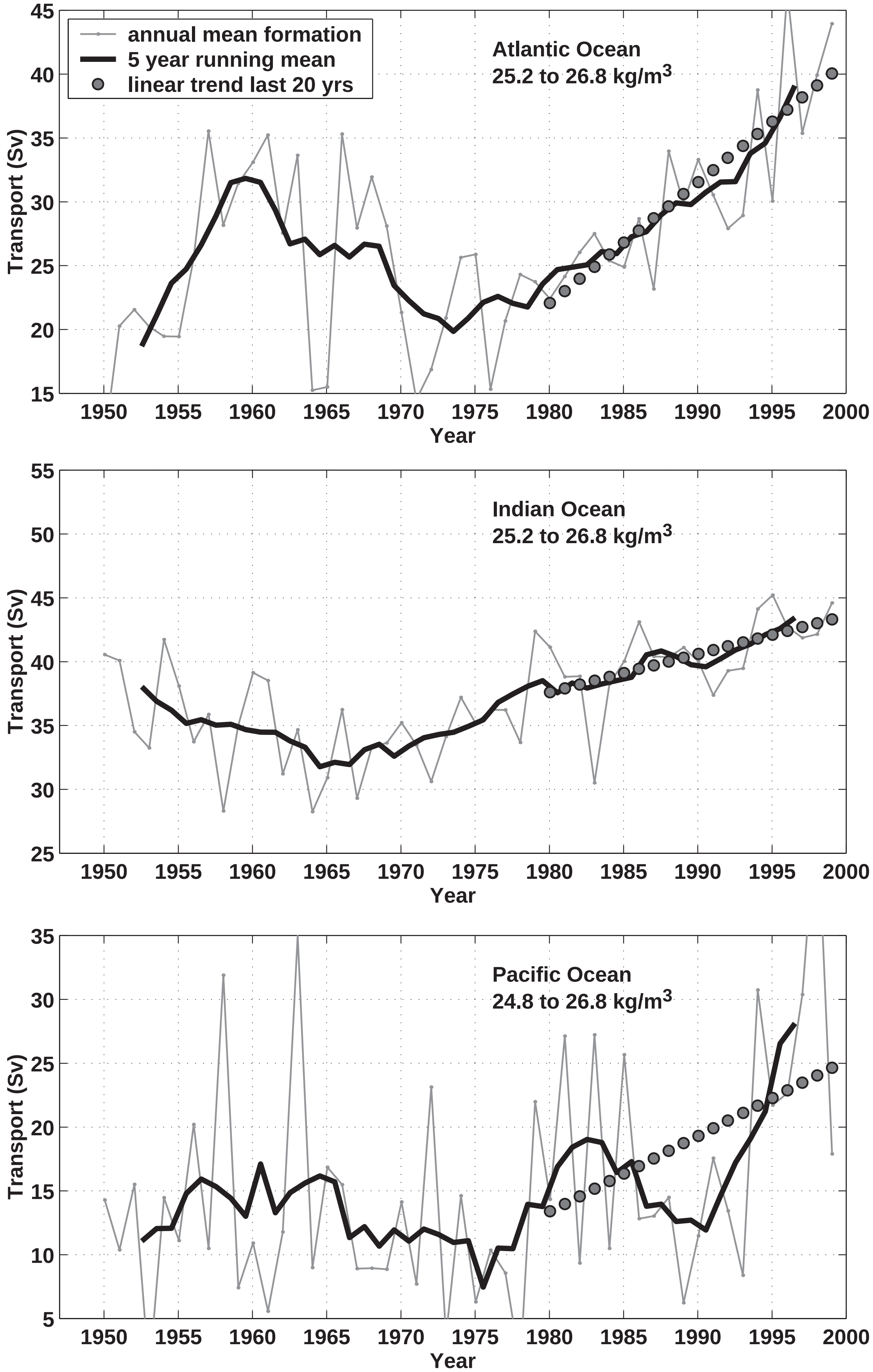


Figure 2: NCEP/NCAR based variability of the annual mean water mass formation over the southern hemisphere ocean in the density range of the thermocline (see Figure 1) between 1950 and 1999. Annual mean (dots and thin line), 5 year running mean (thick gray line, and linear best fit for last 20 years (broken line) are shown. The calculations are based on averages between January to December of each individual year.

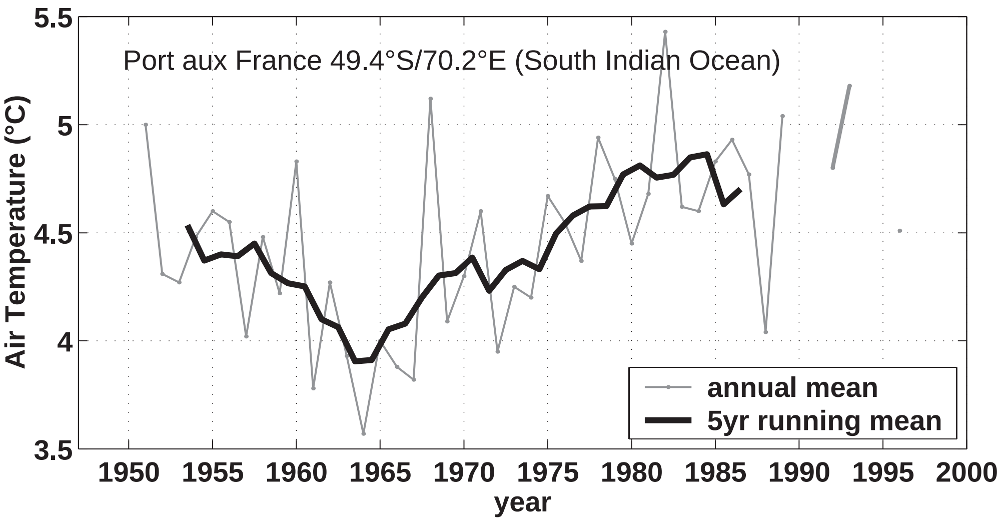


Figure 3: Annual mean and 5 yr running mean air temperature measured at at Port-aux-France, Southern Indian Ocean (49°S, 70°E).

The overall formation in the southern hemisphere is thus in the order of 80 Sv. This number agrees with the overall subduction rate of 100 Sv estimated from hydrographic data (Karstensen and Quadfasel submitted). Different, however, is the distribution of the input. It increases from west to east, being 21 Sv in the South Atlantic, 35 Sv in the South Indian and 44 Sv in the South Pacific Ocean. Hence, some of the water formed in the South Atlantic must flow into the South Indian Ocean and even more water from the Indian Ocean must get exported into the South Pacific where it finally subducts. Sloyan and Rintoul (2001b) from an inverse model study also detected such an interocean exchange of newly formed water masses via the circumpolar water ring. They found some 18 Sv to be exported from the Indian to the Pacific Ocean, in line with our findings.

Variability in time

In a next step we looked at the time series of monthly fluxes in the NCEP/NCAR reanalysis data to possibly detect trends or longer term variability in the water mass formation. Variability in thermocline water formation, in particular the Mode and Intermediate Waters formation, is affected by and may also be relevant for decadal scale climate variability. Warming and cooling signals at midlatitudes are communicated to the thermocline, are advected equatorwards and reappear due to upwelling in the tropics at the surface ocean with decadal delay. These shallow thermohaline cells have been recognized as a communication path between tropics and extra-tropics (Johnson and McPhaden, 1999).

The time series of annual mean water mass formation over the past 50 years for the three oceans is given in Figure 2. Also shown is the 5 year running mean and the linear trend over the last 20 years of the time series where the quality of the product has improved due to the inclusion of satellite data (Kistler et al., 2001). At least for these past 20 years we find a consistent increase in the overall water mass formation rates in all three oceans, which in the South Pacific is obscured by decadal variability.

Changes seen in the interior of the oceans support our findings and this correlation between the variability of the water mass formation rates derived from air-sea fluxes is and the changes seen in the ocean is encouraging. Levitus et al. (2000) compared gridded hydrographic data from 1948 and 1998 and showed a significant increase of the heat content in the upper 1000 m for the South Indian and Atlantic Oceans. An increase in thermocline water formation will lead to a thickening of the thermocline, causing a warming at its lower bound. Most other observational based studies compare synoptic high-quality sections of particular years, giving specific attention to Mode and Intermediate Water. Bindoff and McDougall (2000) found warming for upper waters in the Indian Ocean down to about 900dbar and a freshening for the intermediate water between 500 and 1500 dbar. They also found a 25% increase in thickness of the Subantarctic Mode Waters between 1962 and 1987, but a decrease in thickness of the underlying Intermediate Water. The increase is in line with our findings of an increase in formation from about 35 Sv to 40 Sv.

NCEP's reanalysis individual flux components show a decrease of the latent and sensible heat fluxes from the ocean to the atmosphere. In regions with negative sensible heat flux, such as the South Atlantic and the South Indian Oceans, which are located in the transition zone between the subtropical gyres recirculation and the Southern Ocean, this means an enhanced importance of the sensible heat flux. This is in general in agreement with a direct feedback on recent air temperatures increase (Figure 3). As the water, which is driven over the front from the south is essentially old North Atlantic Deep Water, its temperature has not responded to the recent changes in the surface temperature. Thus an increase in surface temperature translates directly into the sensible heat gain of the ocean and therefore increases the transformation of cold into warmer water. A warming here is associated with a water mass formation increase and hence different from what one may assume a priori.

Acknowledgment

The NCEP/NCAR reanalysis data and reconstructed Reynolds SST data is available from the NOAA-CIRES Climate Diagnostics Centre, Boulder, Colorado, USA, from their Web site http://www.cdc.noaa.gov/. Financial support from the German CLIVAR program and by NOAA through grant NA86GP0375 is acknowledged.

References

Bindoff, N.L., and T.J. McDougall, 2000: Decadal changes along an Indian Ocean Section at 32°S and their interpretation. *J. Phys. Oceanogr.*, **30**, 1207-1222.

Conkright, M.E., S. Levitus, T. O'Brien, T.P. Boyer, C. Stephens, D. Johnson, O. Baranova, J. Antonov, R. Gelfeld, J. Rochester, and C. Forgy, 1998: World Ocean Database 1998, NODC Internal Report 14, CD Rom set Version 2.0, U.S. Government Printing Office, Washington, D.C, USA.

daSilva, A.M., C.C. Young, and S. Levitus, 1994: Atlas of Marine Surface Data. Vol. 2. U.S. Government Printing Office, Washington, D.C, USA, 83 pp.

Gordon, A.L., 1986: Interocean exchange of thermocline waters. *J. Geophys. Res.*, **91**, 5037-5046.

Johnson, G.C., and M. McPhaden, 1999, Interior Pycnocline Flow from the Subtropical to the Equatorial Pacific Ocean. *J. Phys. Oceanogr.*, **29**, 3073-3089.

Karstensen, J., and D. Quadfasel, 2001: On the formation of Southern hemisphere thermocline waters: water mass conversion and subduction. *J. Phys. Oceanogr.*, submitted.

Kistler, R., E. Kalnay, W. Collins, S. Saha, G. White, J. Woollen, M. Challiah, W. Ebisuzaki, M. Kanamitsu, V. Kousky, H. van den Dool, R. Jenne, and M. Fiorino, 2001: The NCEP/NCAR 50-year Reanalysis: Monthly Means CD-Rom and Documentation. *Bull. Amer. Meteor. Soc.*, **82**, 247-267.

Levitus, S., J.I: Antonov, T.P. Boyer, and C. Stephens, 2000: Warming of the world ocean. *Science*, **287**, 2225-2229.

Reynolds, R. W., and T. M. Smith, 1994: Improved global sea surface temperature analyses. *J. Climate*, **7**, 929-948.

Rintoul, S. R., C. W. Hughes, and D. Olbers, 2001: The Antarctic Circumpolar current system. In: *Ocean Circulation and Climate*. G. Siedler, J. Church and J. Gould, (Eds.), Academic Press, London, UK, 271-302.

Sloyan, B.M., and S.R. Rintoul, 2001a: The Southern Ocean Limb of the Global Deep Overturning Circulation. *J. Phys. Oceanogr.*, **31**, 143-173.

Sloyan, B.M., and S.R. Rintoul, 2001b: Circulation, renewal and modification of Antarctic Mode and Intermediate Water. *J. Phys. Oceanogr.*, **31**, 1005-1030.

Speer, K.G., E. Tziperman, 1992: Rates of water mass formation in the North Atlantic Ocean. *J. Phys. Oceanogr.*, **22**, 93-104.

Speer, K., S. Rintoul, and B. Sloyan, 2000: The diabatic Deacon cell. *J. Phys. Oceanogr.*, **30**, 3212-3222.

Tziperman, E., 1986: On the role of interior mixing and air-sea fluxes in determining the stratification and circulation of the oceans. *J. Phys. Oceanogr.*, **16**, 680-693.

Wallin, G., 1982: On the relation between sea-surface heat flow and thermal circulation in the ocean. *Tellus*, **34**, 187-194.

Air-Sea Interaction Associated with the Weddell Polynya

G.W.K. Moore[1], K. Alverson[2] and I.A. Renfrew[3]

[1] University of Toronto, Toronto, Canada
moore@atmosp.physics.utoronto.ca

[2] PAGES International Project Office, Bern, Switzerland

[3] British Antarctic Survey, Cambridge, UK

During the austral winters of 1974-76, a large region of open water or polynya was identified in the center of the normally ice covered Weddell Sea (Gordon, 1978). In a polynya, the absence of sea ice exposes the relatively warm surface waters to the cold polar atmosphere which can lead to an intense exchange of heat and moisture between the ocean and atmosphere. In the case of the Weddell polynya, it is thought that this exchange resulted in a convectively driven overturning of the water column that produced a significant volume of Antarctic Bottom Water, the dominant deep water mass of the world ocean (Gordon, 1978). Observations show that this large infusion of relatively cold and fresh water has now propagated into the South Atlantic Ocean (Coles et al., 1996). Although it has not reappeared in the intervening years, there is data to suggest the occurrence of a polynya in this region during the winter of 1960 (Gordon, 1982). Furthermore, there is recent oceanographic data that suggests the region may be again primed for the re-development of a polynya (Gordon, 1997). The possibility of an episodic occurrence of the polynya and concomitant oscillation in Antarctic Bottom Water formation may be a major source of climate variability on the decadal to centennial timescale (Coles et al., 1996; McPhee et al., 1996; CLIVAR, 1997).

The oceanography of the Weddell polynya has received considerable attention (Gordon, 1982; Martinson, 1991; Alverson and Owens, 1996; Holland, 2001). The same cannot be said of the meteorology and in particular the air-sea interaction that was associated with the polynya. The oceanic convection that took place was most likely forced by air-sea fluxes of heat and moisture. This lack of attention has resulted in uncertainty regarding important aspects of the processes of ocean convection as they occurred within the polynya.

Moore et al. (2001) note that the presence of the polynya in the surface boundary condition fields of the NCEP reanalysis allows for a reconstruction of the associated air-sea interaction. However caution must be exercised in such a reconstruction as the surface flux fields in reanalyses are derived from short-term forecasts and as such are highly model dependent. They are less constrained to be consistent with observations, than (for example) temperature, winds, pressure and moisture fields. In particular systematic problems have been identified in the turbulent heat flux fields of the NCEP reanalysis. Renfrew et al. (2001) showed that for winter conditions in the Labrador Sea, somewhat similar conditions to those of the Weddell Sea, although the surface-layer meteorology in the reanalysis was in good agreement with independent observations, the surface turbulent heat flux fields were not. The discrepancies were on average overestimates of 50% and 30% for the sensible and latent heat fluxes respectively. Much more accurate flux fields were produced by an off-

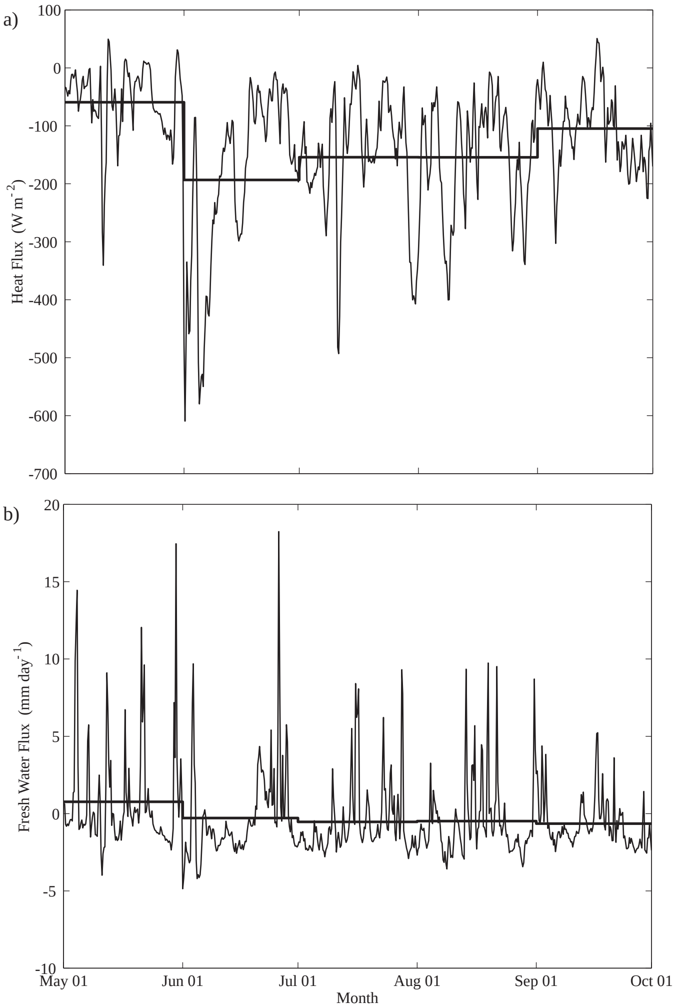


Figure 1: Time-series of the: (a) total turbulent heat flux and (b) fresh water flux at a location in the center of polynya during the austral winter of 1976. The thin lines represent the 6 hourly values of these fluxes while the thick lines represent monthly mean values computed from the 6 hourly values. The sign convention used is that a positive heat flux represents a warming of the surface while a positive fresh water flux represents a freshening of the surface.

line recalculation of the turbulent heat fluxes, using the reanalysis surface-layer variables and a well-established algorithm that had been validated on the same research cruise. The reconstruction by Moore et al. (2001) follows this same methodology.

