INTERNATIONAL COUNCIL FOR SCIENCE

INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION

WORLD METEOROLOGICAL ORGANIZATION

WORLD CLIMATE RESEARCH PROGRAMME

Report on the WGOMD Workshop on Southern Ocean Modelling

Hobart, Australia
9-10 November 2005

August 2006

ICPO Publication Series No 102.

WCRP Informal Report No. 7/2006

CLIVAR is a component of the World Climate Research Programme (WCRP). WCRP is sponsored by the World Meterorological Organisation, the International Council for Science and the Intergovernmental Oceanographic Commission of UNESCO. The scientific planning and development of CLIVAR is under the guidance of the JSC Scientific Steering Group for CLIVAR assisted by the CLIVAR International Project Office. The Joint Scientific Committee (JSC) is the main body of WMO-ICSU-IOC formulating overall WCRP scientific concepts.

Bibliographic Citation

INTERNATIONAL CLIVAR PROJECT OFFICE, 2006: Report on the WGOMD workshop on Southern Ocean Modelling. August. International CLIVAR Project Office, CLIVAR Publication Series No. 102 (not peer reviewed).

Table of Contents

Report on the WGOMD Workshop on Southern Ocean Modelling Nov 9-10, 2005 held at the CSIRO Marine and Atmospheric Research, Hobart, Tasmania, Australia.

Introduction

On November 9 and 10, 2005, the CLIVAR Working Group for Ocean Model Development (WGOMD) sponsored an international science workshop on Southern Ocean Modelling. The workshop was kindly hosted by CSIRO Marine and Atmospheric Research in Hobart, Tasmania, Australia, with financial support from Silcon Graphics (SGI), the University of New South Wales in Sydney, and International CLIVAR. The purpose of this report is to provide a brief summary of the workshop, highlighting some of the key elements of the presentations. Notably, however, as the workshop focused on cutting-edge Southern Ocean science, it is difficult to condense many of the talks to simple bullet points.

The workshop brought together ten international experts on Southern Ocean physics, circulation, modelling, and observations for two days of presentations and discussions. They kindly agreed to have their PowerPoint presentations placed on the WGOMD web page (http://www.clivar.org/organization/wgomd/wgomd.php). In addition to the speakers, there were over 80 registered participants, most from Australia, but many also coming from abroad. The first day of the workshop was devoted to "Observations and Dynamics" and the second day to "Processes and Climate Change"

Day 1: Observations and Dynamics

Steve Rintoul (CSIRO Marine and Atmospheric Research, Hobart, Australia): What can inadequate observations tell us about incomplete models?

David Webb (National Oceanography Centre, Southampton, UK): Ekman transport and the Southern Ocean

Dirk Olbers (Alfred Wegener Institute, Bremerhaven, Germany): The circulation of the Southern Ocean - processes, dynamics and models

John Marshall (Massachusetts Institute of Technology, USA): Theories and models of the ACC and its associated meridional overturning circulation

Aike Beckmann (Division of Geophysics, Department of Physical Sciences, University of Helsinki, Finland): The South End: modelling of the Antarctic marginal seas

Day 2: Processes and Climate Change

Nathan Bindoff (University of Tasmania and CSIRO Marine and Atmospheric Research, Hobart, Australia): South of the Polar Front, modelling the Antarctic slope front, polynyas, eddies, icebergs, ice shelves and southern hemisphere climate

Matthew England (Centre for Environmental Modelling and Prediction, The University of New South Wales, Australia): Southern Ocean water-masses in climate-scale models

Rudiger Gerdes (Alfred Wegener Institute, Bremerhaven, Germany): Sensitivity of the ACC transport in IPCC and CORE simulations

Richard Matear (CSIRO Marine and Atmospheric Research, Hobart, Australia): The future of ocean carbon modelling in the Southern Ocean

Robbie Toggweiler (NOAA/GFDL, Princeton, USA): Why is the Southern Ocean so important for climate change?

A key goal of the workshop was to review elements essential for modelling the Southern Ocean in climate scale simulations, with focus on how present state-of-the-science models perform, and what should be goals for the next model generation (e.g., next five years). Each speaker was allotted one hour for a survey of the Southern Ocean given from their unique perspective (see the schedule of speakers at Annex A). Immediately following, there were upwards of 20 minutes for discussion. This period allowed for an informal airing of questions, comments, and debate from other participants.

Particular questions and topics that the WGOMD asked the speakers to address included the following:
(1) Why is the Southern Ocean so important for Earth system dynamics?
(2) Highlight essential processes (physics, biology, chemistry, other) critical in the Southern Ocean.
(3) How well are Southern Ocean processes represented in the present state-of-the-art (e.g., IPCC AR4) climate models?
(4) What should a global climate model include within the next five years to improve on the present state-of-the-art in Southern Ocean processes?
(5) Comment on the complementary roles of models and observations in the Southern Ocean.

The relatively long presentation and discussion periods allowed the speakers to thoroughly address many research questions, as well as to appeal to the many students and post-doc participants by taking some added time for pedagogy. Furthermore, there was ample informal time between presentations for intimate interactions between the presenters and audience, thus facilitating a better diffusion of the information to student and expert alike.

Summaries

Steve Rintoul (CSIRO Marine, and Atmospheric Research, Hobart, Australia): What can inadequate observations tell us about incomplete models?

The workshop opened with a paper from Steve Rintoul from CSIRO in Hobart. His presentation provided the audience with a firm understanding of the relation between observational capabilities and their limitations. The following provides a summary of points that he raised.

-- The importance of the Southern Ocean for global climate is based on noting that over 90% of the heat absorbed in the climate system since 1955 has been by the ocean, with most of that absorption being within the Southern Ocean.

-- To better understand and model the Southern Ocean, we would ideally like to know observational information about absolute velocity and property transports, rates of mixing, the residual mean circulation and mesoscale eddy fluxes, water mass formation rates, sea ice (including volume) properties, and atmospheric forcing. Unfortunately, these are just those aspects of the system which are most difficult to measure. Instead, water mass distributions and baroclinic flow are about the only thing we measure well. Hence, inferences must be gleaned from intelligent use of inverse methods and forward models.

-- Mixing through the main thermocline in the World Ocean is generally far too weak to support enough upwelling to balance sources of dense water, in particular to explain the large expanse of cold water beneath the thermocline. Instead, air-sea buoyancy fluxes drive water mass transformations in the Southern Ocean, which close the loop of the global overturning circulation cells. Furthermore, Southern Ocean buoyancy fluxes determine upwelling patterns, and hence nutrient supply and community structure.

-- The Antarctic Circumpolar Current (ACC) consists of multiple robust filamentary jet features. Eddies carry momentum downward and both heat and mass poleward. The ACC and global overturning circulation are intimately linked. Wind and buoyancy forcing, eddy fluxes, mixing, and topographic interactions all contribute to the dynamical balance.

-- The simulated ACC transport is extremely sensitive to model details such as the atmospheric forcing, buoyancy forcing from ice melt and shelf processes, topographic resolution, subgrid scale parameterizations, and model grid resolution. Modelled ACC transport is therefore potentially not a very good metric for ocean climate models. In contrast, the divergence of ACC property transport (e.g. heat fluxes) is an important quantity for climate, and so we should focus on this metric when tuning climate models. Furthermore, models indicate that changes in the Southern Annular Mode potentially associated with global warming will result in an increase in ACC transport. However, the sensitivity is not dramatic.

-- Bottom water throughout the Australian-Antarctic Basin is fresher, lighter and higher in oxygen in 2005 than in 1995. The recent changes continue a trend extending back to 1970, resulting in a dramatic basin-wide shift in the T-S curve. The rate of change is comparable to North Atlantic, and may be increasing. Are we seeing a real signal, or aliasing? Both Adelie Land and Ross Sea bottom water sources have become fresher.

- Models can help for understanding the Southern Ocean in the following ways: (1) interpolate between sparse observations to characterise variability, (2) extrapolate (predict future), (3) diagnose mechanisms explaining observations, (4) perform "what if?" experiments, (5) help determine the role of eddies as well as the unobserved barotropic flow.

Dr Rintoul closed with the following questions and recommendations.

Questions:

Why is the ACC transport relatively insensitive to changes in wind? Is it due to topography? What are the roles of eddies? Can coarse resolution models, with their smoothed and hence poorly represented flow and topography, properly capture the response of the ACC to changes in forcing?

What is the magnitude of the residual mean circulation today and how will it change? To what extent do mesoscale eddies compensate Ekman transport? What is the vertical and horizontal distribution of eddy mass transport? Do present eddy parameterisations, such as Gent-McWilliams, do the right thing for both the mean and for the variability in coarsely represented models? What is the spatial structure of the eddy diffusivity?

What has caused observed changes in the Southern Ocean? The Southern Annular Model? Climate change, or natural variability?

Is diapycnal mixing elevated along the path of the ACC? Is it important?

Is there any evidence of feedback from Southern Ocean sea surface temperature (SST) and/or sea ice anomalies to the atmosphere and hence to the regional climate in the Southern Hemisphere?

Recommendations to modellers:

Water mass distributions and baroclinic flow are about the only thing we measure well. Luckily, they provide a sensitive and relevant test for a climate model: to simulate climate change and variability, the model must capture the formation and subduction of water masses correctly and get mean state right. Unluckily, getting this right in climate models is not so easy.

Observational evidence of changes in Southern Ocean climate is still fragmentary, but growing. This evidence is another powerful test for models, a test they may be beginning to pass.

David Webb (National Oceanography Centre, Southampton, UK): Ekman transport and the Southern Ocean

Dr Webb's summary of his presentation is as follows. Climate change studies show that the Southern Ocean is usually the last region to respond to global warming. One likely explanation for this is the cool water brought to the surface by the Ekman layer divergence in the region. The Ekman layer is also involved in the formation of intermediate water masses in the north of the region, the transport of sea ice away from Antarctica and the complex series of processes through which the ocean balances the zonal wind stress at the latitudes of Drake Passage. The latter affects the transport on the Antarctic Circumpolar Current. Thus, through its effect on the water mass exchanges between the different oceans, the transport of sea ice and the formation of intermediate water, changes in the Ekman transport may have significant effects on the long-term climate system.

In recent years there have been few studies of the Ekman Layer in any part of the ocean, possibly because people believe it is well understood. Partly because of this, I think this meeting is a good opportunity to review the properties of the Ekman Layer in the region, discuss potential research problems and encourage further work. The talk was split into three main sections. The first was concerned with the general properties of the mean state and the second its fluctuations in time. The final section discussed a particular problem in detail: the question of how the ocean responds to very rapid changes in the wind stress and the associated rapid changes in the Ekman transport. In many respects the results are unexpected.

1. The mean state

The mean wind stresses in the Southern Ocean are the largest of any ocean. The maximum values lie on a roughly zonal band centered at a latitude just to the north of Drake Passage. Maximum values are found in the Indian Ocean sector, where the stress at the centre of the band reaches 2.5 dyne/sq cm. The stress at the centre of the band drops slightly in the central South Pacific and east of Drake Passage but even here the values match or exceed the maximum values in other oceans.

The long-term variations in the wind field have been studied by J. Richman (OSU) using empirical orthogonal functions. He showed that, since the 1950s, the winds have increased by approximately 30%. This is a significant increase and implies that the Southern Ocean may be experiencing large scale changes in its water properties and transports.

In the Southern Ocean, the Ekman Transport has a similar pattern to the wind stress, except that the vector is rotated by 90 degrees. It is maximum along a band centred to the north of Drake Passage, with a maximum in the Indian Ocean, to the east and west of Kerguelen. There is another small maximum to the west of Drake Passage, with minimum in the central South Pacific and to the east of Drake Passage.

However, when the divergence is calculated, the decreased size of the Coriolis parameter towards the equator produces an anomalous result. In the Southern Ocean, positive values of divergence (corresponding to upwelling) occur in a relatively narrow band around Antarctica. Further north, in the Indian Ocean, there is a broad band of fairly uniform convergence (downwelling) extending from just north of Kerguelen to the tropics. In the Pacific Ocean the convergence to the north is very small, and in the Atlantic, except for a region off South-west Africa, it is again small.

These results pose questions about the mode water and intermediate water formation regions near the southern boundaries of the sub-tropical gyres. They show that there is nothing special about the Ekman pumping in these regions and so raise questions about why subduction should occur, especially in the South-east Pacific where the Ekman pumping is essentially zero.

Model studies, for example using the FRAM results, show that on average, subduction occurs in a fairly narrow band near 40 degrees south. Detailed studies of subduction on a global scale have yet to be carried out but maybe the model results can be used to explain the behaviour and the relationship, if any, to Ekman pumping. What the models do show are regions of strong frontal formation and mixing on the western side of each ocean. These appear to be produced by the northward Ekman transport of cold surface fresh water coming into contact with warm saline water brought south in the western boundary currents. However, the way these are related to the mode water formation regions, often in the centre and eastern sides of each basin, is not clear.

The WOCE sections do not show the fronts as strongly as the annual average model results. However, the WOCE sections were all made during the southern summer. When comparisons are made between model and observations at the same time of year, then the agreement is better.

2. Variations with Time

In addition to the long term changes, Richman's work with the first zonal wind EOF showed changes of 30% in the wind strength over very short periods. Even more dramatic changes are seen in a calculation of the zonal wind stress at the latitudes of Drake Passage in 1993 and 1994. Instantaneous values can vary between -1 and +7 dyne per sq cm, with monthly averages varying between 0 and 4 dyne/sq cm. Again one would expect this to produce large changes in the properties of the ocean.

Similar results come from studies of Ekman Pumping. In the South-east Pacific, point values can vary rapidly between +100 and -100 cm/day. A spatial plot of the r.m.s. value shows a maximum of 100 to 130 cm/day roughly along the line of maximum wind stress. Smaller values are found in the sub-tropics but there is then an increase near the equator because of the reduced Coriolis term.

When averaged over a 12 by 12 degree region, the r.m.s. amplitude is reduced by about a factor of ten, but this is sufficient to excite two important barotropic resonances in the South-east Pacific and in the South Indian Ocean, both of which can be seen in satellite sea surface height data.

Normally one might expect such short-term variability to have little effect on the long-term climate signal. However, one must bear in mind that it can affect the details of key processes, such as the number of leads in the ice field or the mixing produced by advection of the Ekman layer over less dense water masses to the north.