As discussed in Moore et al. (2001), the reconstruction shows that the polynya had a profound impact on the surface meteorology of the region. Surface air temperatures over the polynya were on the order of 20^{o}C warmer than climatology. Total cloud cover over the polynya was 50% higher than climatology. The magnitude of the monthly mean sensible and latent heat fluxes during the winter months were on the order of 150 and 50 Wm^{-2} respectively. In contrast, typical winter sensible and latent heat fluxes are close to zero in the region. The precipitation rate over the polynya was in excess of 1 mm day^{-1} which is approximately 50% larger than climatology. Figure 1 shows the total turbulent heat flux (sum of sensible and latent heat fluxes) and the fresh water flux (difference of precipitation and evaporation), at a temporal resolution of 6 hours, throughout the austral winter of 1976. Also shown are the monthly mean values computed from the 6-hourly data. From this figure, one can see that on average there was a cooling of the surface of the polynya throughout the winter. The 6-hourly time-series of this field indicates that the peak fluxes were significantly larger than the monthly mean values. There are even instances where there was warming at the surface. With regard to the fresh water flux, the situation is more extreme. The probability that the fresh water flux is negative over any 6-hour interval during the austral winter of 1976 is approximately 70%. Despite this, the monthly mean values are close to zero. From the figure, one can see this is the result of the large but relatively infrequent events when the fresh water flux is positive. As discussed by Moore et al. (2001), this high frequency variability in the fluxes can be attributed to the passage of extra-tropical cyclones.

It is of interest to calculate the mean buoyancy loss experienced by the surface waters of the Weddell Sea as a result of the presence of the polynya. Table 1 shows results for the austral winters of 1975 and 1976. Mean and standard deviations of the buoyancy flux and its three components are presented. Values from 1974 are unavailable as the polynya was absent from the NCEP surface fields during June of that year. For comparison, we also show estimates from Gordon (1981), as these have been widely used in modelling studies of ocean convection within the polynya (Akitomo et al., 1995; Alverson and Owens, 1996). In this table, the fresh water flux has been expressed in terms of an 'equivalent' heat flux. This is accomplished by calculating the heat flux required to effect the same change to the buoyancy of the surface waters as occurs from a given fresh water flux. This approach, which is described in more detail in Moore et al. (2001), allows for an easier comparison of the relative importance that thermal and haline forcings make to the buoyancy flux. The air-sea fluxes in 1975 and 1976 were similar, with the only notable difference being that in 1976 the fresh water forcing was higher, indicating more precipitation fell during that year. The data indicate that the buoyancy flux, and each of its components are all highly variable in time. A comparison with Gordon's estimates indicates that his estimate of the total turbulent heat flux is larger than that derived from the reanalysis while the fresh water flux is of the opposite sign. In addition, his estimate of the net radiative flux is significantly smaller in magnitude than that of the reanalysis. Although these discrepancies are somewhat self-canceling the net result is that the mean buoyancy flux derived from Gordon's estimates is 30-40% lower than that derived from the reanalysis.

The reconstruction by Moore et al. (2001) provides the first quantitative details of the air-sea interaction associated with the Weddell Polynya. The air-sea interaction within the polynya was highly variable in time, with numerous distinct surface cooling and precipitation events. The peak surface cooling was in excess of 600 W m^{-2} while

	Gordon	NCEP 1975	NCEP 1976
Total Turbulent Heat Flux (W m^{-2})	-136	-104 (70)	-100 (74)
Fresh Water Flux (W m^{-2})	25	-25 (92)	-5 (103)
Net Radiative Flux (W m^{-2})	-6	-55 (48)	-50 (50)
Buoyancy Flux (10-7 m^2 s^{-3})	-0.106	-0.168 (0.152)	-0.141 (0.170)

Table 1: Comparison of mean buoyancy flux and its components over the Weddell Polynya for the Period March 1-Oct 1. The fresh water flux is expressed in units of Wm^{-2} as discussed in Moore et al. (2001). For the NCEP reanalysis, the standard deviations of the 6 hourly data about the means are also indicated in brackets. Data in the column titled 'Gordon' are from Gordon (1981).

the peak precipitation rate was in excess of 1 mm hr^{-1}. For the heat fluxes and the precipitation rate, the peak values were significantly larger than the monthly mean values. As a result of the non-linear nature of air-sea interaction processes, high temporal resolution data (e.g. 6-hourly) are required to calculate accurate surface flux fields on monthly and longer timescales. Moore et al. (2001) present evidence that coherent atmospheric weather systems, i.e. extra-tropical cyclones are responsible for the high frequency variability of the fluxes. Hence an accurate representation of synoptic-scale processes in the atmosphere is required for accurate air-sea fluxes over the polynya. Martinson et al. (1981) in their model of ocean convection in the polynya attempted to include high frequency variability in the air-sea fluxes by representing them as stochastic variations. The results of Moore et al. (2001) suggest that such random fluctuations probably do not accurately represent the variability in the atmospheric forcing that actually occurred. The reconstructed buoyancy flux within the polynya during the winter was on average negative, indicating that the surface waters were becoming denser thereby driving oceanic convection and Antarctic Bottom Water formation. Nevertheless there were instances when the buoyancy flux was positive. During these events, the fresh water flux due to precipitation was larger than the effect of cooling, thus resulting in a reduction in the density of the surface waters of the polynya. This result suggests that precipitation should not be neglected as a forcing term in studies of oceanic convection in the Weddell Sea as has been done in the past, e.g. Alverson and Owens (1996), Holland (2001). The reconstructed integrated buoyancy flux over the winter months of both 1975 and 1976 exceed previous estimates by 30-40%. This result implies that the oceanic convection that took place as a result of the existence of the polynya may have been more vigorous than previously thought. There are still uncertainties with respect to the larger scale atmospheric and oceanic responses to this event. Our ability to assess the fidelity with which these analyses represent the air-sea interactions within such a polynya will not be answered until one is able to collect *in-situ* data under similar environmental conditions.

References

Akimoto, K., T. Awaji, and N. Imasato, 1995: Open-ocean deep convection in the Weddell Sea: two-dimensional numerical experiments with a nonhydrostatic model. *Deep-Sea Res.*, **42**, 53-73.

Alverson, K., and W.B. Owens, 1996: Topographic preconditioning of open ocean deep convection. *J. Phys. Oceanogr.*, **26**, 2196-2213.

CLIVAR, 1997: CLIVAR (Climate Variability and Predictability) Initial Implementation Plan, International CLIVAR Project Office, Southampton, UK, (http://www.clivar.org), 360pp.

Coles, V.J., M.S., McCartney, D.B. Olson, and W.M. Jr. Smethie,1996: Changes in Antarctic Bottom Water properties in the western South Atlantic in the late 1980s. *J. Geophys. Res.*, **101**, 8957-8970.

Gordon, A.L., 1978: Deep Antarctic convection west of Maud Rise. *J. Phys. Oceanogr.*, **8**, 600-612.

Gordon, A.L., 1981: Seasonality of Southern Ocean sea ice- *J. Geophys. Res.*, **85**, 4193-4197.

Gordon, A.L., 1982: Weddell Deep Water variability. *J. Marine Res.*, **40**, 199-217.

Gordon, A.L., 1997: The AABW Story: What, where, & how much and its global significance. In: *Proceedings of the ACSYS Conference on Polar Processes and Global Climate.*, K. Aagaard, (Ed.), ACSYS Project Office, Oslo, Norway, 68-70.

Holland, D.M., 2001: Explaining the Weddell Polynya- a large ocean eddy shed at Maud Rise. *Science*, **292**, 1697-1700.

Martinson, D.G., 1991: Open ocean convection in the Southern Ocean. In: *Deep Convection and Deep Water Formation in the Oceans*, P.C. Chu and J.C. Gascard, (Eds.), Elsevier, Ammsterdam, The Netherlands, 382pp.

Martinson, D.G., P.D. Killworth, and A.L. Gordon, 1981: A convective model for the Weddell Polynya. *J. Phys. Oceanogr.*, **11**, 1741-1755.

McPhee, M.G., S.F. Ackley, P. Guest, B.A. Huber, D.G. Martinson, J.H. Morison, L. Padman, and T.P. Stanton, 1996: The Antarctic Flux Experiment. *Bull. Amer. Meteor. Soc.*, **77**, 1221-1232.

Moore, G.W.K., K. Alverson, and I.A. Renfrew, 2001: A reconstruction of the air-sea interaction associated with the Weddell Polynya. *J. Phys. Oceanogr.*, in press.

Renfrew, I.A., G.W.K. Moore, P. Guest, and K. Bumke, 2001: A comparison of the surface-layer and surface turbulent-flux observations over the Labrador Sea with ECMWF analyses and NCEP reanalyses. *J. Phys. Oceanogr.*, in press.

Sea Ice Anomalies in the Eastern Weddell Sea

Aike Beckmann, Ralph Timmermann, Adriene F. Pereira, and Christian Mohn
Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany
beckmann@AWI-Bremerhaven.DE

1. Introduction

Even 25 years after its occurrence, the *Great Weddell Polynya* (Carsey, 1980; Gordon, 1982) of the mid–1970s remains one of the major mysteries of Southern Ocean climate variability. Several hypotheses about the mechanisms for its formation and maintenance have been put forward, focusing both on atmospheric wind and temperature anomalies (Martinson et al., 1981; van den Broeke, 2000; Holland, 2001), as well as oceanic mixed layer thickness and temperature anomalies (Martinson et al., 1981; Gordon and Huber, 1984; Lemke, 1987). In many cases it has been assumed that the polynya is related to the presence of *Maud Rise*, a large submarine bank at 2° 30'E, 65°S (Gordon and Huber, 1984; Martinson, 1990; Muench et al., 2001; Holland, 2001). Compared to the ambient ocean, the region near Maud Rise regularly features a relatively thin sea ice cover (Harms et al., 2001) with intermittent polynyas (e.g., Gordon and Comiso, 1988; Muench et al., 2001); this is the area where the Weddell Sea ice begins to break up in spring (Gloersen et al., 1992).

Yet, the origin of sea ice anomalies in the eastern Weddell Sea are still a matter of much speculation. Recently, two new pieces have been added to the puzzle as a result of numerical modeling efforts.

The first (Beckmann et al., 2001) offers a previously overlooked physical mechanism for the climatological thinning of sea ice in the Maud Rise area: tidally generated waves at the isolated topography and their effect on vertical mixing. The second features results from a circumpolar climate model run with NCEP forcing (Beckmann and Timmermann, 2001).

2. Flow at Maud Rise

Flow at seamounts is often dominated by a pronounced doming of the isopycnals, due to the combined effects of steady impinging flow (Chapman and Haidvogel, 1992) and the rectification due to time-variable (e.g., tidal) motion (e.g., Haidvogel et al., 1993). In addition, the waves generated at the seamount (both trapped and free) enhance the variability and vertical mixing in the seamount area. In both cases, the effects of seamounts on the circulation and thermohaline structure of the upper ocean can be significant: localized vertical motion and increased vertical mixing due to both steady and oscillatory impinging currents will lead to a spatial inhomogeneity of the mid- to upper-level hydrography and flow field.

Both forcing mechanisms also exist at Maud Rise: The barotropic large scale current system features a generally westward flow of about 1 cm s^{-1} (Schröder and Fahrbach, 1999). Barotropic tidal models of this region (*Pereira*, pers. comm.), estimate the typical deep ocean tidal amplitudes as 1.5 cm s^{-1} and 2.5 cm s^{-1} for the diurnal and semidiurnal frequencies, respectively. The corresponding isopycnal doming was detected in hydrographic measurements by Bersch et al. (1992).

Based on these conditions, Beckmann et al. (2001) conducted a process study with a coupled sea ice–ocean model, which featured Maud Rise in the center of a double periodic domain.

The model was initialized with horizontally uniform profiles of potential temperature and salinity, and no flow. The stratification was taken from the Hydrographic Atlas of the Southern Ocean (Olbers et al., 1992), choosing the deep ocean northeast of Maud Rise as representative of the "undisturbed" ocean state. Thus, the initial state resembled the regional hydrography with its pronounced sub-surface temperature and salinity maxima – except for the anomaly above the seamount. Atmospheric forcing consists of a constant wind of 2 m s^{-1} from the southeast, representing the generally off-shore winds in this region. Daily mean solar radiation and spatially uniform atmospheric temperatures were prescribed, beginning at -4°C in May and varying sinusoidally to -15°C in September. The dew point temperature was set 2 degrees lower; precipitation was assumed to be zero. Again, the atmospheric forcing was uniform in space, such that any anomaly can be attributed to the topography.

With this forcing, the model was integrated for 180 days, beginning in May and comprising the main freezing period.

2.1 Effect of tidal flow amplification on sea ice cover

Modelled tidal currents at Maud Rise reach about 9 cm s^{-1}, i.e., they are amplified only weakly (by a factor of about 2.5) relative to deep ocean values. Nevertheless, the local response was sufficient to erode the thermocline above Maud Rise almost completely. Within a month after first ice formation, about 80 cm of ice were formed thermodynamically. Above Maud Rise, the sea ice thickness reached a maximum of only 50 cm, which represents a reduction of local ice volume by roughly 30% (Fig. 1a, page 18). At day 120, i.e., in early September, the time of minimum atmospheric temperature, the anomaly (defined by a 20% reduction of ice thickness) had grown to over 150 000 km^2 and had been advected westward at an average rate of 2.5 cm s^{-1} as the result of time-mean oceanic advection and wind induced drift (Fig. 1a). While the ice thickness was significantly reduced, the ice concentration anomaly was less pronounced – both consistent with observations.

To demonstrate the crucial role of tides in the formation of the modeled sea ice anomaly, an experiment without the tidal forcing was carried out. It turns out that without the vertical mixing due to the seamount trapped waves, the large–scale flow divergence around Maud Rise is hardly capable of imprinting the topographic signature on the sea ice fields and sea ice thickness gradients are much smaller (Fig. 1b). Obviously, this mechanism is predominantly thermodynamic rather than dynamic (as the one suggested by Holland, 2001). Further sensitivity studies (with varying oceanic mean flows and variable winds) indicate that the results are robust.

3. Interdecadal climate system variability

The other intriguing idea originates from a regional climate model of the Southern Ocean.

In recent years, a number of independent sea ice–ocean hindcasts of the last decades using atmopsheric reanalyis data have been carried out. These forcing data should, in principle, contain at least part of the signature of the Weddell Polynya. Although none of the simulations succeeded in reproducing the observed polynya, the 40-year integration of the BRIOS regional coupled ice–ocean model (Timmermann et al., 2001) using data from the NCEP reanalysis has shown a significant thinning of the sea ice cover west of Maud Rise during the years 1975 and 1976 (Beckmann and Timmermann, 2001; Fig. 2, page 18), and only during these years.

3.1 An Interdecadal Circumpolar Wave

A first analysis of these model results identified a large–scale near–bottom temperature anomaly pattern close to the Antarctic coast, propagating counterclockwise around the continent. Its westward propagation is consistent with a 2-2.5 cm s^{-1} advection with the coastal current. An anomaly large enough to survive dissipation will advectively propagate around the continent within 25-30 years. Alternatively, a coastal trapped wave with circumpolar mode 1 could also have a similar phase speed. In that case, the *Antarctic Circumpolar Coastal Wave* (ACCW) could be interpreted as a quasi-periodic up- and downslope shift of the interface between warmer deep and colder coastal water masses (Beckmann and Timmermann, 2001).

The model shows the passage of a warm anomaly at the Greenwich Meridian in the mid-to-late 1970s, with a maximum just prior to the occurrence of the modelled and observed negative sea ice anomaly. Therefore, a connection with the Weddell Polynya seems likely. Unfortunately, this link cannot easily be tested, as the BRIOS circumpolar modeling system does not have sufficient resolution to explicitly include all potentially relevant processes (e.g., the details of flow around Maud Rise), nor does it involve an active atmosphere, which might contribute to the maintenance of the Weddell polynya (Timmermann et al., 1999).