3. The effect of sudden changes on the Drake Passage Transport

Previous studies using models and in situ data indicate that the Antarctic Circumpolar Current (ACC) transport through Drake Passage responds rapidly to the wind stress. FRAM, for example, was started from a motionless ocean at a temperature of 0 degrees C and a salinity of 35 ppt. The temperature and salinity fields were then slowly relaxed towards climatological values (i.e. Levitus). While this happened there was a slow increase in the ACC transport.

Initially there was no surface wind stress, but during the fourth year of the run this was linearly increased from zero to its climatological value. The model results, based on data saved every 20 days, showed that there was an equivalent linear increase in the ACC transport. This implied that the model was responding to any change in the wind within the 20 day period.

Experimental studies carried out by Hughes and colleagues has shown that the sea level around Antarctica is highly correlated. Correlations with sea level to the north is weak but there is evidence that it is correlated with changes in ACC transport. In both these and the FRAM model results, the lack of any significant time delay indicates that barotropic processes are involved. This is unexpected given the usual emphasis on baroclinic processes in controlling the momentum balance and ACC transport in the Southern Ocean.

To investigate the problem further (and because this meeting was coming up and it seemed a suitable topic) we investigated the effect of sudden changes, making use of a 1 degree version of the OCCAM global ocean model. Tests using a 1/4 degree version of the model are underway but the results were not available in time for the meeting.

The model was started from the Levitus climatological data set of ocean temperature and salinity. It was forced with an annual average surface wind stress and had the temperature and salinity field in the surface layer relaxed to Levitus, to represent the surface forcing due to heat and fresh water.

The model was initially run for ten years to produce a quasi steady ocean circulation in which there were no major transients. The resulting model state was then used as the starting point of three short runs. In the first, the control, there was no change to the forcing. In the second, the perturbation run, the zonal wind stress at the latitudes of Drake Passage was increased by 0.1 dyne/sq cm. In the third run it was reduced to zero in this band and in the fourth run the wind stress was reduced to zero everywhere.

The model results showed that direct effect of the wind in the model is relatively small. In the control run the total transport was about 144 Sv. In run 2, which corresponds roughly to a 5% increase in wind stress, this increased by approximately 1 Sv. Run four, with no wind anywhere, reduced the transport by approximately 14 Sv. Thus most of the ACC transport in the model is due to the density field.

A second, and significantly more striking result, is the fact that the main ACC response to the changes occurred within 2.7 days. This implies that the ocean responds barotropically to the changes in the wind stress and rapidly reaches a quasi-equilibrium. (It is interesting to note here that the energy in the tides, another barotropic process, has a decay time of about three days).

Visualizations of the differences in the sea surface height (SSH) field of the two runs, show tide like waves propagating northwards away from the region and the rapid development of a region of low sea level around Antarctica. The contours of SSH difference tend to follow the topography when the corresponding geostrophic currents are northwards, but cross the deep ocean basins where the transport is southward in the South-East Pacific and South Atlantic. As the SSH field develops, evidence of the two resonant modes of the South-East Pacific and South Indian Ocean, can also be seen.

The work with FRAM showed that a lot of information on the downward transfer of momentum from the wind can be obtained from the zonally averaged overturning stream function. The results from the control run are fairly standard in this respect, showing a strong surface Ekman layer, a return flow below the level of topography and strong upwelling at latitudes near Drake Passage.

The results from run 2, the perturbation run, are similar, but if one subtracts the two experiments, one sees a very striking closed circulation. There is increased northward flow at the surface, as expected, a deep return flow below the level of the topography and strong vertical flows completing the circulation at the north and southern limits of increased wind stress. In the FRAM analysis this overturning was called the Deacon Cell. It was thought to be primarily a baroclinic phenomenon, but here it looks as if it is a barotropic response of the ocean.

It is surprising that the barotropic, depth independent, flow can set up such a vertical overturning circulation within a few days. But plots of the northward component of velocity, along a latitude line going through Drake Passage, show how this happens. Subtracting the velocities of run 2 and run 1 after two days, one finds that in addition to the increased northward transport, run 2 has increased northwards velocity over shallow topography and increased southward transport in the deep ocean basins. If one integrates the field zonally, this gives a net northward transport in the surface layer, southward transport below the level of topography and zero north-south transport in the intermediate layer where the northward and southward flows cancel out.

This behaviour is essentially that indicated by the difference in the SSH fields. However, evidently the solution is not a final steady state. Instead it seems that longer period barotropic Rossby waves are excited, which do not affect the basic momentum balance, but which after 30 days produce a more complicated barotropic velocity field.

As a check that the change in the Deacon Cell was due solely to barotropic processes, the barotropic field, after excluding the Ekman layer, was calculated and used by itself to estimate the change in the overturning stream function. It was found that after 30 days it could explain all but 0.56% of the observed change in the Deacon Cell.

Eventually one expects baroclinic processes to be involved, in particular because the vertical flows associated with the Deacon Cell must distort the density surfaces. A study of the terms contributing to the bottom pressure torque, show that initially it is produced solely by changes in the SSH field but that after 30 days, the baroclinic density field has been modified enough to contribute 10% to the bottom pressure term. This may increase in time but, instead of being a direct response to the changed wind stress, at the moment it looks as if it is really a passive response to the primary changes produced by the barotropic field.

Conclusions

The main conclusion of the presentation is that there is still a lot we do not understand about the large scale processes occurring within the Southern Ocean, many of which affect long term climate. I have focused on the Ekman layer because it is a relatively simple physical system to study but one which can have important effects on both the near surface and interior properties of the ocean. I hope that in doing this I have highlighted some areas where useful research can be carried out. I also hope I have shown that even relatively simple pieces of research can still provide striking new insights into the properties and behaviour of the Southern Ocean.

Dirk Olbers (Alfred Wegener Institute, Bremerhaven, Germany): The circulation of the Southern Ocean - processes, dynamics and models

Dr Olbers' presentation covered three specific areas. His summary is as follows:

Part A: The dynamical balance of the ACC and the forcing functions for transport (Olbers, Lettmann, Timmermann)

What are the mechanisms of forcing that set the zonal transport of the Antarctic Circumpolar Current (ACC)? All previous attempts with numerical models could generally not reveal dependencies of the ACC transport on forcing function, as proposed by scaling or analytical concepts. What clearly emerged from these studies, however, is that the ACC transport depends not only on the amplitude of the zonal windstress, but also on its meridional structure such as the curl or the Ekman pumping, and on the surface fluxes of heat and freshwater, and most important, on the shape of the marine topography. There are some important features, which a transport theory must explain.

Using the reduced physics model BARBI in a Southern Ocean configuration, we have analysed various wind and buoyancy driven ACCs concerning the local balances of momentum, depth integrated and averaged vorticity, and baroclinic potential energy and shown the enormous influence of topographic terms in these balances (bottom torque, JEBAR, planetary-topographic Jacobian, Ekman effects by baroclinic and barotropic velocities acting on the background stratification). Generally, in the balances of vorticity and potential energy the topographic terms are dominant and almost cancel pairwise, indicating that the physical mechanisms which control the flow are associated with the bottom current and bottom pressure rather than depth integrated variables (as the total transport, JEBAR etc). On the basis of these balance features, we are proposing a new transport equation for the ACC where the forcing functions (curl of windstress, Ekman pumping and a buoyancy source from ocean internal mixing) are in balance with beta and vertical momentum diffusion (associated with the Gent-McWilliams parameterization).