4. Summary and Discussion

Numerical process studies show that tidally induced flow and mixing at Maud Rise leads to a local preconditioning of the upper water column, with increased upward oceanic heat flux. This causes a pronounced reduction of the sea ice volume in the area. The region of reduced sea ice volume moves downstream as the result of time–mean wind and steady oceanic flow. It thus provides an explanation for the observed "climatological" thinning of the sea ice cover near Maud Rise. It seems conceivable that in some years, under favorable large–scale (atmospheric and/or oceanic) circumstances, the effects may be enhanced and lead to the formation of a polynya, as observed in the mid-1970s.

In particular, one might speculate that a combination of the tidally induced mixing and the interdecadal circumpolar temperature anomaly associated with the passage of the Antarctic Circumpolar Coastal Wave (ACCW) will lead to an area of open water. A large scale westward propagating anomaly like the ACCW can not only explain the three-year duration of the polynya and the absence of it ever since , it also points to a possibly periodic nature of this apparently singular phenomenon. Further modeling studies are currently underway.

References

Beckmann, A., and R. Timmermann, 2001: Circumpolar Influences on the Weddell Sea: Indication of an Antarctic Circumpolar Coastal Wave. *J. Climate*, **14**, 3785-3792.

Beckmann, A., R. Timmermann, A.F. Pereira, and C. Mohn, 2001: The Effect of Flow at Maud Rise on the Sea Ice Cover – Numerical Experiments. *Ocean Dynamics*, **52**, 11-25.

Bersch, M., G.A. Becker, H. Frey, and K.P. Koltermann, 1992: Topographic effects of the Maud Rise on the stratification and circulation of the Weddell Gyre. *Deep Sea Res.*, **39**, 303-331.

Carsey, F.D., 1980: Microwave observations of the Weddell Polynya. *Mon. Wea. Rev.*, **108**, 2032-2044.

Chapman, D.C., and D.B. Haidvogel, 1992: Formation of Taylor caps over a tall isolated seamount in a stratified ocean, *Geophys. Astrophys. Fl. Dyn.*, **64**, 31-65.

Gloersen, P., W.J. Campbell, D. Cavalieri, J.C. Comisco, H.J. Zwally, and C.L. Parkinson, 1992: Arctic and antarctic sea ice, 1978-1987: satellite passive-microwave observations and analysis. *NASA special publication*, SP- 511; Washington, D.C., 290 pp.

Gordon, A.L., 1982: Weddell deep water variability. *J. Marine Res.*, **40**, 199-217.

Gordon, A.L., and B.A. Huber, 1984: Thermohaline stratification below the southern ocean sea ice. *J. Geophys. Res.*, **89**, 641-648.

Gordon, A.L., and J.C. Comiso, 1988: Polynyas in the Southern Ocean. *Scientific American*, **258**, 70-77.

Haidvogel, D.B., A. Beckmann, D.C. Chapman, and R.-Q. Lin, 1993: Numerical simulation of flow around a tall isolated seamount: Part II: Resonant generation of trapped waves. *J. Phys. Oceanogr.*, **23**, 2373-2391.

Harms, A., E. Fahrbach, and V.H. Strass, 2001: Ice transports in the Weddell Sea. *Geophys. Res.*, submitted.

From A. Hall and M. Visbeck: Ocean and Sea Ice response to the Southern Hemisphere Annular Mode: Results from a coupled climate model, page 4:

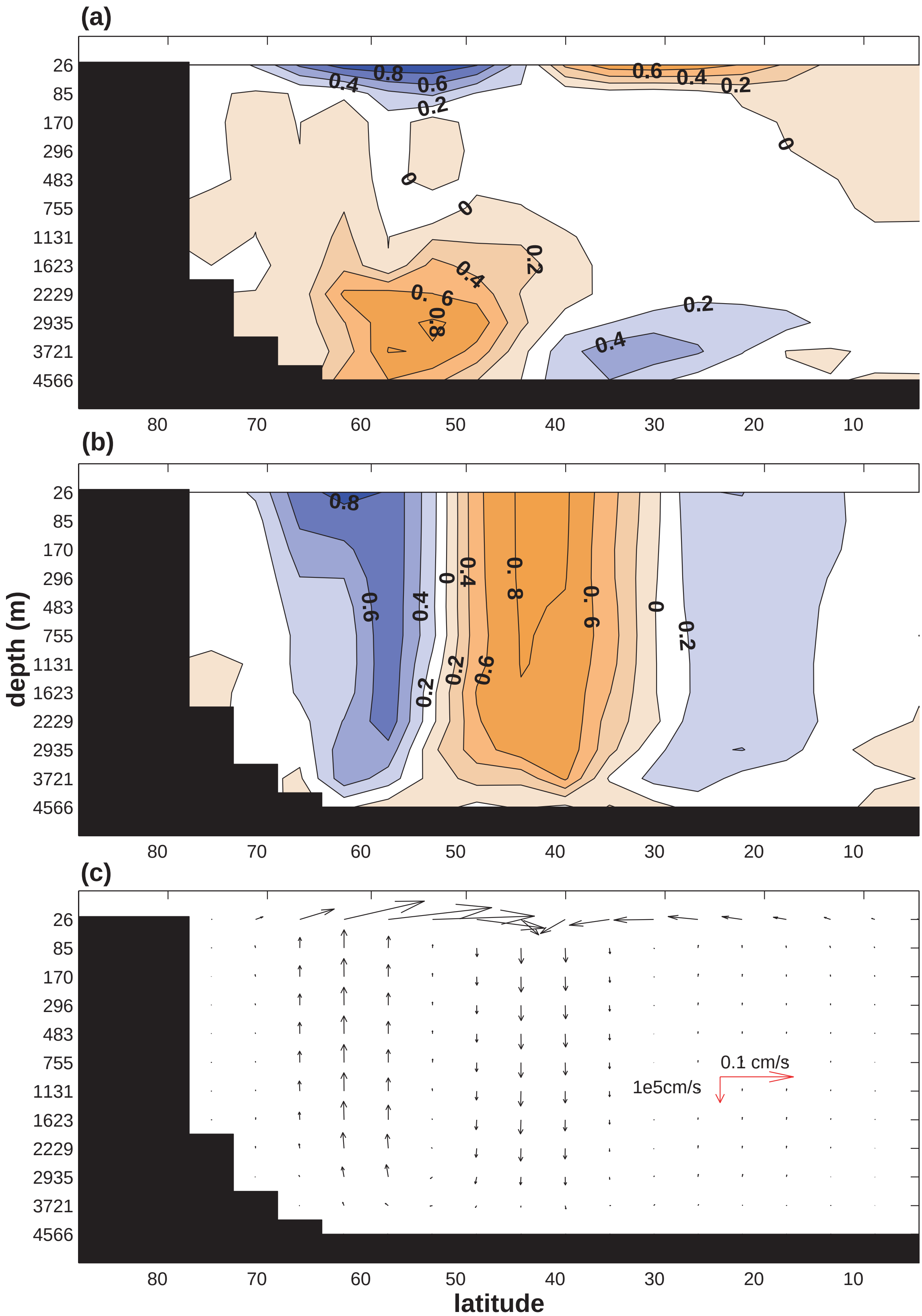


Figure 3: (a) the correlation between zonal-mean, annual-mean meridional currents throughout the SH ocean and the annual-mean SAM index. (b) the correlation between zonal-mean, annual-mean vertical currents throughout the SH ocean and the annual-mean SAM index. (c) the regressions of zonal-mean,annual mean meridional and vertical currents onto the annual-mean SAM index. Arrows illustrating the scaling of the two components of the vectors are shown in red.

From C. Reason et al.: Interannual winter rainfall variability in SW South Africa and potential influences from the Southern Ocean region, page 6:

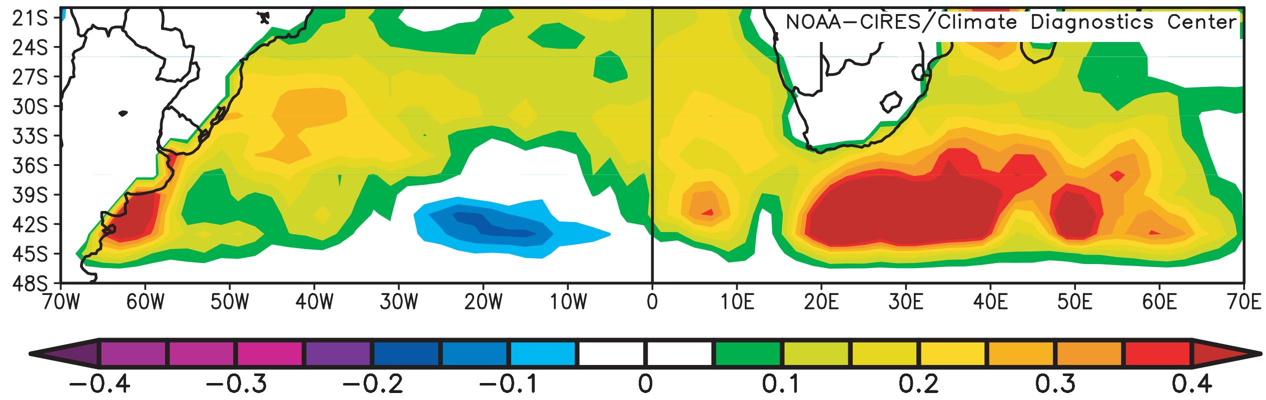


Fig. 4: SST anomalies for wet composite Reconstructed Sea Surface Temperatures (SST) (°C) anomalies for wet composites, May to Sept. 1954, 1957, 1962, 1974, 1977, 1991, 1996. SST data from Reynolds.

From A. Beckmann et al.: Sea Ice Anomalies in the Eastern Weddell Sea, page 15:

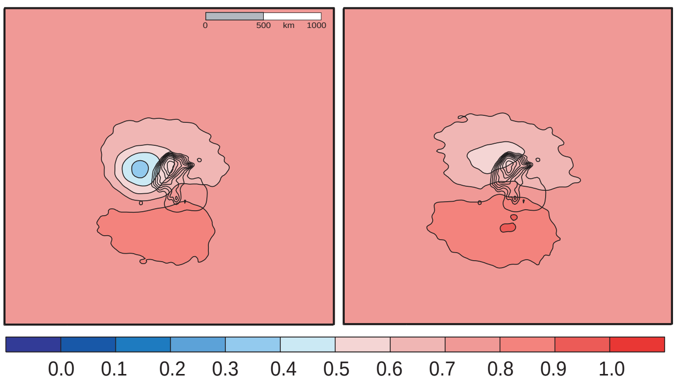
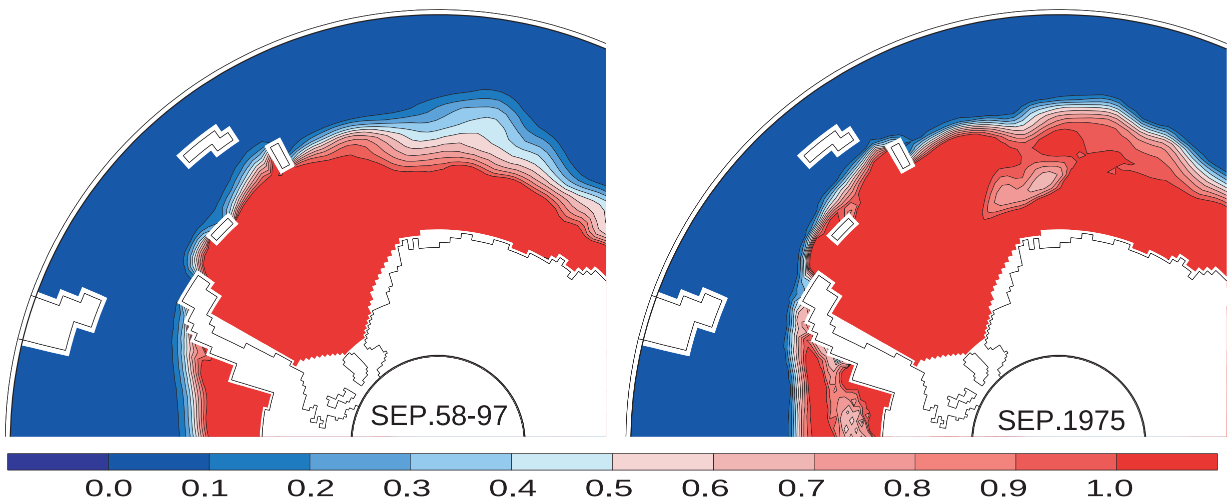


Figure 1 Ice thickness at day 120 (early September) (a) in the reference experiment and (b) with steady ocean forcing only (after Beckmann et al., 2001).

Figure 2:Weddell Sea september sea ice thickness in the BRIOS-2/NCEP experiment: (a) climatological mean; (b) 1975 (after Beckmann and Timmermann, 2001).



From R. Robertson et al.: Long-term Warming of Weddell Sea Warm Deep Water, page 21:

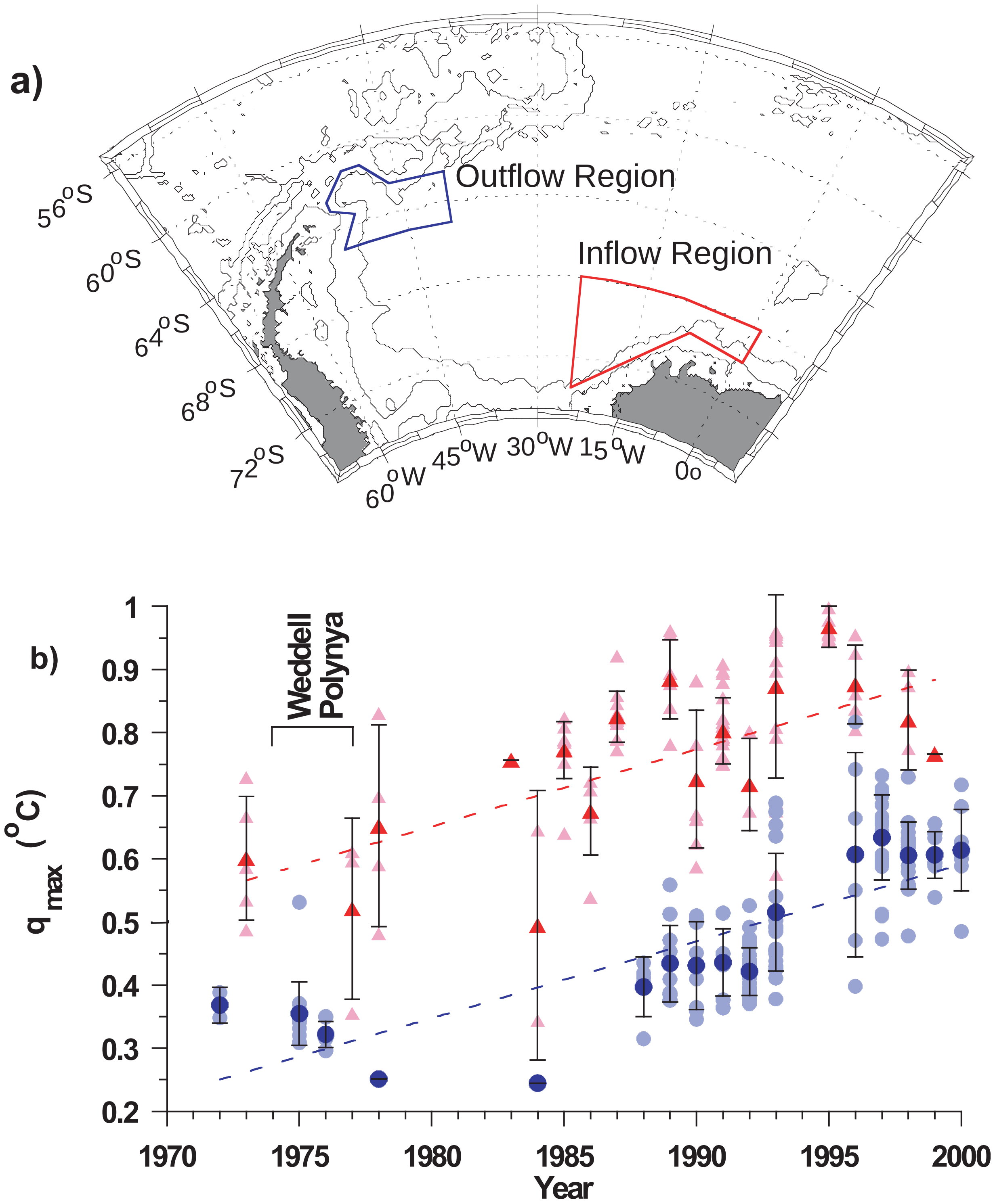


Figure 1. a) The bathymetry for the Weddell Sea with contours at 500 and 3000 m. The inflow and outflow regions are indicated by red and blue boxes, respectively. b) Annual average potential temperature profiles were calculated for three depth ranges representing the core of the WDW (bottom depths of 3000 to 3500 m, 3500 to 4000 m, and 4000 to 4500 m) for the inflow and outflow regions. The maximum potential temperature, q_{MAX}, determined for each of these average profiles is shown for the inflow region (red triangles) and the outflow region (blue dots). The pink triangles and light blue dots are the values for the individual profiles in the inflow and outflow regions, respectively. The error bars represent one standard deviation of the values. The red and blue dashed lines are fitted trends for the inflow and outflow regions, respectively. For a complete explanation of the technique, see Robertson et al. (2002).

From S. Gille: Southern Ocean ALACE Float Temperatures are Warmer than Historic Temperatures, page 22:

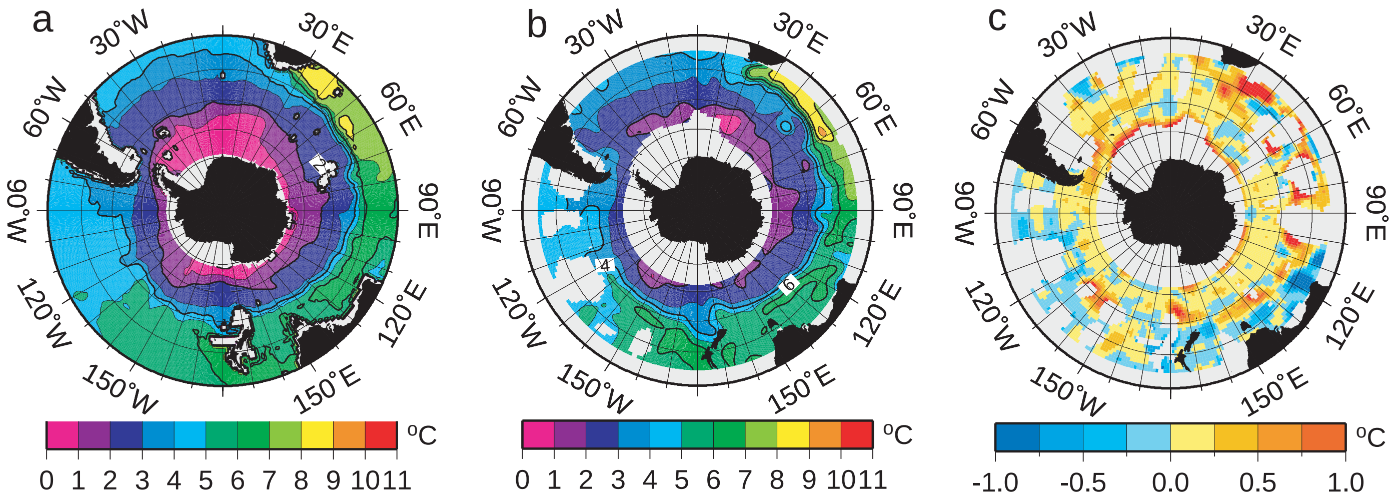


Figure 1: (a) Objectively mapped hydrographic temperature at 900 m depth from the Gouretski et al. (1998) atlas, primarily collected prior to 1990. (b) Objectively mapped temperature at 900 m depth from ALACE floats, collected since 1990. These results are based on mean temperatures measured over 10 to 25 day drift periods. (c) ALACE float minus hydrographic difference, indicating warming in the southern part of the region.

From R. Timmermann et al.: Parameterization of deep convection in the Weddell Sea, page 26:

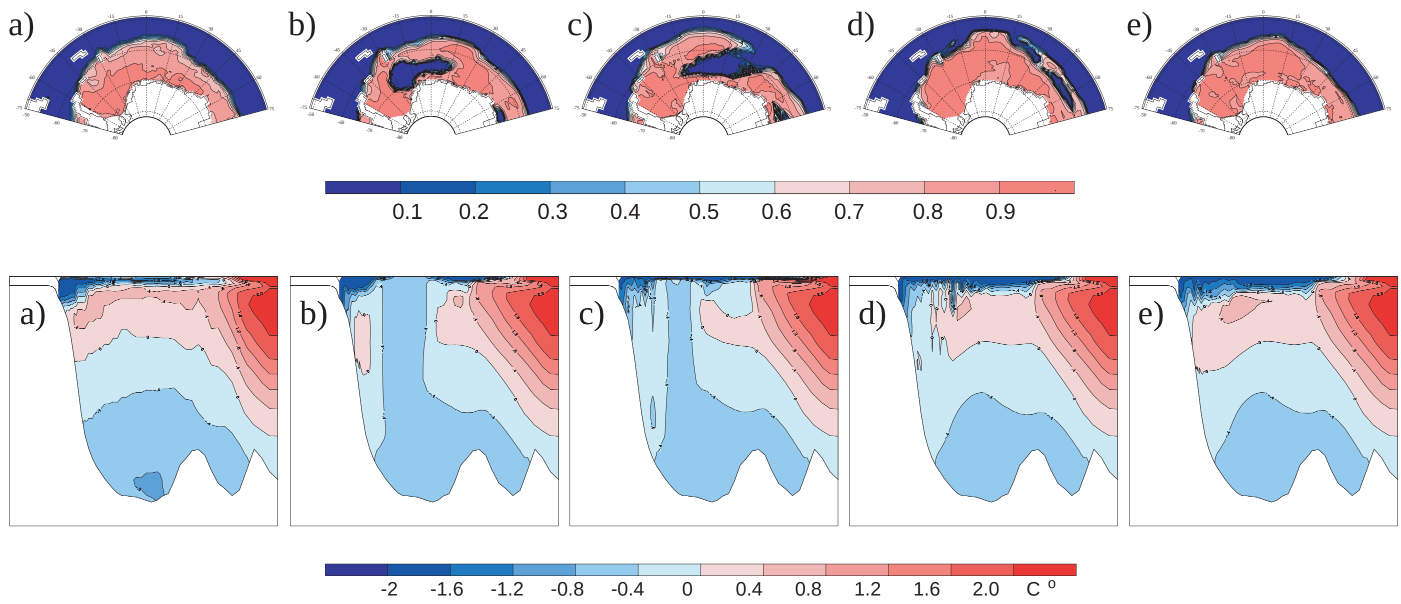


Figure 1: Ice concentrations (top) and temperature sections along 25°W (bottom) according to (a) observations (PELICON: Heygster et al., 1996; Hydrographic Atlas of the Southern Ocean: Olbers et al., 1992), and from the ninth year of integration of a circumpolar coupled sea ice-ocean model with (b) Convective Adjustment (Rahmstorf, 1993), (c) the original Pacanowski and Philander (1981) mixing scheme, (d) the KPP-scheme (Large et al., 1994), and (e) a scheme combining the Richardson number and the Monin-Obukhov length.

Holland, D.M., 2001, Explaining the Weddell Polynya – a Large Ocean Eddy Shed at Maud Rise. *Science*, **292**, 2697-2700.

Lemke, P., 1987: A coupled one-dimensional sea ice–ocean model. *J. Geophys. Res.*, **92**, 13164-13172.

Martinson, D.G., P.D. Killworth, and A.L. Gordon, 1981: A Convective Model for the Weddell Polynya. *J. Phys. Oceanogr.*, **11**, 466-487.

Martinson, D.G., 1990: Evolution of the Southern Ocean winter mixed layer and sea ice; open ocean deep water formation and ventilation. *J. Geophys. Res.*, **95**, 11641-11654.

Muench, R.D., J.H. Morison, L. Padman, D. Martinson, P. Schlosser, B. Huber, and R. Hohmann, 2001: Maud Rise revisited. *J. Geophys. Res.*, **106**, 2423-2440.

Olbers, D.J., V. Gouretski, G. Seiß, and J. Schröter, 1992: Hydrographic Atlas of the Southern Ocean. AWI, Bremerhaven, 82pp.

Schröder, M., and E. Fahrbach, 1999: On the structure and the transport of the eastern Weddell Gyre. *Deep Sea Res*, **46**, 501-527.

Timmermann, R., P. Lemke, and Ch. Kottmeier, 1999: Formation and maintenance of a polynya in the Weddell Sea. *J. Phys. Oceanogr.*, **29**, 1251-1264.

Timmermann, R., A. Beckmann, and H.H. Hellmer, 2001: Simulation of ice-ocean dynamics in the Weddell Sea. Part I: Model configuration and validation. *J. Geophys. Res.*, in press.

van den Broeke, M., 2000: On the interpretation of Antarctic temperature trends. *J. Climate*, **13**, 3885-3889.

Long-term Warming of Weddell Sea Warm Deep Water

Robin Robertson, Martin Visbeck, and Arnold L. Gordon
Lamont-Doherty Earth Observatory
Palisades, NY, USA
rroberts@ldeo.columbia.edu

Warming of the deep water in the Weddell Sea has important implications for Antarctic Bottom Water (AABW) formation, melting of pack ice, and the regional ocean-atmosphere heat transfer. In order to evaluate temporal changes in the deep waters of the Weddell Sea, a historical data set encompassing CTD and bottle data from 1912 to 2000 was analyzed for both trends and variability in the Warm Deep Water (WDW) (Robertson et al., 2002). We focused on two regions with the highest data concentration (Figure 1a, page 19): an inflow region, near where the Circumpolar Deep Water (CDW) flows into the Weddell Sea, and an outflow region after where the WDW interacts with shelf waters to form Weddell Sea Deep Water, a precursor to AABW.

The WDW was warmer in both the inflow and outflow regions during the 1990's than in the 1970's (Figure 1b). Most of the coldest maximum potential temperatures occurred during 1973 through 1978, which surrounds the time of the Weddell Polynya (1974-1976). Since then, 1984 had the coldest q_{MAX} values for the inflow and outflow regions.

The post Weddell Polynya warming trend was 0.012 ±0.007 ^{o}C yr^{-1} for both regions (dashed lines in Figure 1b). Since the temperatures of the late 1980's matched the pre-1970 temperatures and the temperatures of the 1990's were higher than those of the 1980's (Figure 1b), the warming indicates not only a return to pre-Weddell Polynya temperatures but further subsequent warming. The increase in temperature was not compensated by a change in salinity, with the result that the WDW became less dense from the 1970's to the 1990's (Robertson et al., 2002)

The observed warming trend was comparable to the average warming of the surface of the global ocean since the 1950's, 0.31^{o}C or 0.006 ^{o}C yr^{-1} (Levitus et al., 2000) and the warming trend of ~0.01^{o}C yr^{-1} for the Weddell Sea Bottom Water from 1989-1995 observed by Fahrbach et al. (1998) in the central Weddell Sea. Although there is no direct connection between the surface ice temperature and the WDW, the trend was also comparable to warming of the surface ice from 1970 to 1998 in the Weddell Sea, ~0.01-0.02^{o}C yr^{-1}, observed in satellite data by Comiso (2000).

The cause of the warming trend is hypothesized to be modification of the inflow waters with warmer or a larger quantity of Circumpolar Deep Water flowing into the Weddell Sea. Either of these changes could be linked to movement of the Weddell Front. The short record and gaps in the data precluded determination of a robust (lag) correlation between either the Southern Annular Mode (Antarctic Oscillation) (Hall and Visbeck, 2001) or the location of the Antarctic Circumpolar Front and the changes at the inflow region.

Acknowledgements:

We are grateful to E. Fahrbach, G. Rohardt, K. Nicholls, and C. Pudsey for providing us with data for this work. This study was funded by grant UCSIOPO 10075411 from the National Oceanic and Atmospheric Agency (NOAA). The views expressed herein are those of the authors and do not necessarily reflect the views of NOAA or any of its subagencies.

References:

Comiso, J.C., 2000: Variability and trends in Antarctic surface temperatures from in situ and satellite infared measurements. *J. Climate*, **13**, 1674-1696.

Fahrbach, E., R. Meyer, G. Rohardt, M. Schröder, and R.A. Woodgate, 1998: Gradual warming of the Weddell Sea

Deep and Bottom Water. *Filchner-Ronne Ice Shelf Program*, Report No. **12**, Alfred-Wegener-Institut, Bremerhaven, Germany, 24-34.

Hall, A., and M. Visbeck, 2001: Ocean and sea ice response to the southern hemisphere annular mode: esults from a coupled climate model. *CLIVAR Exchanges*, this issue.

Levitus, S., J.I. Antonov, T.B. Boyer, C. Stephens, 2000, Warming of the World Ocean. *Science*, **287**, 2225-2229.

Robertson, R., M. Visbeck, A.L. Gordon, E. Fahrbach, 2002: Long-term Temperature Trends in the Deep Waters of the Weddell Sea. *Deep Sea Res.*, in revision.

Southern Ocean ALACE Float Temperatures are Warmer than Historic Temperatures

Sarah T. Gille
Scripps Institution of Oceanography and Dept. of Mechanical and Aerospace Engineering, UCSD,
La Jolla, CA, USA
sgille@ucsd.edu

As part of the World Ocean Circulation Experiment (WOCE) in the 1990s, some 300 Autonomous Lagrangian Circulation Explorer (ALACE) floats were deployed south of 30°S. The basic measurements from ALACE floats include mid-depth temperatures and velocities, averaged over 10 to 25 day time intervals (Davis et al., 1992). Around the globe, ALACE velocity data have been used to examine mean and varying flow fields in a variety of regions e.g. Davis et al. (1996), Davis (1998). Since 1990, ALACE floats have collected nearly 13,000 Southern Ocean observations. This is equivalent to roughly two-thirds the total number of mid-depth temperature observations collected by ships in the Southern Ocean since the 1930s, and it thus represents a significant increase to the global database. Some of the more recently deployed floats also recorded vertical temperature profiles, but these have not been included in the present analysis.

This note compares objectively mapped temperature fields at 900 m derived from 1990s ALACE observations with Gouretski et al.'s (1998) objectively mapped temperature fields from shipboard data collected primarily between 1950 and 1990 (although Gouretski et al included 1990s WOCE data when it was available.) Figure 1a (page 20) shows the atlas temperatures at 900 m depth, and Figure 1b shows objectively mapped ALACE temperatures at 900 m depth. In both cases, data were mapped using the algorithm described by Bretherton et al. (1976), assuming a Gaussian covariance function with an isotropic decorrelation scale of 500 km. ALACE floats drifted at depths between 700 and 1100 m depth, and historic vertical temperature gradients were used to extrapolate the ALACE measurements to 900 m. Floats that were entrained into the Antarctic Circumpolar Current (ACC) tended to disperse themselves more uniformly around the Southern Ocean, so geographic coverage in Figure 1b is better within the ACC than it is to the north or south of the current.

ALACE data are on average 0.16°C warmer than atlas data. This apparent warm bias in ALACE data exceeds instrumental errors (<0.02°C, but these should be unbiased), statistical errors (<0.01°C), and formal mapping errors (estimated to be about 0.1°C). Figure 1c shows the temperature difference between objectively mapped ALACE and hydrography. (High error bar regions have been eliminated from this comparison.) Both data sets are noisy, and ice edge effects may bias the temperature difference at the southern end of the domain, since ALACE is unable to return measurements in ice-covered regions. Nonetheless, careful examination of the data suggests that the atlas/ ALACE temperature difference is indicative of a longterm warming trend concentrated in the southern portion of the Southern Ocean. (Gille, 2001a) provides a detailed discussion of the point by point differences, and two other manuscripts examine mapped mean flow (Gille, 2001b) and eddy heat fluxes (Gille, 2001c).

Acknowledgements

Russ Davis generously shared the ALACE data as well as his thoughts on the data analysis. This work has been supported by the US National Science Foundation under grant OCE-9985203/OCE-0049066.

Bretherton, F.P., R.E. Davis, and C.B. Fandry, 1976: A technique for objective analysis and design of oceanographic experiments applied to MODE-73. *Deep Sea Res.*, **23**, 559-582.

Davis, R.E., 1998: Preliminary results from directly measuring middepth circulation in the tropical and South Pacific. *J. Geophys. Res.*, **103**, 24,619-24,639.

Davis, R.E., D.C. Webb, L.A. Regier, and J.Dufour, 1992: The Autonomous Lagrangian Circulation Explorer (ALACE). *J. Atmos. Ocean. Tech.*, **9**, 264-285.

Davis, R.E., P.D. Killworth, and J.R. Blundell, 1996: Comparison of Autonomous Lagrangian Circulation Explorer and fine resolution Antarctic model results in the South Atlantic. *J. Geophys. Res.*, **101**, 855-884.

Gille, S.T., 2001a: Warming of the Southern Ocean since the 1950s. *Science*, submitted.

Gille, S.T., 2001b: Float Observations of the Southern Ocean: Part 1, Estimating Mean Fields, Bottom Velocities, and Topographic Steering. *J. Phys. Oceanogr.*, submitted.

Gille, S.T., 2001c: Float Observations of the Southern Ocean: Part 2, Eddy Fluxes. *J. Phys. Oceanogr.*, submitted.

Gouretski, V.V., and K. Jancke, 1998: A new climatology for the World Ocean, Tech. Rep. WHP SAC Tech. Rep. No. 3, WOCE Report No. 162/98, Southampton, UK.