From this study with BARBI, we reach the following conclusions.

- Dynamics of ACC transport is governed by linear response of topographic-planetary waves (two gravest modes) to wind and buoyancy forcing (=interior vertical turbulent buoyancy flux > mixing).
- Direct wind driving and Ekman pumping on stratification are of comparable size.
- Baroclinicity breaks the f/h constraint and restores f-characteristics (but bottom pressure is still governed by f/h).
- Eddy diffusion from the Gent-McWilliams scheme overwhelms eddy viscosity in shaping circulation and transport of the ACC.
- JEBAR is not a good concept.

Part B: Interpreting eddy fluxes (Eden, Greatbatch, Olbers)

Consistent ways of interpreting eddy buoyancy fluxes averaged at constant height are presented and compared with previous interpretations, in particular the Transformed Eulerian Mean (TEM) of Andrews and McIntyre (1978), and the Temporal Residual Mean (TRM) of McDougall and McIntosh (1996). The previous decompositions imply eddy induced diapycnal mixing related to local cross isopycnal eddy fluxes that may not be physically justified. In particular, this diapycnal mixing is not necessarily vanishing for adiabatic and steady flow, and can become large (compared to the mean diabatic forcing) for weakly diabatic flow as revealed in numerical simulations.

Consideration of the full hierarchy of tracer moments and generalizing ideas reaching back to Marshall and Shutts (1981) yields a TRM version with eddy induced (or enhanced) diapycnal diffusion in the steady case, only if there are local covariances between the diabatic forcing and the tracer. The new consistent version can be evaluated for any stratification and to any order in perturbation amplitude. It is shown that all the new flux decompositions collapse to a single, consistent one in the adiabatic and steady case, giving also well defined boundary conditions for the residual stream function.

The generalised Temporal Residual Mean (TRM-G) is a fully consistent formulation that

(i) combines advective, diffusive and rotational fluxes,
(ii) gives zero diffusivity in steady, adiabatic conditions,
(iii) can be adapted to any kind of averaging, including isopycnal averaging and 3-D situations,
(iv) the diffusivity K is, in general, down the mean gradient when (a) there is growth of eddy variance (non-steady) or (b) irreversible removal of eddy variance (steady).

Part C: The SO overturning model (Olbers, Visbeck)

The ocean area south of the Antarctic Circumpolar Current (ACC) frontal system is a region of major water mass modification. Influx of North Atlantic Deep Water (NADW), small-scale mixing, eddy transport and diffusion, as well as the fluxes of momentum and buoyancy at the sea surface combine in a complex array of processes to generate the unique stratification of the Southern Ocean with its southward uprising isopycnals and northward flux of Antarctic Intermediate Water (AAIW) and Antarctic Bottom Water. Comprehensive analytical models of this scenario are rare. We have developed and applied a model based on zonally and temporally averaged theory to explain the conversion of NADW into AAIW with all of the aforementioned processes contained in an extremely simplified way.

Eddies appear via a transformed Eulerian mean (TEM) approach with a conventional downgradient parameterization of the meridional density flux. The structure of the eddy coefficient is estimated from hydrographic and wind stress data by a simple inverse approach. Mixing is limited to a near-surface layer and is treated in a most simple entrainment form. The model determines the zonal mean density stratification in the Southern Ocean and the baroclinic transport of the ACC from the applied wind stress and the surface density flux and unravels the role and importance of the different processes responsible for shaping the stratification (Ekman and eddy-induced advection and pumping, mixing, surface buoyancy flux, and eddy-induced diffusion). All of these processes must be present to yield an agreement between the simulated stratification and the observed one, but details of their parameterization might not be too critical.

- eddy K ~ O(500 1000) below ML, with near surface maximum
- deep K relates to NADW transport
- gross features of SO overturning can be modelled by simple mixed layer physics (wind, surface buoy flux, mixing, eddies) and adiabatic ocean interior
- strength and depth of overturning depend on all parameters: windstress, surface buoyancy flux, mixing in ML and eddy field
- wind and eddy driven overturning partially compensate (for the present forcing functions)

John Marshall (Massachusetts Institute of Technology, USA): Theories and models of the ACC and its associated meridional overturning circulation

Combining observations, models and theory, Dr Marshall reviewed what is known about the dynamics of the ACC and its overturning circulation emphasing:

(i) deductions that can be made from observations of air-sea momentum and buoyancy fluxes,
(ii) the role of cross-stream eddy transports can be deduced from rates of mesoscale eddy stirring,
(iii) theoretical models of the streamwise-average dynamics of the ACC and its overturning circulation built around residual-mean theory.

Finally, recommendations were made about how to improve the above processes in ocean models used in the study of the coupled climate.

Aike Beckmann (Division of Geophysics, Department of Physical Sciences, University of Helsinki, Finland): The South End: modelling of the Antarctic marginal seas

Dr Beckman noted that the hydrosphere and marine cryosphere of the Antarctic Marginal Seas (roughly defined by the area south of the Antarctic Circumpolar Current) are characterized by a number of unique processes: interactions between atmosphere, ocean, sea ice and ice shelves, leading to complex chains of water mass transformation and exchanges between surface and deep ocean, which are, at least in some regions, strongly affected by tides and episodically subject to freshwater input through drifting and melting icebergs.

Numerical investigations of this system have been carried out by the BRIOS group at AWI Bremerhaven, Germany, using a regional sigma-coordinate ice-ocean model that included the ice shelf cavities and the interactions between ice shelves and ocean. This model system was extensively validated with respect to oceanic transports, water masses, sea ice distribution and thickness, ice shelf melting and freezing, as well as tracer spreading. The main conclusion was that coarse (1.5 x 1.5cos(phi) degree, where phi is latitude) resolution models can achieve a high degree of realism with respect to many aspects of the ice-ocean system. Examples were presented.

Nowadays, the Southern Ocean is modelled as part of global models of comparable resolution, but receives comparatively little attention. As a consequence, some of the major ice-ocean phenomena (sea ice cover, water masses, Antarctic Coastal Current) are represented quite poorly. Among the potential factors are: the neglect and/or crude parameterization of ice shelf cavities and melting, the treatment of topography (i.e., the vertical model coordinate), as well as several sub-gridscale parameterizations, in particular the vertical mixing in seasonally ice covered regions.

The lecture highlighted the lessons learned from the BRIOS project by pointing out shortcomings of current global OGCMs and proposing two apparently crucial additions/improvements: an ice-shelf melting parametrization and a new hybrid (s-z) vertical coordinate to better represent the bottom topography in regions with weak stratification. The talk closed by mentioning remaining unresolved issues: the inclusion of tidal motion and mixing in climate models (stressing the importance of flow-topography effects for sea ice and water mass modification), the development of adequate parametrizations for coastal polynyas as well as iceberg calving, drift and melting.

Nathan Bindoff (University of Tasmania and CSIRO-Hobart): South of the Polar Front, modelling the Antarctic slope front, polynyas, eddies, icebergs, ice shelves and southern hemisphere climate

Dr Bindoff provided a survey of processes occurring south of the polar front, which included discussions of regional and global eddying processes and models of the Antarctic slope front, polynyas (with focus on the Mertz Polyna), mesoscale eddies, icebergs, ice shelves and Southern Hemisphere climate. Examples were provided where models do a reasonable job of representing ocean processes occurring near ice shelves, if sufficient resolution is given to the ocean model.