The CORC/ARCHES Observing System for Weddell Sea Deep and Bottom Water Variability

Martin Visbeck[1], Arnold Gordon[1], Bill Smethie[1], Peter Schlosser[1], John Toole[2], Buce Huber[1], and Gerd Krahmann[1]

[1] **Lamont-Doherty Earth Observatory, Palisades, NY, USA**

[2] **Physical Oceanography Department, Woods Hole Oceanographic Institution, Woods Hole, MA, USA**

visbeck@ldeo.columbia.edu

The abyssal ocean is filled with cold, dense water that obtains it characteristics on the Antarctic continental shelf and by mixing while sinking along the slope. Recent estimates of water mass formation rates using CFC inventories suggest that a total of 8 Sv of Antarctic Bottom Water (AABW) are formed (Orsi et al., 1999). The Weddell Sea Gyre transports about 5 Sv of Deep and Bottom water and thus contributes as much as 50% to the formation of AABW (e.g. Gordon et al., 2001, Fahrbach et al., 1994; 1995; Meredith et al., 2001). Global steady state tracer budgets have yielded much larger southern hemispheric abyssal ventilation rates for waters below 1500m (Broecker et al., 1998; Peacock et al., 1999). However, Orsi et al. (2001) point out that part of the controversy can be explained by separately considering the layer below 2500m. Obviously we need to know more about the mean and equally importantly about the variability of AABW formation rates and processes. In what way is ventilation from the south responding to changes in the surface boundary conditions and might we expect rapid change with global consequences (Broecker et al., 1999).

Much of the global AABW production is feed by the Bottom Waters formed by mixing between warm circumpolar deep water and Shelf Waters around Antarctica. Streams of relatively low salinity Weddell Sea Deep Water with temperature between 0° and -0.7°C are found along the outer rim of the Weddell Sea with varying degree of oxygen saturation (Figure 1) (Gordon et al., 2001). Between 1989 and 1998 Fahrbach et al. (2001) deployed a current meter array east of Joinville Island which allowed for the first glimpse at interannual variability in temperature, thickness and transport of the WSBW formed in the Weddell gyre region. Starting in April 1999 we continued the time series at a down stream location south of the South Orkney Islands with a small mooring array (Figure 2). This location is easier to maintain since the sea ice covered season is shorter on average. Our program has two elements: A repeat hydrographic section across the northwestern Weddell gyre outflow including observations of trace elements (CFCs and Tritium/Helium) and an array of three moorings. Two of them are equipped with nominally two current meter, two TS recorder and several T recorder covering a 500m thick layer above the sea floor. The third mooring consists of a profiling CTD and current meter package which is capable of obtaining a 1000m long profile every other day.

Gordon et al. (2001) give a recent review of the hydrography of the region pointing out the two streams of bottom water found on both sides of the Endurance ridge. Here we present repeat hydrographic sections sections for five occupations and show the evolution of the temperature and CFC 11 distributions (Figure 2). We found warming of the Warm Deep Water (WDW) in the 200-500m layer of warmest temperature (Robertson et al., 2001). However, the temperature changes in the bottom waters are not as simple (Figure 2). In particular the 1999 survey showed a colder bottom water type. Was this just a short term event? Or was the whole seasons bottom water production characterised by a cooler variety? Figure 2 also shows two years of data from mooring M2 just south of the S. Orkney Islands. Indeed, we find cooler bottom waters throughout the season with warmer conditions returning just a few month prior to the February 2000 survey. The southern mooring M3 could not be recovered in 2001 due to an unusually strong ice cover. However, an even more dramatic warming was found during the first year. The cold water during 1999 was seen a year earlier in the AWI array upstream (stars in Figure 2, (Fahrbach et al., 2001)). The profiling mooring M1 saw warming throughout a layer from 200m to 1500m depth during the first season (not shown). In addition to the thermal profiles detailed information about the vertical current structure revealed a strong internal wave signal propagating energy upward into the water column (Figure 3).

The evolution of the theta/CFC relationship in the bottom water is different for the branch north of Endurance Ridge (M2) and the branch south of the ridge (M3) (Figure 4). North of the ridge the theta/CFC relationship is the same for 1997/1998 and 1999/2000 with a distinct increase in CFC concentration between 1998 and 1999. This may be the result of greater ventilation in the shelf regions during the formation of the 1999 and 2000 vintages or may be from the increase atmospheric CFC concentrations over the period when the water formed. South of the Endurance Ridge the CFC concentration with respect to temperature decreases between 1997 and 1998, increases between 1998 and 1999, and decreases between 1999 and 2000. Also the temperature of the bottom water warms between 1999 and 2000. These observations indicate variability in the air-sea interaction processes that form the shelf water before it flows off the shelf or variability in entrainment after it exits the shelf.

We plan and have partial funding to continue the observations for the CLIVAR decade to document changes in the Weddell Sea Bottom Water characteristics. We are interested to expand our array to include moored observa-

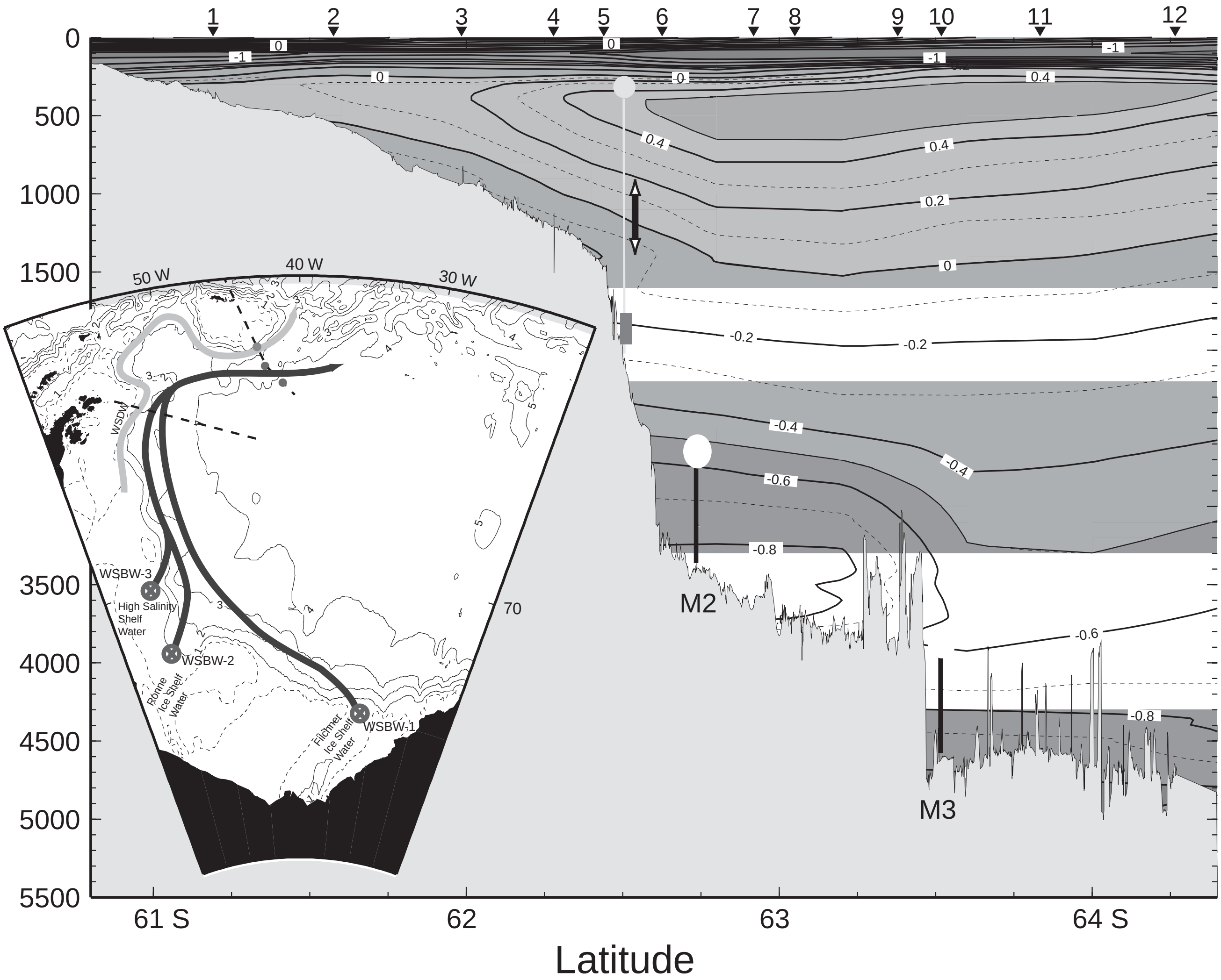


Figure 1. Potential temperature section south of the South Orkney Islands with the location of the mooring array superimposed. Inset: Bathymetric map of the Weddel Sea Gyre indicating the position of several streams of newly formed Weddell Sea Bottom Water (Gordon et al. 2001) and the CORC/ARCHES repeat section and mooring array.

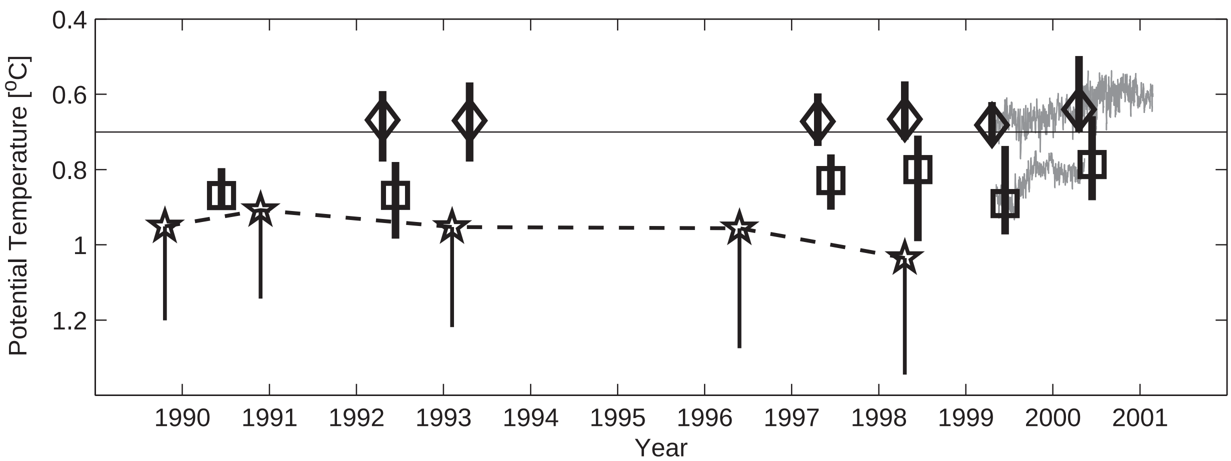


Figure 2. Potential temperature time series as obtained from repeat hydrographic sections in the northwestern Weddell gyre. Diamonds denote the mean temperature between 2600 and 3200 m water depth near 62.5°S 43.5°W (near M2). Squares denote the mean temperature between 4000 and 4600 m water depth near 63.5°S 42.0°W (near M3). The bars covers the total range of observed temperatures. The thin gay lines represent the 40h low pass filtered temperatures averaged over all sensors at mooring M2 and M3 respectively. The stars are the plume mean temperatures from Fahrbach et al. (2001) at their upstream array location. The solid line connects the plume mean with the coldest temperature found during each survey.

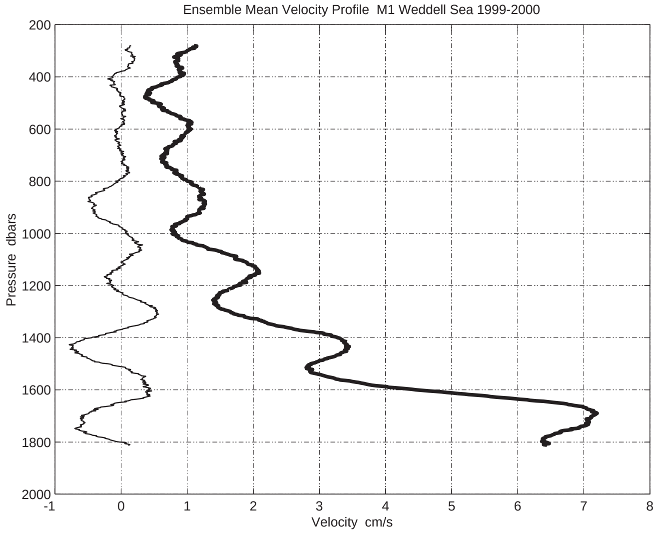


Figure 3. Deployment mean velocity profile from the moored profiler. Thick line denotes along slope velocity and the thin line the across slope velocity component. It is not clear if the high vertical wave number signal is due to lee waves or due to the limited time sampling of a strong tidal signal.

tions of sea-ice thickness and velocity and a moored water sampler for CFCs. The extended time series (Figure 2, 4) can then be compared to variability in the surface fluxes of buoyancy and momentum, sea ice cover and other changes in the environment such as mayor shifts in the ice shelf topography. They also provide bench marks for any model based study of climate variability in the region.

This work is funded by the Office of Global Programs (NOAA) as part of the ARCHES (Abrupt Climate Changes Studies) program. Significant logistical support was received from the Office of Polar Programs (NSF) and the Antarctic Program of Brasil.

References

Broecker, W. S., S. Peacock, S. Walker, R. Weiss, E. Fahrbach, M. Schroder, U. Mikolajewicz, C. Heinze, R. Key, T.-H. Peng, and S. Rubin, 1998: How much deep water is formed in the Southern Ocean? *J. Geophys. Res.*, **103**, 15833-15843.

Broecker, W. S, S. Sutherland, and T.-H. Peng, 1999: A possible 20th-century slowdown of Southern Ocean Deep Water formation. *Science*, **286**, 1132-1135.

Fahrbach, E., G. Rohardt, M. Schroder, and V. Strass, 1994: Transport and structure of the Weddell gyre. *Ann. Geophys.*, **12**, 840-855.

Fahrbach, E., G. Rohardt, N. Scheele, M. Schroder, V. Strass, and A. Wisotzki, 1995: Formation and discharge of deep and bottom water in the northwestern Weddell Sea. *J. Mar. Res.*, **53**, 515-538.

Gordon, A.L., M. Visbeck, and B. Huber, 2001: Export of Weddell Sea Deep and Bottom Water. *J. Geophys. Res.*, **106**, 9005-9017.

Meredith, M.P., A.J. Watson, K.A. Van Scoy, and T.W.N. Haine, 2001: Chlorofluorocarbon-derived formation rates of the deep and bottom waters of the Weddell Sea. *J. Geophys. Res.*, **106**, 2899-2919.

Orsi, A.H., G. C. Johnson, and J.L. Bullister, 1999: Circulation, mixing, and production of Antarctic Bottom Water. *Prog. Oceanogr.*, **43**, 55-109.

Orsi, A., S. Jacobs, A. Gordon, and M. Visbeck, 2001: Cooling and Ventilating the Abyssal Ocean. *Geophys. Res. Lett.*, **28**, 2923-2926.

Peacock, S., M. Visbeck, and W. Broecker, 1999: Deep water formation rates inferred from global tracer distributions: An inverse approach. *Inverse Methods in Global Biogeochemical Cycles*, Kasibhatla et al., (Eds). American Geophysical Union, Washington, DC, USA,185-195.

Robertson, R., M. Visbeck, and A.L. Gordon, 2001: Long-term Warming of Weddell Sea Warm Deep Water. *CLIVAR Exchanges*, this issue.

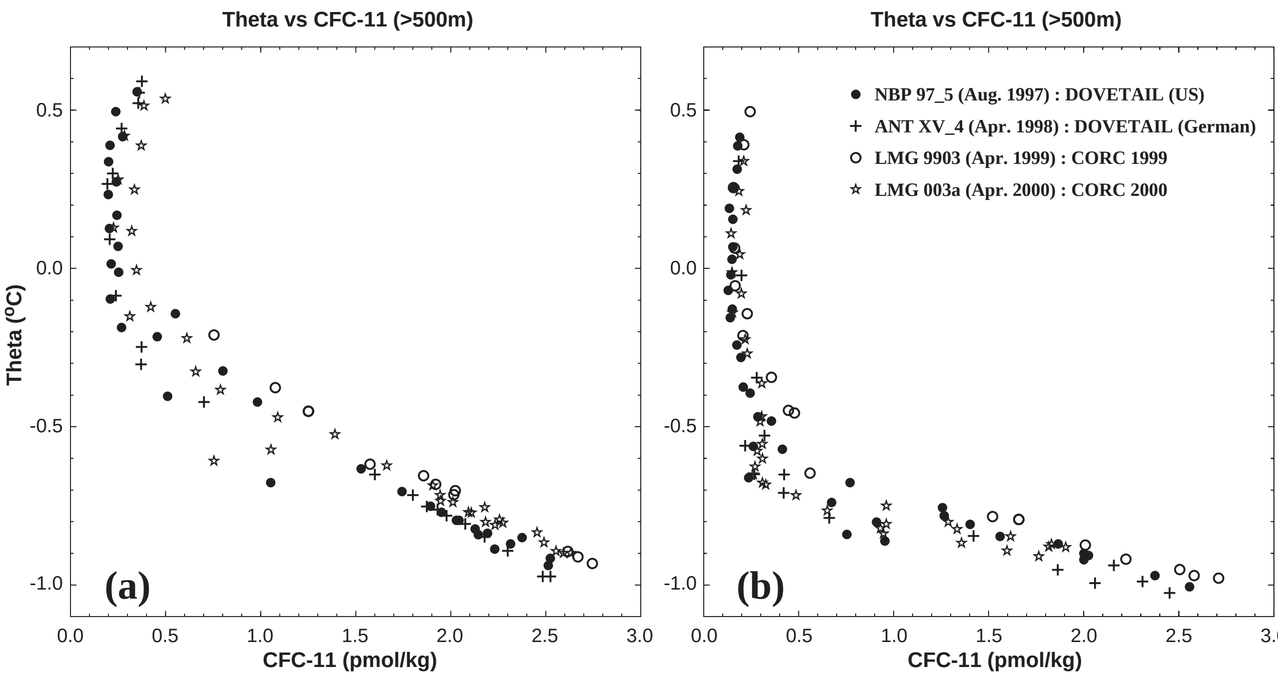


Figure 4. Potential temperature verses CFC-11 for deep and bottom water (a) north and (b) south of Endurance Ridge south of the South Orkney Plateau for four different repeat hydrographic surveys.