Observed outflow of water from the shelves near the Mertz Polyna is ~0.2-0.3 Sv, implying ~0.6-0.9 Sv bottom water formation. Under climate sensitivity studies, there is ~25% reduction of dense water in strong polynya years, ~80% reduction of dense water in weak polynya years. ~40% reduction over all years. Assuming that the Mertz response is typical of other Antarctic coastal polynya regions, then we expect a slowdown of Southern Hemisphere thermohaline circulation under climate change scenarios. If future climate tends towards more weak thermohaline circulation, we expect a shutdown. This shutdown has already been predicted in coarse resolution models. It is reassuring that when better representing the physical processes, the models possess similar sensitivity.

Pathways from shelf break to abyss are very poorly resolved and modelled in present climate models. The role of canyons and bottom roughness and bottom boundary layer schemes (not too diffusive) may prove critical. It is important to have realistic coastal geometries (e.g. Mertz Glacier), realistic sea-floor, and coastal bathymetry for proper circulation and water mass representations (e.g., retaining high salinity shelf waters).

Ice shelves are very sensitive to melt (i.e., ocean temperatures). Amery ice shelf and Mertz Glaciers currently melt ~30% of total ice that is calving. Increased ice melt is an important component of Southern Ocean stratification. Much of the melt is coming from depth < 400 metres. Too much emphasis has been placed on deep cavities; more should be placed on shallower depths. There is also a need to focus on whole of Antarctica in order to better determine role of ice shelves in climate change.

What is missing in our understanding/representations of the oceans? The contribution of (increased) ice-shelf melt to the Southern Ocean freshwater balance is one factor. Evidence comes from freshening of bottom waters (Ross Sea, Adelie Land). This should impact on Southern Ocean stratification and overturning circulation. What's missing in our understanding/representation of the ice shelves? Static thickness and volume, and active ice shelves, particularly with ice melt. Notably, the time scales for shelves can be short.

Observed climate changes in the Southern Ocean include (1) Sub-Antarctic Mode Water (SAMW), which seems to be changing throughout the Southern Ocean, (2) Antarctic Intermediate Water (AAIW) is now fresher (and cooler), (3) Circumpolar Deep Water (CDW) is unchanged north of the SAF, but (4) CDW has warmed (saltier) south of SAF, (5) There is some evidence that Antarctic Bottom Water (AABW) is now fresher. These changes are qualitatively the same as a climate change mode in the HadCM3 and CSIRO Mk3 models. Aliasing from natural variability cannot be ignored. We can provide a rigorous testing of models against current climate. There has been a significant improvement in model quality over the last few years. It is important to save model diagnostics such as mixed layer depths and subducted water mass volumes.

To better understand the role of mescale eddies in the Southern Ocean, a 1/8 x 1/8 ocean model was configured with fixed wintertime surface forcing. High time resolution and statistics collection allows the mean and eddy components of the total transport to be well calculated, and fixed forcing implies that all variability is due to internal model dynamical instabilities. The simulation generally provides good representation of mass/heat transport, with high resolution allowing for Agulhas and Tasman leakages. Eddy transport and flux is greatest in the tropics, western boundary currents and confluences, and along the SAF. Eddy transports have a large length scale in the tropics, but are much shorter elsewhere. Most eddy activity is restricted to the upper 1000 m. Anti-correlations are found between mean and eddy divergences for both heat and freshwater fluxes, possibly due to regions of strong mean flow inducing compensating eddy transports via increased baroclinic instability.

Matthew England (Centre for Environmental Modelling and Prediction, The University of New South Wales): Southern Ocean water-masses in climate-scale models

Dr England began by noting that a fundamental benchmark of global ocean model performance is the representation of Southern Ocean water-masses, including Subantarctic Mode Water (SAMW), Antarctic Intermediate Water (AAIW), Circumpolar Deep Water (CDW), and Antarctic Bottom Water (AABW). This is because these water-masses are intimately linked to the global ocean thermohaline circulation and the Southern Hemisphere wind-driven circulation. Southern Ocean water-mass formation rates are also directly tied to key climate indices such as the poleward transport of heat, the rate of oceanic CO_2 uptake, and the rate of change of SST (and therefore also surface air temperature) due to atmospheric CO_2 increases. The assessment of model skill with respect to water-mass formation rates is also relatively well-constrained by observations of interior oceanic T-S and geochemical tracers, unlike baroclinic velocities and integrated transport quantities such as poleward heat transport, that suffer from high-frequency variability and incomplete data coverage, respectively.

The present class of global-scale ocean models used in climate research often poorly resolve the large-scale water-masses of the Southern Ocean. This is generally due to poor representation of Antarctic sea-ice, the bottom boundary layer, and gravity currents (AABW), inaccurate simulations of the outflow rate and properties of NADW (CDW), simplifications in the model treatment of isopycnal mixing, and mixed-layer – eddy interactions (AAIW), and errors in the modelled patterns of open ocean convection and mixed layers (SAMW). It is therefore not surprising that model inadequacies remain, as present generation ocean climate models struggle to capture accurate air-sea and ice-sea fluxes (heat, freshwater and momentum), and many oceanic processes rely on parameterised physics (e.g., downslope flows, entrainment fluxes, open ocean convection, non-hydrostatic processes, mixed layer physics, isopycnal and diapycnal mixing, and eddy fluxes).

Despite these difficulties, much progress has been made in the past 30 years. The first global scale models used in climate research suffered from large errors in abyssal ocean T-S and generally lacked any signature of AAIW, largely due to poor representation of lateral diffusion, excessive diapycnal mixing, and the lack of any scheme to include the effects of eddy-induced advection. Antarctic sea-ice effects were also generally poorly resolved. More recently, the inclusion of eddy-induced advection, the coupling of ocean models to Antarctic sea-ice models, the inclusion of sophisticated bottom boundary layer schemes, and more accurate air-sea and ice-sea fluxes has seen an order of magnitude decrease in the typical errors seen in model Southern Ocean T-S fields.

Recent assessment of Southern Ocean T-S fields in the upcoming IPCC Fourth Assessment Report (Russell et al. 2005) shows notable deficiencies in all IPCC class climate models, and an alarming spread of poleward heat transport rates in the latitude band of 15-70°S. In these non-eddy permitting models, errors in interior model T-S are a result of at least one of the following: (1) erroneous surface T-S, (2) spurious rates of ocean overturn within the surface mixed layer, (3) incorrect interior ocean circulation, and (4) unrealistic mixing processes in the model. Errors in surface T-S may themselves be a result of incorrect air-sea heat, freshwater or momentum fluxes, and/or errors in surface circulation and mixing. Thus the diagnosis of subsurface ocean model T-S against observations is not unambiguous: errors may be symptomatic of any number of problems in ocean model forcing, circulation and/or physics. Despite these challenges, and the temptation to tune model physics to optimize fidelity against popular observational benchmarks, parameter sensitivity studies ought to be at the fore of our efforts (see, e.g., Gnanadesikan and Griffies, 2006). This is because such studies seek to objectively map model sensitivity independently of model skill, thereby revealing where theoretical efforts are required to develop accurate model physics schemes (the *US Climate Process Teams* are a particularly good concept in this regard, bringing together modellers, observationalists and theoreticians to advance ocean model physics).

Eddy-permitting and eddy-resolving models generally exclude any explicit water-mass analysis in assessments of model skill, instead relying on 'metrics' such as the EKE density, baroclinic/barotropic flow rates, poleward heat transport, and property transports in density classes. The reason water-masses are generally excluded is that fine resolution models are only integrated for short time periods (typically decades), and so are not equilibrated in interior ocean T-S. However, Sen Gupta and England (2004) have shown that off-line tracer models can be easily constructed that incorporate chemical tracers such as CFCs and even radiocarbon (multi-millennia integrations are possible in an off-line context as the tracer equation can adopt a relatively large time step). Thus, even the next generation ocean climate models at fine resolution, can and should be subjected to benchmarking against water-mass ventilation rates.

To conclude, water-mass transport rates and properties remain the key metric for assessing IPCC-class ocean models. Sensitivity and process-oriented studies are crucial in identifying those aspects of ocean models that need refined or more accurate physics. In the Southern Ocean context, future ocean model development efforts are required in a number of areas, including vertical coordinate schemes (z*, hybrid, …), partial-cell techniques, BBL schemes, inhomogeneous mixing, ice shelves, polynyas, eddy – mixed-layer interactions, gravity currents, and convection. Ocean model assessment probably has to continue across each of the genres of model (from coupled climate models and ICCMs to ocean-only models). Given the availability of global hydrographic measurements, well-constrained T-S and geochemical tracer benchmarks, and off-line techniques for tracer transport diagnosis, no model ought to escape some form of water-mass assessment.

References

Effects in a climate model of slope tapering in neutral physics schemes, 2006: A.Gnanadesikan, S.M. Griffies, B.L. Samuels, Ocean Modelling accepted.

Russell, J.L., R.J. Stouffer and K. Dixon, Intercomparison of the Southern Ocean circulation in the IPCC coupled model control simulations. *J. Climate*, submitted. Sen Gupta, A., and M.H. England, 2004: Evaluation of interior circulation in a high resolution global ocean model, Part I: Deep and Bottom Waters, *J. Phys. Oceanogr.*, **34**, 2592-2614.

Rudiger Gerdes (Alfred Wegener Institute, Bremerhaven, Germany): Sensitivity of the ACC transport in IPCC and CORE simulations

1. Baroclinic potential energy as a diagnostic for the ACC

ACC transports in numerical models vary over a large range. The wind stress, wind stress curl, surface buoyancy fluxes, strength and properties of North Atlantic Deep Water (NADW), and subgrid-scale parameterisations all seem to exert an influence on the ACC. These sensitivities differ between models. Here, we consider the sensitivity of the strength of the ACC to various forcing fields using the influence of different processes on the meridional gradient in the baroclinic potential energy distribution as main diagnostic.

For the ACC the dominant balance in the barotropic vorticity equation is between the topographic and planetary vorticity terms on the one hand and the JEBAR term $J(H^{-1},\chi)$ on the other hand (Borowski et al., 2002; see also the talk by D. Olbers)

$$J\left(\frac{1}{H}, f_o\Psi - \chi\right) = 0$$

Here, χ is the baroclinic potential energy and H is the bottom depth. We have assumed that variations in the Coriolis parameter can be neglected. This relationship also follows from geostrophy when the velocity at the bottom vanishes. The close relationship between the streamfunction for the vertically integrated volume transport Ψ and the baroclinic potential energy χ offers the opportunity to estimate the sensitivity of the ACC to the different forcing agents by the influence on the baroclinic potential energy. These estimates are not model dependent and can to some degree be made for observed changes in the density field. The basic ingredients we need for our analysis are the in-situ density field and the surface buoyancy fluxes as well as the Ekman transport. For water mass analysis, temperature and salinity fields are necessary.

The full potential of the baroclinic potential energy was not been exploited in this presentation. The examples below may be taken as a motivation for further and more thorough examination of model results and observations. Because relatively little information is required, the method lends itself to multi-model comparisons like the assessment of IPCC scenario calculations.

Some simple conclusions can immediately be drawn from the above equation. The same surface buoyancy flux will have a more pronounced influence on χ when applied to a weakly stratified water column compared to a well-stratified water column because the resulting density anomaly reaches deeper down. Deep convection due to sea ice formation is a typical case of deep density anomaly generation. An anomaly of +20% in the northward sea ice transport (estimated as 0.02 Sv) and corresponding ice growth would change the density by 0.1kgm^{-3} over the whole water column (south of 65^{o}S) within 10 years. The corresponding change in ACC transport is around 20 Sv. Ekman pumping would transport a change in the density of surface waters north of the subantarctic front to depth at a rate of around 10^{-6}m/s. If water in the depth range 200-400m would thus be replaced by water 2kgm^{-3} lighter than previously, then the ACC transport would increase by 20Sv. The time scale for this to happen is around 10 years. Changes in Ekman transport itself act on correspondingly longer time scales.

Changes in water mass distribution are more complicated. A change in the strength of NADW flow can affect the ACC in unexpected ways. The time scale for NADW changes to be felt in the ACC is more than 100 years. A common problem with current global models is the accumulation of relatively fresh water south of the subpolar front because the northward transport of fresh water in the AAIW is not properly reproduced. This introduces a tendency for a weakening of the ACC because the waters on the right side of the current become less dense over time.

2. CORE simulations

a) GFDL

As a concrete example we consider the CORE 1 (Coordinated Ocean Reference Experiments) simulation with the GFDL MOM4 ocean-sea ice model. (Griffies et al., 2005). The CORE forcing (Large and Yeager, 2004, see also http://data1.gfdl.noaa.gov/nomads/forms/mom4/CORE.html) is based on NCEP reanalysis data but incorporates many improvements relevant for ocean-sea ice simulations. In the CORE 1 experiments, the forcing consists of a seasonal cycle and high frequency variability taken from a typical year.

In the GFDL model, the ACC transport at Drake Passage decreases from 163 Sv to 126 Sv over the first 100 years of the integration. Later, it recovers to 147 Sv. The strength of NADW cell undergoes a similar evolution. During the first 100 years the southern ocean south of the ACC axis becomes lighter (χ becomes smaller) and the belt around 50^{o}S becomes denser. This implies a reduction in the strength of the ACC. After 500 years we see opposite tendencies. There is a stronger branch of the ACC along the South Shetland and South Orkney Island arch. The branch of the ACC through the Argentine basin has become narrower and weaker. The stronger Weddell Gyre is due to increased convection and dense water production in the Weddell Sea. The deep convection over large regions near the Antarctic continent must be considered as model artefact.