Parameterization of deep convection in the Weddell Sea

Ralph Timmermann, Hartmut H. Hellmer, and Aike Beckmann
Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany
rtimmerm@AWI-Bremerhaven.DE

1. Introduction

Deep convection in high latitudes is one of the critical processes for formation of deep and bottom waters. In most OGCMs, convection is supposed to be an instantaneous process applied to the whole grid box - which does not account for the complex small scale nature of this process. In coupled sea ice-ocean models this can lead to an unrealistic representation of sea ice coverage and water mass characteristics and thus to unrealistic water mass distributions and circulation patterns. A subproject of the German CLIVAR/marin aims at an improved understanding and an adequate numerical description of convection in ice covered seas.

2. Modelling approach

A coupled sea ice-ocean model (BRIOS-2; Timmermann et al., 2001a), based on a dynamic-thermodynamic sea ice-model (Hibler, 1979; Lemke et al., 1990) and a modified version of the *s-Coordinate Primitive Equation Model* SPEM (Haidvogel et al., 1991) is run in a circumpolar model domain with a horizontal grid focussed on the Weddell Sea. Experiments are initialized using the *Hydrographic Atlas of the Southern Ocean* (Olbers et al., 1992) and forced with 6-hourly data from the ECMWF-reanalysis of 1985-1993. We present results from a series of experiments using different parameterizations of surface convection.

3. Sensitivity Studies and Results

Comparison of model results with observed ocean temperature and sea ice concentrations (Fig. 1 a, page 20) indicates a high sensitivity of simulated hydrography and sea ice distribution to the parameterization of convection.

3.1 Convective adjustment

Experiments using the *convective adjustment* scheme (Rahmstorf, 1993) feature a large, reoccuring polynya in the central Weddell Sea and a homogenization of the water column down to 3000 m depth (Fig. 1 b) after only three years of integration. Variations of sea ice or coupling parameters within reasonable limits do not solve this problem. Quite similar results (not shown) are obtained using an implicit vertical diffusion scheme with a vertical diffusivity of 1 $m^2 s^{-1}$ in case of static instability.

In both cases, quasi-instantaneous mixing leads to a very large upward heat flux causing rapid melting of sea ice. For each convection cell, a vertical diffusivity of the order of 1 $m^2 s^{-1}$ may be a reasonable approach, but these cells are typically 0.5 to 1 km in diameter (Schott and Leaman, 1991; Send and Käse, 1998) and thus much smaller than model grid boxes in large-scale simulations. Between the individual cells, stratification of the water column is preserved for a while so that the effective, grid-cell scale mixing is considerably smaller.

Reducing the vertical diffusivity for the treatment of static instability to 0.01 $m^2 s^{-1}$ improves model results. Evidence of unrealistic convection is significantly reduced for several years of integration. However, this scheme still does not include any representation of near surface wind mixing. Thus, the freshening of the near surface water column during sea ice melt is restricted to the uppermost layer. Salt accumulates within the winter water layer until - after roughly a decade - intense density-driven deep convection below that level again leads to a vertical homogenization of the water column and to unrealistic polynyas in the central Weddell Sea.

3.2 Pacanowski-Philander (PP)

Using the Pacanowski and Philander (1981) parameterization in its standard formulation does not yield a significant improvement in the seasonally ice covered part of the model domain: Deep convection and a large polynya in the central Weddell Sea are produced even after introducing 0.01 $m^2 s^{-1}$ as an upper limit for vertical diffusivity (Fig. 1 c).

Using PP with a background diffusivity of 10^{-3} $m^2 s^{-1}$ within the upper 100 m of the water column as a crude parameterization of near-surface wind mixing, however, the model has been succesfully applied in studies of mean circulation and interannual variability in the Southern Ocean (Timmermann et al., 2001b; Beckmann and Timmermann, 2001). The drawback of this *ad hoc*-formulation is that summer mixed layers appear too deep and show no interannual variability.

3.3 K-Profile Parameterization (KPP)

The KPP-scheme of Large et al. (1994) explicitly considers the production of turbulent kinetic energy as a function of the surface friction velocity u^*. Profiles of turbulent exchange coefficients are diagnosed from the surface fluxes and profiles of temperature, salinity and velocity. Like in the PP scheme, but unlike the Krauss-Turner type of models, there is no *a priori* assumption of a well-mixed layer. Simulations with this scheme reveal a largely realistic sea ice distribution and hydrography (Fig. 1d). However, the parameterization tends to produce regional, grid-scale anomalies of vertical heat fluxes, leading to the formation of small but unrealistic polynyas directly south of the ice edge.

3.4 PP + Monin-Obukhov length

In the last experiment presented, we combined the Pacanowski and Philander (1981) parameterization (modified by limiting diffusivities to values below 0.01 $m^2 s^{-1}$) with a diagnostic scheme using the Monin-Obukhov length ^*h* (see, e.g., Lemke, 1987) as a function of both the surface friction velocity (u^{*3}) and the velocity difference between ice and ocean. For 0<*z*<-^h, we add a vertical "background" diffusity of 0.01 $m^2 s^{-1}$ to the diffusivities provided by the parameterization of Pacanowski and Philander (1981). Thus, the Monin-Obukhov length is used as a measure for the depth of the wind-mixed layer, while the Pacanowski and Philander (1981) scheme provides an increased vertical mixing (i.e. increased entrainment) for decreasing static stability.

This combined scheme provides an adequate description of vertical mixing in a seasonally ice-covered ocean: Surface mixed layer depth in the central Weddell Sea ranges from 30 to 450 m in the seasonal cycle; convection cells during autumn and winter ventilate the Weddell Sea Deep Water but do not homogenize the water column. Sea ice coverage and water mass properties (Fig. 1 e) are reproduced in close agreement with observations even for integrations over several decades.

In contrast to the central Weddell Sea, parameterization of convection in the cold water column on the southwestern continental shelf appears to be relatively straightforward. High salt input during sea ice formation leads to density-driven convection and to a homogenization of the water column down to the bottom without a large upward heat flux. This process, which forms a major component of the Weddell Sea Bottom Water (Foster und Carmack, 1976) is reasonably represented in all tested parameterizations.

4. Conclusions

We have presented results from a series of numerical experiments with a coupled sea-ice ocean model for the Weddell Sea using different parameterizations of convection. Convection on the continental shelf in the southwestern Weddell Sea is represented quite reasonably in all the models. However, simulations which underestimate the effect of wind mixing feature an accumulation of salt in the winter water layer and subsequent deep convection in the central Weddell Sea. This leads to a homogenization of the water column and to large, unrealistic polynyas.

To achieve a realistic representation of the hydrography and sea ice coverage in climate simulations it appears crucial to explicitly account for the production of turbulent kinetic energy as a function of the surface friction velocity u^*. While the KPP-scheme produces unrealistic small scale polynyas, we obtain thoroughly convincing results with a parameterization which uses (a) the Richardson number dependent scheme of Pacanowski and Philander (1986) with a maximum diffusivity of 0.01 $m^2 s^{-1}$ and (b) applies a constant diffusivity of the same size over a depth given by the Monin-Obukhov length.

Note that this is not only a statement about the right choice of modeling tools: Our results indicate that vertical distribution of fresh water input during the austral summer months plays an important role in shaping the regional hydrography in the central Weddell Sea.

References

Beckmann, A., H. H. Hellmer, and R. Timmermann, 1999: A numerical model of the Weddell Sea: Large-scale circulation and water mass distribution. *J. Geophys. Res.*, **104** (C10), 23375-23391.

Beckmann, A. and R. Timmermann, 2001: Circumpolar influences on the Weddell Sea: Indication of an Antarctic Circumpolar Coastal Wave. *J. Climate*, **14** (17), 3785-3792.

Foster, T.D., and E. C. Carmack, 1977: Antarctic Bottom Water Formation in the Weddell Sea. *Polar Oceans*, M. J. Dunbar, (Ed.), 167-177.

Haidvogel, D.B., J. L. Wilkin, and R. E. Young, 1991: A semi-spectral primitive equation ocean circulation model using vertical sigma and orthogonal curvilinear horizontal coordinates. *J. Comput. Phys.*, **94**, 151-185.

Hibler, W. D., 1979: A dynamic thermodynamic sea ice model. *J. Phys. Oceanogr.*, **9** (4), 815-846.

Large, W.G., J.C. McWilliams, and S.C. Doney, 1994: Oceanic vertical mixing: A review and a model with a nonlocal boundary layer parameterization. *Rev. Geophys.*, **32**, 363-403.

Lemke, P., 1987: A coupled one-dimensional sea ice - ocean model. *J. Geophys. Res.*, **92** (C12), 13164-13172.

Lemke, P., W. B. Owens, and W. D. Hibler, 1990: A coupled sea ice - mixed layer - pycnocline model for the Weddell Sea. *J. Geophys. Res.*, **95** (C6), 9513-9525.

Olbers, D., V. Gouretski, G. Seiss, and J. Schröter, 1992: Hydrographic atlas of the Southern Ocean. Alfred Wegener-Institut für Polar- und Meeresforschung, Bremerhaven, Germany.

Pacanowski, R. C., and S. G. H. Philander, 1981: Parameterization of vertical mixing in numerical models of the tropical oceans. *J. Phys. Oceanogr.*, **11**, 1443-1451.

Rahmstorf, S., 1993: A fast and complete convection scheme for ocean models. *Ocean Modelling*, **101**, 9-11.

Schott, F., and K. D. Leaman, 1991: Observations with moored acoustic Doppler current profilers in the convection regime in the Gulf of Lions. *J. Phys. Oceanogr.*, **21**, 556-572.

Send, U., and R. H. Käse, 1998: Parameterization of processes in deep convection regimes. In: *Ocean Modeling and Parameterization*, E. P. Chassignet and J. Verron, (Eds.), NATO Science Series, **516**, 191-214.

Timmermann, R., A. Beckmann, and H.H. Hellmer, 2001a: Simulation of ice-ocean dynamics in the Weddell Sea. Part I: Model configuration and validation. *J. Geophys. Res.*, in press.

Timmermann, R., H.H. Hellmer, and A. Beckmann, 2001b: Simulation of ice-ocean dynamics in the Weddell Sea. Part II: Interannual variability 1985 - 1993. *J. Geophys. Res.*, in press.

On the Seasonal Variability of the Southern Ocean Meridional Overturning

Hartmut H. Hellmer and Aike Beckmann
Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany
hhellmer@awi-bremerhaven.de

1. Introduction

Recent numerical model results focussed on the Southern Ocean meridional overturning (Hellmer and Beckmann, 2001) support the observationally derived formation rate of dense Antarctic Bottom Water (AABW) of the order of 10 Sv, mainly confined to the Atlantic sector of the Southern Ocean (Orsi et al., 1999). The numerically derived rate doubles if a slightly lighter component of the Indian-Pacific (IP) sector is included, supporting the hypothesis that the sources in the southern and northern hemisphere contribute equally to the ventilation of the world ocean abyss (Broecker et al., 1998). Most of the estimates based on observations, however, repesent long-term means which do not reflect the seasonal and interannual variability inherent to the bottom water formation process (e.g., Fahrbach et al. (2001)).

In the framework of BRIOS (Bremerhaven Regional Ice Ocean Simulations) we run a model with a horizontal resolution of 20-100 km in the Weddell Sea sector, embedded in a coarser circumpolar Southern Ocean, and a vertical resolution of 24 terrain-following levels (Beckmann et al., 1999). The model domain extends from 82°S, including the major ice shelf cavities, to 50°S where temperature and salinity fields are strongly restored to the climatology of Olbers et al. (1992). BRIOS is forced with averaged monthly mean surface fluxes of momentum and freshwater, all resulting from a stand-alone sea ice model (after Lemke et al. (1990), which is driven with 6-hourly ECMWF reanalysis data of the period 1985-93.

Our analysis concentrates on the zonally integrated overturning transport streamfunction plotted as a function of latitude and density (σ_2). This presentation is preferred to latitude and depth, because most of the water masses are modified at the same latitude and within the same depth range as they move with the southern branches of the subpolar gyres. The density was chosen relative to 2000 meters to present an isopycnal range which coincides with Orsi et al.'s (1999) density based definition of AABW formed south of the Antarctic Circumpolar Current (ACC), $\sigma_2 \geq 37.16$ kg m^{-3}. In the following, we focus on the seasonal variability of the meridional overturing.

2. Results and Discussion

Spatial and temporal separation of the Southern Ocean meridional overturning into Atlantic and Indian-Pacific sectors south of 66°S and into summer (DJF) and winter (JAS) months, respectively, shows that the densest water is found year-round on the the Ross Sea continental shelf

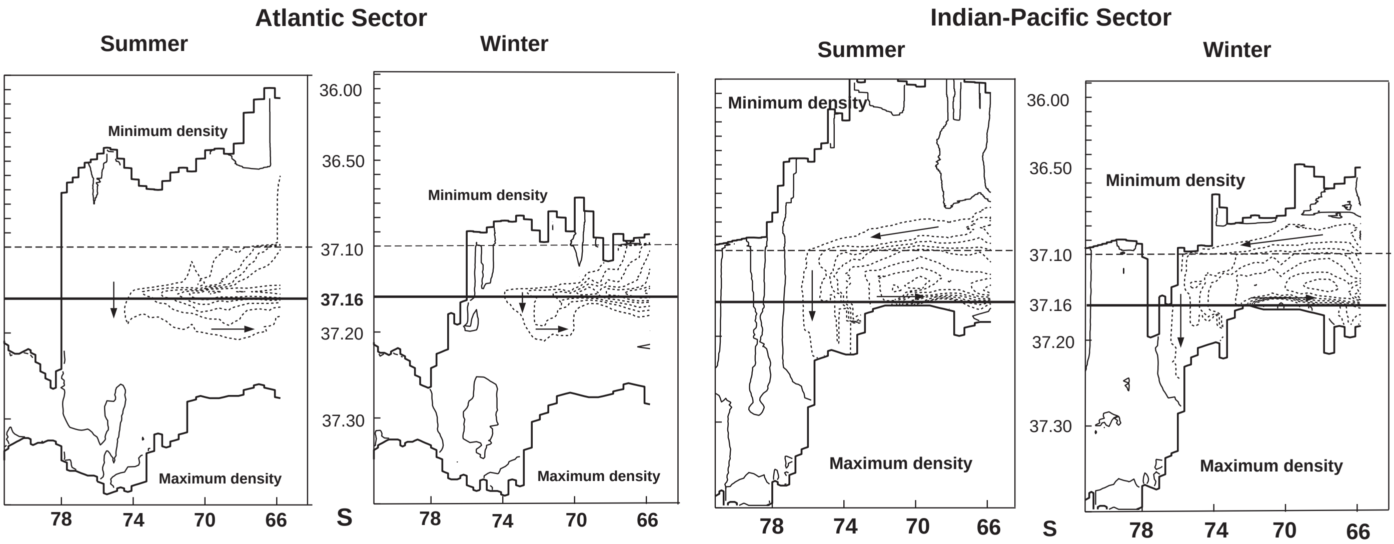


Figure 1 Summer and winter overturning transport streamfunction for the Atlantic (upper) and Indian-Pacific (lower) sectors of the Southern Ocean south of 65°S as a function of latitude and density (σ_2). Since a sensible transport streamfunction calculation requires a coast-to-coast integration, the Atlantic sector extends from Enderby Land (50°E) to Antarctic Peninsula (60°W) while the Indian-Pacific sector encompasses the remaining Southern Ocean. This results in an Indian-Pacific coastline two-times longer than the Atlantic coast. For densities $\sigma_2 \geq 37.1$ kg m^{-3} (dashed line), the vertical scale is stretched to better present the narrow dense water transports. The thick line marks the density $\sigma_2 = 37.16$ kg m^{-3} defined as upper bound for dense AABW formed south of the ACC (Orsi et al.,1999). Dashed contours indicate counter-clockwise, solid contours clockwise circulations (see arrows). Bold solid lines represent the minimum (upper) and maximum (lower) density value for each latitudinal band. Contour spacing is 2 10^6 m^{3}s^{-1} starting from ±1 10^6 m^{3}s^{-1}.