The most important contributions to the baroclinic potential energy are from below 500m depth (the tendencies

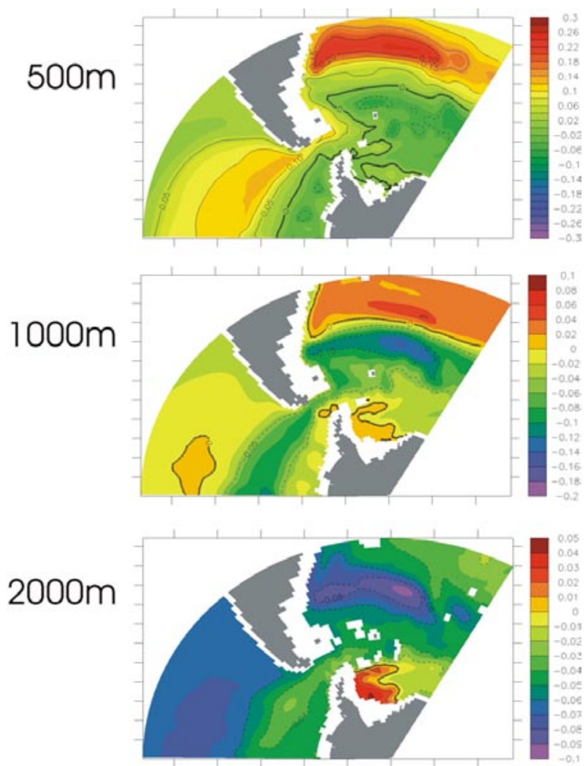

Figure 1. Changes in density between model states after 500 years and 100 years of integration at different depths.

at 500m depth and above actually point in the wrong direction). At depth we see denser water at the continental margin and lighter water at around 50°S. Between 500 years and 100 years, density decreases below 500m between the two eastward branches of the ACC, strengthening the southern branch, weakening the northern branch (Fig. 1). The decrease in density is related to the increasing temperature due to a stronger presence of NADW.

In an integration where a massive reduction in NADW overturning was forced by a fresh water flux anomaly in the northern North Atlantic (Gerdes et al., 2006) the ACC does not change considerably after 100 years of integration. Changes in the production of NADW become important for the ACC transport on timescales larger than 100 years. For the GFDL CORE experiment changes in the first 100years are governed by southward shifts in the subpolar front and a thickening of the thermocline. The latter might be related to a retreat of the AAIW.

b. Leibniz Institute for Marine Sciences Kiel

Do models with "identical" forcing and similar set-up produce similar results and exhibit similar sensitivities? To answer this question we turn to the results of CORE 1 simulations performed at the IfM Kiel with the OPA-9.0 ocean model coupled to the LIM sea ice model (ORCA).

After 100 years of integration, changes in the CDW and the AAIW are similar to those in the GFDL model. Density decreases between the surface and 2000m depth between 65°S and 50°S while it increases further north. Both tendencies lead to a weakening of the ACC. Density in this case is salinity related (contrary to the GFDL result) and changes in AAIW are most important. Density north of 50°S increases because both temperature and salinity contribute (they compensate in GFDL to some degree). Thus, the northern branch of the ACC weakens as in the GFDL model. However, no intensification of the southern branch occurs in this case.

Between years 100 and 500 the ACC weakens in this model by around 10 Sv. The main current axis shifts southward just east of the Antarctic peninsula. There is little change in the upper 1 to 2 km: However, below 2 km depth there are major changes; the water becomes cooler and fresher (Fig. 2). This is due to the very strong production and transport of AABW. AABW production becomes weaker during the integration but is still relatively strong after 500 years of integration. This may be made possible by the lack of NADW in high southern latitudes. The in-situ density increases slightly due to the colder temperatures.

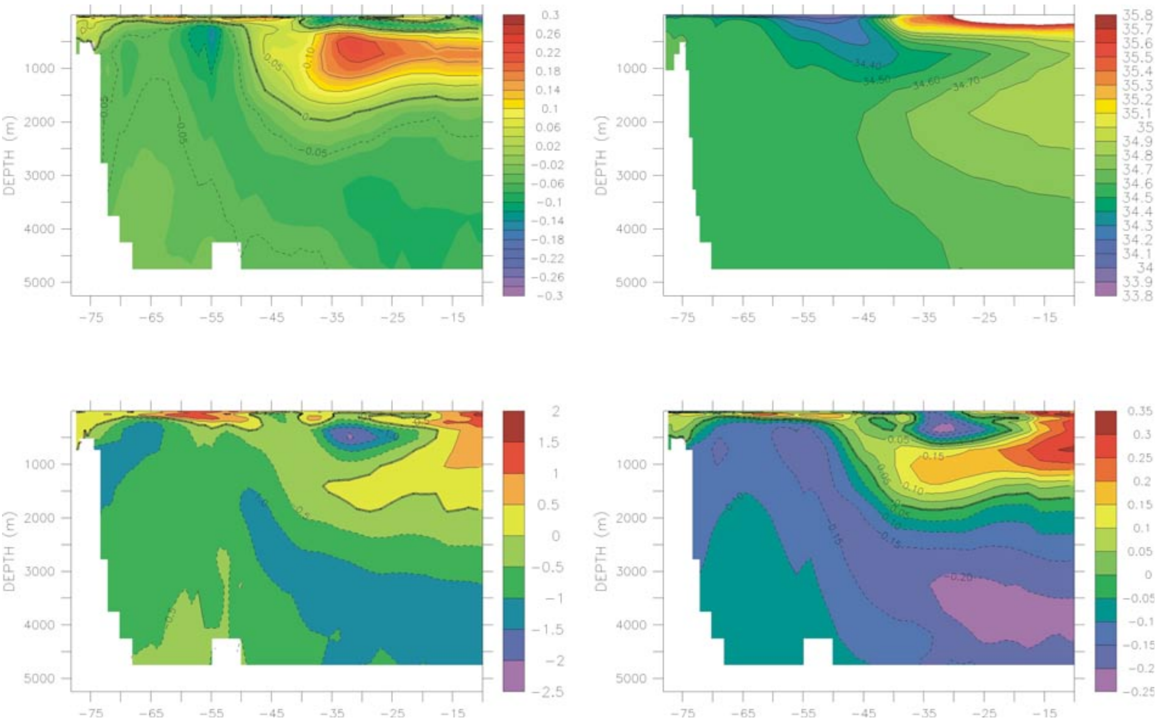

Figure 2. Changes in density (s_o, upper left), potential temperature (lower left), salinity (lower right) between years 500 and 100 averaged over the Atlantic sector of the CORE simulation with the Kiel model. Salinity after 500 years of integration is shown in the upper right panel.

The rather large differences between the GFDL and Kiel results are due the large production of AABW (mid depths are apparently dominated by southward recirculating water of AABW origin) and a rather weak and shallow NADW cell. Furthermore, there is no increase in density close to the AA continent in the Kiel CORE simulation. Kiel has very deep convection in the Weddell Sea but not as excessive as GFDL.

3. Future development of the ACC in the GFDL A1B IPCC scenario simulation

As a last example we consider results from a greenhouse warming scenario (A1B) run with the GFDL coupled climate model. The oceanic component is virtually identical to the ocean model used in the CORE 1 simulation above. Over the 21st century the ACC is rather stable. Sea ice increases in the Weddell Sea. The sea ice edge moves slightly poleward everywhere else. This means a slight shift in the melting and freezing regions that is visible in the water flux to the ocean. Only in the Weddell Sea do we see a reduction in the water flux to the ocean due to locally increased sea ice production. The northward Ekman transport across the latitude of Drake Passage increases by 6Sv, roughly 15% of the transport at the end of the 20th century.

The surface fresh water flux and the Ekman transport represent processes that could potentially lead, besides oceanic teleconnections between northern and southern hemispheres, to an increase in the strength of the ACC. As pointed out previously, these changes need time to affect the ACC transport. In fact, the strength of the ACC does increase markedly only after the year 2100. At the end of the 23hd century, it reaches 150 Sv.