(Fig. 1). However, this dense water does not reach the deep basins as the admixture of lighter bottom water between 72°S and 68°S seems to erase the high-density signal of the Ross Sea outflow. Instead, the densest water crossing 66°S year-round is formed at the southern Weddell Sea continental slope in winter propagating northward as the year progresses. Dense water formation occurs close to the edges of Filchner-Ronne (Atlantic) (Timmermann et al., 2001) and Ross (IP) ice shelves (Jacobs and Giulivi, 1998), and is related to ocean surface processes as indicated by the steep increase of minimum (surface) densities north of ~ 78°S (Fig. 1). The lack of a seasonal signal in the distribution of maximum (bottom) densities indicates that the reservoirs of dense shelf water are not drained totally before the onset of new brine release during sea ice formation.

Dense AABW ($\sigma_2 \geq 37.16$ kg m^{-3}) is formed mainly in the Atlantic sector at an annual mean rate of ~10 Sv (Hellmer and Beckmann, 2001). This is twice the rate of dense bottom water formation in the IP sector which occurs north of 68°S (Fig. 1) and corresponds to the continental slopes off Adélie Land (Rintoul, 1998) and Prydz Bay (Jacobs and Georgi (1977); Schodlok et al., 2001). A slightly lighter AABW ($\sigma_2 \geq 37.15$ kg m^{-3}) is mainly formed in the IP sector also at an annual mean rate of ~10 Sv (Hellmer and Beckmann, 2001).

In contrast to the formation of light AABW, the dense AABW formation is subject to seasonal variability which ranges from 7 Sv (3 Sv) in summer to 11 Sv (5 Sv) in winter for the Atlantic (IP) sectors. This is more than inferred from the circumpolar tracer budget (Orsi et al., 1999). However, the IP sector produces ~30% of the Southern Ocean's dense AABW in both seasons which agrees well with the 72% estimated for the Weddell Sea/Atlantic sector (Carmack, 1977). In addition, lighter bottom water might form at the southern Weddell Sea continental shelf since the mid-80's due to the disturbance of the shelf regime by stranded icebergs (Grosfeld et al., 2001) which is not covered by this model. In summary, we emphasize that our model provides the transport of bottom waters without considering their degree of ventilation which could post the modeled ranges as an upper estimate.

References

Beckmann, A., H.H. Hellmer, and R. Timmermann, 1999: A numerical model of the Weddell Sea: Large scale circulation and water mass distribution. *J. Geophys. Res.*, **104**, 23375-23391.

Broecker, W.S., S.L. Peacock, S. Walker, R. Weiss, E. Fahrbach, M. Schröder, U. Mikolajewicz, C. Heinze, R. Key, T.-H. Peng, and S. Rubin, 1998: How much deep water is formed in the Southern Ocean. *J. Geophys. Res.*, **103**, 15833-15843.

Carmack, E. C., 1977: Water characteristics of the Southern Ocean south of the Polar Front. In: *A Voyage of Discovery, George Deacon 70th Anniversary Volume,* M.V. Angel, (Ed.), Suppl. to *Deep-Sea Res*., Pergamon Press, Oxford, UK, 15-41.

Fahrbach, E., S. Harms, G. Rohardt, M. Schröder, and R. Woodgate, 2001: Flow of bottom water in the northwestern Weddell Sea. *J. Geophys. Res.*, **106**, 2761-2778.

Grosfeld, K., M. Schröder, E. Fahrbach, R. Gerdes, and A. Mackensen, 2001: How iceberg calving and grounding change the circulation and hydrography in the Filchner Ice Shelf/ocean system. *J. Geophys. Res.*, **106**, 9039-9056.

Hellmer, H.H., and A. Beckmann, 2001: The Southern Ocean: A ventilation contributor with multiple sources. *Geophys. Res. Lett*., **28**, 2927-2930.

Hoppema, M., O. Klatt, W. Roether, E. Fahrbach, K. Bulsiewicz, C. Rodehacke, and G. Rohardt, 2001: Prominent renewal of Weddell Sea Deep Water from a remote source. *J. Marine Res.*, **59**, 257-279.

Jacobs, S.S., and D.T. Georgi, 1977: Observations in the southwest Indian/Antarctic ocean. *A Voyage of Discovery, George Deacon 70th Anniversary Volume,* M.V. Angel, (Ed.), Suppl. to *Deep-Sea Res*., Pergamon Press, Oxford, UK, **24**, 43-89.

Jacobs, S.S., and C.F. Giulivi, 1998: Interannual ocean and sea ice variability in the Ross Sea. In: *Ocean, Ice, and Atmosphere,* S.S. Jacobs and R.F. Weiss, (Eds.). *Antarctic Res. Ser.*, **75**, AGU, Washington, DC, USA, 83-99.

Lemke, P., W.B. Owens, and W.D. Hibler, 1990: A coupled sea ice-mixed layer-pycnocline model for the Weddell Sea. *J. Geophys. Res.*, **95**, 9513-9525.

Olbers, D. J., V. Gouretski, G. Seiß, and J. Schröter, 1992: *Hydrographic Atlas of the Southern Ocean.* Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany, 82pp.

Orsi, A.H., G.C. Johnson, and J.L. Bullister, 1999: Circulation, mixing, and production of Antarctic Bottom Water. *Prog. Oceanogr.*, **43**, 55-109.

Rintoul, S.R., 1998: On the origin and influence of Adélie Land bottom water. In: *Ocean, Ice, and Atmosphere,* S.S. Jacobs and R.F. Weiss, (Eds.). *Antarctic Res. Ser.*, **75**, AGU, Washington DC, USA, 151-171.

Schodlok, M.P., C.B. Rodehacke, H.H. Hellmer, and A. Beckmann, 2001: On the origin of the deep CFC maximum in the eastern Weddell Sea – numerical model results. *Geophys. Res. Lett*., **28**, 2859-2862.

Timmermann, R., H.H. Hellmer, and A. Beckmann, 2001: Simulations of ice–ocean dynamics in the Weddell Sea. PartII: Interannual variability 1985–1993. *J. Geophys. Res.*, in press.

International Antarctic Zone (IAnZone): A SCOR-Affiliated Programme

Robin D. Muench[1] and Hartmut Hellmer[2]
[1]**Earth & Space Research, Seattle, WA, USA**
rmuench@esr.org
[2]**Alfred-Wegener-Institut for Polar and Marine Research, Bremerhaven, Germany**

Introduction

IAnZone originated in the early 1990s as a sequence of informal biennial meetings of Southern Ocean researchers, primarily physical oceanographers, who were interested in understanding the Southern Ocean and its role in climate change. This interest focussed on the Antarctic Zone, which extends from the Antarctic Circumpolar Current to the coastline of Antarctica and is the primary southern hemisphere region of deep water mass formation. IAnZone was accorded status as a SCOR-Affiliated Program in early 1997. Its overarching goal is to advance our understanding of climate relevant processes, their seasonal cycles and interannual and decadal variability, within the Antarctic Zone. It serves as a planning and organizational forum for coordinated, international studies addressing these issues. Additional information can be found at http://www.ldeo.columbia.edu/physocean/ianzone.

Recent and Current Activities

The International Deep Ocean Ventilation Through Antarctic Intermediate Layers (DOVETAIL) Program.

DOVETAIL is the third and most recent in a sequence of research programs organized under IAnZone over the past decade, and is an integrated field and modeling study that addresses the transport of newly formed deep waters from the Weddell Sea north through the South Scotia Ridge region, from whence it contributes to ventilation of the global ocean. One source region for these waters, the western Weddell Sea, has been investigated in detail as part of the first field experiment coordinated by IAnZone: the winter 1992 drifting sea ice-based Ice Station Weddell (ISW-1) experiment. DOVETAIL participants have obtained field data annually, either from shipboard, from moored instruments, or both, since the program start in 1996. Numerical modeling efforts are underway and are being integrated with the field results. Ongoing activities include a multi-year shipboard program as part of a Brazilian/German cooperative effort under the auspices of PROANTAR (Programa Antartico Brasileiro), a multi-year US moored instrument program to assess interannual variability in the northern Weddell Sea, and a number of modeling efforts. A collection of DOVETAIL papers is presently in the final stages of review for 2002 publication in a special issue of Deep-Sea Research II.

DOVETAIL has evolved from a focussed study of physical processes in the South Scotia Ridge region into a long-term study of interannual variability. The possibility now exists that we may obtain an unprecedented decade-long time series documenting interannual variability in the region and, in so doing, gain valuable new insight into the interactions among the Southern Ocean and global climate. Additional information can be found at http://www.esr.org/dovetail.

Studies of the Antarctic Margins; Water Mass Conditioning and Escape of Modified Waters From the Shelf

A recognition of the importance of shelf and slope processes to the transport of shelf conditioned waters to the deep basin has led, through discussion at both the 1997 and 1999 IAnZone biennial meetings, to a fourth IAnZone effort. This effort seeks to define the roles of the Antarctic shelf break front and continental slope morphology in the exchanges of mass, heat and freshwater between the shelf and oceanic regimes, in particular, those leading to deep-reaching outflows of shelf water mixtures. The AnSlope (Antarctic Slope) study would focus on these issues through an integrated US field and German modeling effort in the Ross Sea, where the shelf-slope region remains relatively accessible throughout the year and where dense water is known to form. It includes the Italian CLIMA (Climatic Long-Term Interaction for the Mass Balance in Antarctica) program, which has been addressing some of these issues for several years.

Ocean Mixing, Convection and Equation of State Issues

In the Weddell Sea, deep ocean convection is believed to occur under special conditions, as in the mid-seventies during the large Weddell polynya event near Maud Rise. This issue is addressed by large-scale surveys and small-scale process studies. During austral winter 1994 a field effort studied ocean heat fluxes in the vicinity of Maud Rise, in the eastern Weddell Sea, under the auspices of the ANZFLUX (Antarctic Zone Fluxes) experiment. This was the second of three programs that have come to fruition, to date, under the IAnZone umbrella. The ANZFLUX program greatly increased our understanding of turbulence and mixing in a weakly stratified ocean and contributed to our knowledge of physical conditions in the eastern Weddell Sea. The results also raised significant issues concerning small-scale processes, such as cabelling and thermobaricity, that involve the equation of state for seawater. The German WECCON (Weddell Sea Convection Control) project has addressed long-period variability by monitoring sea ice and ocean stratification in that region since 1996 using moored instruments and shipboard hydrographic observations. The German BRIOS (Bremerhaven Regional Ice Ocean Simulations) coupled ice-ocean modeling program provides a large-scale modeling capability to complement these efforts.

IAnZone and SO CLIVAR

The Antarctic Zone comprises the southernmost region of interest to the SO CLIVAR program, other regions being that of the Antarctic Circumpolar Current and associated subduction, and areas farther north where Sub-Antarctic Mode Water is formed. The Antarctic Zone is the primary site for surface formation of dense water and for the subsequent downslope entrainment flows that are believed to drive the southern meridional oceanic convection cell. Processes in this zone must exert a strong control over the ultimate supply of Antarctic Deep and Bottom waters to the global ocean. The ongoing IAnZone coordination of research addressing these processes can make a significant contribution to the SO CLIVAR planning effort, and plans are underway to coordinate planned IAnZone and SO CLIVAR activities.

PIRATA-8 Meeting Report

Jacques Servain[1] and João Lorenzzetti[2]
[1]IRD, Brest, France
Jacques.Servain@ird.fr
[2]INPE, San Jose dos Campos, Brazil

The 8th meeting of PIRATA programme (PIRATA-8) took place at the University of Paris 6, Paris, 29–31 August, 2001. It was sponsored by IRD, IOC/GOOS, Météo-France and Ifremer. Approximately 35 people from 8 different countries attended the meeting. PIRATA-8 was scheduled back to back with the CLIVAR Tropical Atlantic Variability (CLIVAR-TAV) workshop (see the following article for a summary).

The PIRATA-8 meeting firstly dedicated to the national and international status of the backbone array of the programme, the last PIRATA events from PIRATA-7 (Natal, April 2000), and the perspectives for the next years ("consolidation" phase). Despite the good quality of the data, there was some concern about the average data return. Predominantly caused by vandalism (possibly by tuna fishing), the PIRATA data return during the pilot phase (1997-2001) has been of the order of 70 % , as compared to 85 % for the TAO/TRITON array in the Pacific. The two sites in the eastern basin at 2°N-10°W and 2°S-10°W were decommissioned (Fig. 1) to limit the problem. That required a change in the allocation of the functions of maintenance of the now ten ATLAS sites between Brazil and France. Henceforth, and during the entire phase of consolidation of the program (2001-2005), Brazil will maintain the 5 ATLAS moorings in the western part of the basin, and France the 5 other ATLAS moorings in the central and eastern parts. Discussions were also carried out about present, scheduled and proposed complementary instrumentation (as well as observations of sea level, met, oceanic currents, ...). First scientific papers using the PIRATA data are now appearing in the literature and some of them were presented during the subsequent CLIVAR-TAV workshop. In addition, the use of the PIRATA data in the models (through data assimilation) was discussed.

It was stressed that a more detailed coordination between the PIRATA project with the CLIVAR Atlantic Panel (including receiving their advice and feedback) is needed to integrate the PIRATA observations in the tropical Atlantic with other observing systems (including the Argo floats, XBT ship lines (high and low density), other moored buoys, surface drifters and satellite observations).

In the following, proposals of PIRATA extensions from the original array (Fig. 1) were presented and discussed. Some surface (equipped with meteorological instruments) and subsurface moorings (with current meters), different from ATLAS moorings, have already been deployed by Germany and the US in the NW of the PIRATA array. They can then be considered as relevant for the PIRATA objectives since they will contribute to improve our knowledge of the air-sea fluxes and of the seasonal variability in the meridional overturning circulation and its effect on interhemispheric water exchange.

Three proposals of PIRATA extensions using ATLAS moorings are presently under discussion (Fig. 1). They are all relevant for the observation of key oceanic variables and their variability and for climatic forecast of the surrounding countries. A first extension, PIRATA-SWE, led by Brazil, proposes to extend the PIRATA array to the SW, i.e. off the Brazilian coast, south of the equator. The scientific objectives are

(i) to monitor the divergence of the south Atlantic shallow waters which is a key in the interhemispheric water exchange by feeding several currents going north (NBC), south (BC) and east (EUC) through the complex subtropic cell (STC) system, and
(ii) to survey the atmospheric convergence circulation (SACZ) and associated precipitation over Eastern Nordeste, through its link to the SST of this oceanic region.

The two other extensions using ATLAS systems are both located along the African coast, in regions with seasonal upwelling, where fisheries are very dependent of strong climate variations.

PIRATA-SEE, led by South Africa, proposes to extend the PIRATA array to the SE, i.e. off the Angola coast, in the region of the Angola dome and the Benguela-Angola front, which is the "favourite" domain of the "Atlantic El Niño" events.

PIRATA-NEE, led by Morocco, proposes to extend the PIRATA array to the NE, i.e. off the Mauritania-Senegal-Guinea coast, in the region of the Guinea dome and the Canary front.

The regions of these two last extensions are also recognised of having an important impact over the climate of

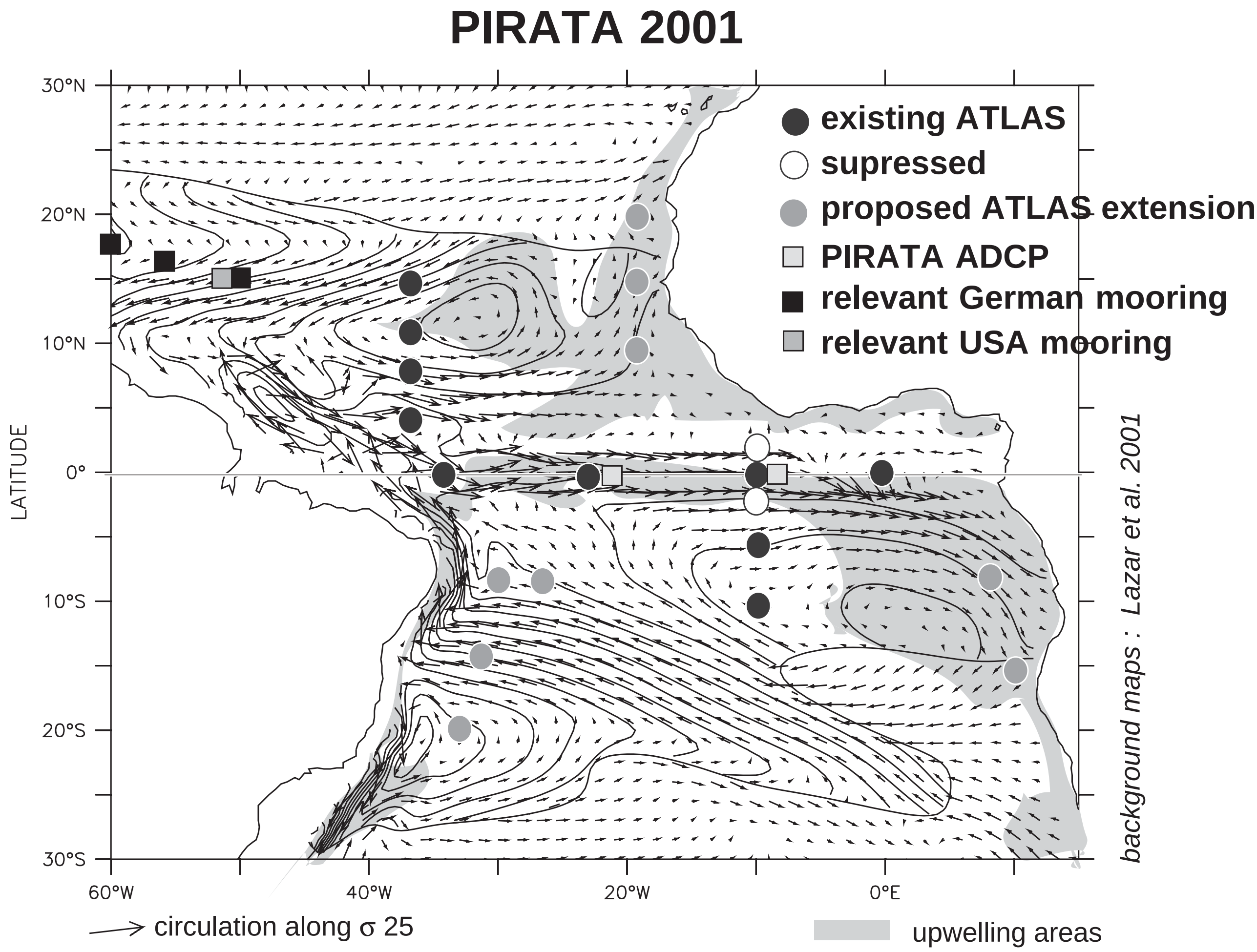


Fig. 1: The PIRATA array and possible future extensions

the African surrounding countries. Scientific and implementation drafts for these three extension projects are being prepared. They will be submitted in the next months to the PIRATA Scientific Steering Committee and the CLIVAR-SSG for endorsement. Funding, ship time, material, and human facilities could come from surrounding countries (Brazil, South Africa, Morocco), with additional contributions from other national partners (France, USA, Germany, etc.), and international parties (WB, GEF, EC, etc.).

A final discussion was raised about the national commitments for maintaining the PIRATA backbone array and the perspective for the next years. Especially for Brazil and France, that provide the whole shiptime for the entire programme, there are major concerns to fulfil the present and future commitments. Due to drastic constraints in the ship availability for PIRATA versus other national priorities, it is for instance not possible, that to monitor the PIRATA backbone twice a year, as it is done for the TAO/TRITON array in the Pacific. As a consequence, this is recognized as one of the main reasons for a lower data return rate of the PIRATA vs. TAO/TRITON. It is not possible that such a situation remains the same after the end of the consolidation phase of PIRATA. Furthermore, because at this time (around 2005), it is expected that the other pilot PIRATA extensions will join the PIRATA backbone. The most adequate solution would be that the full PIRATA array (about 20 ATLAS systems, more other moorings and instrumentation) will be managed in an unique Centre, which must be located close to the centre of gravity in the tropical Atlantic. A present proposal from Brazil is to create and organize such a Centre in Natal, in the 'Nordeste' of Brazil, by enhancing the facilities of the present INPE Centre, which already serves for PIRATA-Brazil. The idea is that this new Centre could become a collaborative International Climatic Centre for the oceanic observation of the whole tropical Atlantic. France, through IRD, is committed to play an active role in that project. The USA, through NOAA, is also interested by the idea. Finally, to fully monitor the whole tropical Atlantic (and perhaps the South Atlantic) it is being proposed that a dedicated Research Vessel (R/V) be used for (most of) all the operational oceanography experiments which will be done in the region from 2005. The concept of a dedicated R/V could also be conceived, with the ship construction and operation management done according to an international agreement in the same spirit of the Natal Centre.

At present the members of the PIRATA-SSC are: Bernard Bourles (IRD, France), Tony Busalacchi (Univ. Maryland, USA), João Lorenzzetti (INPE, Brazil) Co-Chair, Mike McPhaden (NOAA/PMEL, USA), Antonio D. Moura

(IRI, Brazil), Serge Planton (Météo-France, France), Jacques Servain (IRD, France) Chair, Ilana Wainer (Univ. São Paulo, Brazil), and Shang-Ping Xie (Univ. Hawaii, USA).

A Memorandum of Understanding (MoU) giving details of an agreement to maintain the PIRATA backbone and stating the conditions for new projects of extension during the phase of consolidation (2001-2005) was officially signed at the end of PIRATA-8 meeting between representatives of the main PIRATA partners: INPE for Brazil, IRD and Météo-France for France, and NOAA/OGP for USA.

CLIVAR Workshop on Tropical Atlantic Variability

Silvia L. Garzoli
NOAA/AOML/PHOD, Miami, FL, USA
silvia.garzoli@noaa.gov

The CLIVAR workshop on Tropical Atlantic Variability (TAV) took place at UNESCO, Paris, September 3- 6, 2001. The workshop originated as a follow up of the COSTA meeting held in Miami during May 1999 (http://www.aoml.noaa.gov/phod/COSTA/).

The main objectives of the Paris workshop were to review advances in science since the last workshop, and to coordinate international efforts toward a sustained observing system in support of understanding, modeling and predicting TAV. The workshop was sponsored by the International CLIVAR Project Office. At its conclusion detailed recommendations were presented to the CLIVAR Atlantic Implementation Panel, on an implementation plan for tropical Atlantic (TA) research. The workshop was attended by 120 scientists from 10 different countries.

This article briefly summarizes the workshop. A complete can be found at:
http://www.clivar.org/organization/atlantic/TAV/.

During the first three days of the workshop, keynote presentations were made during the morning, and interactive poster sessions were held in the afternoon. At the end of the day, the attendants met in a plenary session, in which rapporteurs lead a discussion of the oral and poster presentations that took place during that day.

The first day was dedicated to a discussion of the role of local air-sea interaction in TAV (presented by S. P. Xie), the coupling between TAV and other regions (R. Sutton), and the local air-sea flux exchanges with the ocean (S. Planton).

On the second day, the first part of the morning session was dedicated to a discussion of the influence of the tropical Atlantic atmosphere/ocean circulation on climate variability over the Americas (J. Paegle and P. Nobre), and the interactions between tropical Atlantic and African climate (C. Thorncroft). The second part of the morning was dedicated to the interaction between TAV and the large-scale atmosphere/ocean circulation. A discussion of its relation to the North Atlantic oscillation (NAO) and the meridional overturning circulation (MOC), (by B. Blake), was followed by a discussion on the shallow overturning cells and cross-gyre exchange in the region (by W. Johns), and by a presentation of potential links to decadal variability, secular variability and climate change (R. Fine).

The third day was dedicated to the observing system. A summary of the present observing system in the tropical Atlantic (by J. Servain) was followed by a discussion of the role of GODAE in the future observing and prediction systems (N. Smith). Finally, representatives of NCEP and ECMWF (P. Arkin, and T. Stockdale) discussed observational needs for prediction, what we have learned from model assimilation of data from the current observing system, and whether the existing data streams satisfy the assimilation and prediction needs.

Following the oral and poster presentations, three working groups (WG) were created:

- WG1: Coupled Ocean Atmospheric Systems
- WG2: Climate Impact and Predictability
- WG3: Links between the upper Tropical Atlantic, the Deeper Ocean and the other Basins

The charge to the Working Groups was to summarize the science and the observational needs based on the workshop discussions, and to make recommendations towards an implementation plan. The following is a summary of these recommendations.

Report from WG1: Coupled Ocean-Atmospheric Systems.

Recent analyses and modeling studies concerning TAV indicate several critical issues, such as the emerging consensus on the existence of a local ocean-atmosphere coupling in the equatorial region and the importance of external forcing (i.e., by atmospheric or oceanic teleconnections) in affecting regional variability. Also of significance is the fact that TAV displays a large range of variability from interannual to decadal scales and that these time scales seem to be interdependent. Moreover, the specific meridional configuration of the tropical Atlantic basin, bordered by two large landmasses with complex boundaries (South America and Africa), confer a strong predominance to the seasonal cycle, which consequently interacts with lower frequency variability. The variability in the tropical Atlantic thus remains difficult to understand, model, and predict. With this in mind, it is proposed that progress in understanding and predicting TAV can be achieved by emphasizing two key scientific themes:

1. The regional three-way coupling between atmosphere, ocean and land-surface interactions.
2. The regional links between the seasonal mean evolution of the background state and its variation on all time scales.

These should be emphasized in both, analysis and modeling studies. In the modeling approach to these topics, perturbation experiments are recommended to clarify the role of the different interactions between atmosphere, ocean, and land-surface patterns. Perturbation experiments are also needed to clarify the slower oceanic teleconnections between the tropical region and the mid-latitudes. In addition, regional coupled modeling studies are recommended to explore the local effects of atmospheric teleconnections from other regions (e.g., the tropical Pacific and North and South Atlantic) and how they interact with local processes. It is also recommended to conduct studies that will help understand and correct the discrepancies in present coupled model simulations of the local amplitude and phase of the annual cycle in the atmosphere, land, and ocean. Continued modeling and analysis towards an improved understanding of the processes ,which control the SST variability, is also recommended.

Report from WG 2: Climate Impacts and Prediction

The goal of WG2 was to facilitate communication between ongoing prediction efforts related to the tropical Atlantic and the science and ocean observing community in order to improve prediction. Such communication will help identify needs in the areas of ocean observations, development of models and data assimilation methodologies, and the identification and design of crucial process studies. In addition, the group aimed to facilitate through this communication the fertilization of ideas leading to improve forecasting methods and forecast applications. In its discussions, WG2 identified three areas that need attention: data gaps, climate impacts and predictability.

There are obvious gaps in surface ocean data due to the nature of VOS tracks and the location of permanent platforms. Lagrangian tracers also display patterns of convergence that leave some areas unsampled. These gaps result in the loss of necessary information not only where climate variability is concerned but also, in some regions, in fundamental aspects of the mean seasonal cycle. Other less obvious gaps are linked to failures to constrain regional data assimilation products with observations (these are partially related to model discrepancies, see above discussion of WG1). It is recommended that these issues be continually monitored with help from operational centers and the observational programs of GCOS and GOOS.

On the problem of impacts, it is clear that while much is known on the links between fluctuations of climate variables important to society and tropical Atlantic sea surface temperature (SST), much more needs to be done in terms of identifying the actual societal effects of this variability, the composition of the end user community, and the implied priorities. It is therefore recommended that continued emphasis be given to the need for impact related research (if possible end-to-end) and that increased attention be given to the variability and the southern tropical Atlantic (STA) region.

There is need to better define the predictability limits of TAV and related phenomena through diagnostics of data and model experiments. This also requires an improved definition of model (numerical and statistical) limitations.

Finally, this working group addressed the link to operational centers and Climate Outlook Fora. It was recommended to plan an international workshop meant to facilitate discussion between prediction centers/climate fora and the research community. Such workshop should be preceded by establishing contact with the climate centers involved in operational prediction for the tropical Atlantic and the identification of key topics and issues for discussion.

Report from WG 3: Links between the upper Tropical Atlantic, the deeper ocean and the other basins

The overarching question discussed in WG3 was the role of four-dimension advection in affecting tropical Atlantic (SST), and specifically, the role of subsurface to deep circulation in determining TAV, the inter-tropical convengerce zone (ITCZ) position and (SST).

Sub-tropical Cells (STCs) and the role of the meridional overturning circulation were largely discussed. In particular, the need to understand the mean STCs and their variability, the mean pathways relating subduction areas with upwelling, and the relative roles of the interior meridional exchange versus western boundary undercurrents was emphasized. Also discussed was the relative role of equatorial and off-equatorial upwelling, the transformation of thermocline waters into surface waters, and the role of North Brazil Current (NBC) rings in inter-hemispheric water mass exchange. On the topic of STC variability, the relation between the North Brazil Undercurrent, equatorial upwelling, and SST was discussed as well as the role of planetary waves.

On the relation between TAV and larger scale circulation, the discussion was centered on the need to determine mean cross-equatorial exchanges, water mass transformations, and their variability. Also discussed, in general terms, was the effect of decadal and inter-decadal variability of Meridional Overturning Circulation (MOC) structure on the North Atlantic Deepwater (NADW), and on the warm water return flow through different South Atlantic source waters. The need to understand the role of

MOC/NADW pulses in TAV at different time scales was addressed as well as how TAV affects NAO and MOC.

On implementation issues, process studies are proposed for three of the science objectives: STCs, MOC transformation study, and NADW pulse effects on the TAV. Of the three, the STC process study is judged the one most ready for implementation because of the work done during the 2000 Venice CLIVAR Workshop on the STC (for more information see: http://www.clivar.ucar.edu/organization/atlantic/STC/STC_rep0801.pdf).

It is therefore recommended that an Implementation Workshop be organized for a basin wide STC international process study. Recommendations are also made on sustained observations. These include MOC transport time series and STC transports. It was also recommended to improve the VOS fleet by adding the capability of measuring currents (ADCP) and thermosalinograph for tracks crossing the tropical Atlantic.

The Workshop was co-chaired by S. Garzoli (NOAA/AOML, US) and J. Servain (IRD/FR). C. Andrie (LODYC,FR) was the local organizer. Members of the organizing committee were: E. Campos (USP/BR), J. Carton (UMd/US), P. Chang (TAMU, US), P. Delecluse (LODYC/CNRS/FR), J. Hurrell (NCAR/US), M. McPhaden (NOAA/US), P. Nobre (INPE/CPTEC/BR), and S. Planton (Meteo/FR). CLIVAR Atlantic Implementation Panel Representatives to the committee: Y. Kushnir (LDEO/US), and R. Sutton (Reading/UK).

CLIVAR Exchanges Call for contributions

We would like to invite the CLIVAR community to submit papers to CLIVAR Exchanges for the next issue.

The overarching theme of the next one will be on **Tropical-Extratropical Interactions**, e.g., ENSO teleconnnections, monsoon interactions and influences, links between extratropical phenomena and the Tropics, etc.

In particular, we would like to encourage scientists in East Asia to contribute since the next CLIVAR SSG meeting will be in China in May 2002.

The deadline for this issue is February 1, 2002.

Guidelines for the submission of papers for CLIVAR Exchanges can be found under: http://www.clivar.org/publications/exchanges/guidel.htm

CLIVAR Calendar

2002	Meeting	Location	Attendance
January 13-17	82nd Annual American Meteorological Society (AMS) Meeting	Orlando, USA	Open
January 29 - February 2	Workshop on Advances in the Use of Historical Marine Data: Sea Surface Temperature and Other Key Climate Variables	Boulder, USA	Limited
February 4-7	JSC/CLIVAR Working Group on Coupled Modelling (WGCM), 5th Session	Bracknell, UK	Invitation
February 5-7	VAMOS/CLIVAR Conference on South American Low-Level Jets (SALLJ)	Santa Cruz Bolivia	Open
February 7-9	CLIVAR Pacific Implementation Panel Meeting	Honolulu, USA	Invitation
February 11-15	AGU 2002 Ocean Sciences	Honolulu, USA	Open
February 25-27	Variability of the African Climate System (VACS) Panel 2^{nd} Session	Niamey, Niger	Invitation
March 11-13	CLIVAR Southern Ocean Panel, 1^{st} Session	Hobart, Austr.	
March 13-16	CLIVAR VAMOS Panel, 5th Session	San Jose, Costa Rica	Invitation
March 18-23	Joint Scientific Committee of WCRP, 23th Session	Hobart, Austr.	Invitation
April 22-26	European Geophysical Society, XXVII General Assembly	Nice, France	Open
May 22-25	CLIVAR Scientific Steering Group, 11^{th} Session	Xi'an, China	Invitation
May 28- June 1	AGU Spring Meeting	Washington, USA	Open

Check out our Calendar under: ***http://clivar-search.cms.udel.edu/calendar/default.htm*** *for additional information*

Contents

In this issue

The CLIVAR Newsletter Exchanges is published by the International CLIVAR Project Office.

ISSN No.: 1026 - 0471

Editors: Andreas Villwock and John Gould

Layout: Andreas Villwock

Printed by: Technart Ltd., Southern Road, Southampton SO15 1HG, UK.

CLIVAR Exchanges is distributed free-of-charge upon request (icpo@soc.soton.ac.uk).

If undelivered please return to:

International CLIVAR Project Office
Southampton Oceanography Centre, Empress Dock, Southampton, SO14 3ZH, United Kingdom