At that time, the model re-establishes warm CDW south of 60^{o}S that was destroyed by excessive convective activity in the control run. The NADW domain cools while the AAIW domain becomes warmer. The strongest warming is present in the upper 1500m between 50^{o}S and 35^{o}S, the region affected by the stronger convergence of the Ekman transport. These tendencies persist throughout the 300 years of the integration (Fig. 3).

The lower branch of the NADW becomes fresher while the upper parts become more saline. The increased downwelling around 45^o/40^{o}S is also visible in the salinity field although less pronounced than in the temperature. There is an apparent stabilization of the stratification at the southern end of the section, consistent with the reestablishment of the CDW.

The density (sigma-2) decreases in the upper layers north of the ACC and increases south of the ACC (with the one exception of the shelf seas adjacent to Antarctica). This density change is associated with the acceleration of the ACC that occurs after the year 2100 in the scenario calculation.

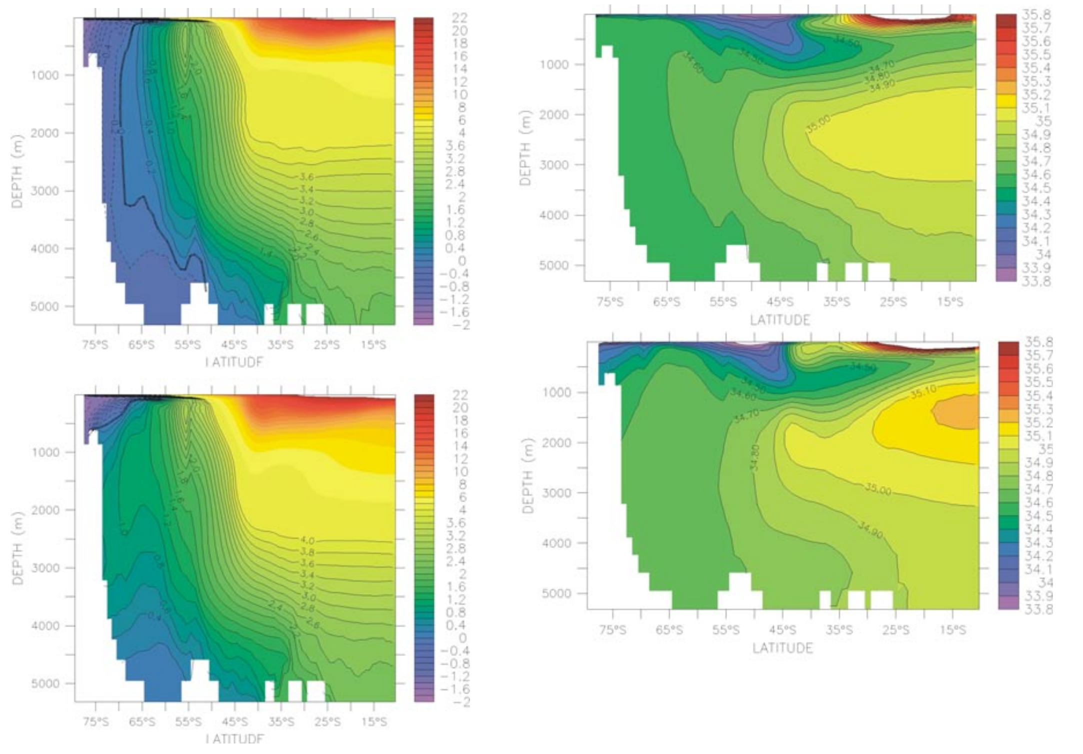

Figure 3. Potential temperature (left) and salinity (right) averaged over the Atlantic sector in the GFDL A1B scenario simulation for year 2100 (top) and year 2300 (bottom).

4. Summary:

The baroclinic potential energy is a useful diagnostic for changes in the ACC in models and in nature. The effect of different processes on the density distribution is usually easier to assess than the effect on the momentum or vorticity balance. We have here considered three examples from recent calculations with state-of-the-art global ocean circulation models. The external forcing of the ACC does not result in short term transport fluctuations because the most efficient density changes occur at depth and need time to establish. The shortest time scale in the models is associated with deep convection south of the polar front, something that is not commonly observed in nature. Changes in NADW production only become important after more than a century. The effect of NADW changes on the ACC is not straightforward and may differ from model to model. This implies that statements regarding the future strength of the ACC might not be robust.

References:

Borowski, D., R. Gerdes, and D. Olbers, 2002: Thermohaline and wind forcing of a circumpolar channel with blocked geostrophic contours, J.Phys.Oceanogr., **32**, 2520-2540

Gerdes, R., W.Hurlin, and S.M.Griffies, 2005: Sensitivity of a global ocean model to increased run-off from Greenland, Ocean Modelling (in press)

Griffies, S.M., A. Gnanadesikan, K.W. Dixon, J.P. Dunne, R. Gerdes, M.J. Harrison, A. Rosati, J. Russell, B.L. Samuels, M.J. Spelman, M. Winton, R. Zhang, 2005: Formulation of an ocean model for global climate simulations, Ocean Science, 1, 45-79.

Large, W., and S. Yeager, 2004: Diurnal to decadal global forcing for ocean and sea-ice models: the data sets and flux climatologies. NCAR Technical Note: NCAR/TN-460+STR. CGD Division of the National Center for Atmospheric Research.

Richard Matear (CSIRO Marine and Atmospheric Research, Hobart, Australia): The future of ocean carbon modelling in the Southern Ocean

This talk consisted of the following material:

A review the role of the oceans in the global carbon cycle. The oceans are largest active reservoir of carbon. Carbon stored in the ocean is 40 times greater than the anthropogenic carbon that has accumulated in the atmosphere in the last 200 years. On millennium time-scales, it is the ocean that determines the atmospheric level of CO_2. The oceans have the chemical capacity to eventually take up 80-85% of the anthropogenic carbon. Oceanic uptake is slow because of sluggish ocean circulation.

Presentation of the observed storage of carbon in the ocean, The southern mid- to high-latitude oceans are the largest zonally-integrated storage region of anthropogenic CO_2. Anthropogenic CO_2 is carried into the ocean interior by water masses formed in the SO. New estimates of anthropogenic CO_2 accumulation between 1980-99 are based on CFC-12 observations.

Discussion of the simulated CO_2 uptake by the oceans, with and without climate change - high variability in the Southern Ocean. The Southern Ocean accounts for ~50% of the inter-model variance in simulations of pre-industrial oceanic uptake of CO_2.

Presentation of the projected response of the Ocean and Terrestrial Carbon Cycles to global warming. Climate models suggest the Southern Ocean overturning will slow down as a result of global warming. Warming and freshening increases the high latitude stratification, shutting down AABW formation. Is this result realistic? Can we observe the change in stratification? What are the impacts? The Ocean response to global warming is small (< 100 PgC) compared to the terrestrial response (460 Pg). But the marine biological representation of ocean carbon models is extremely simple. How big could the oceanic uptake of carbon be?

Limitation of the present ocean carbon models and new questions to tackle. There is potential for the ocean carbon cycle to feedback on climate, but there are other important questions independent of the oceanic uptake of CO_2. How will the marine ecosystems response to direct impact of rising CO_2 in the oceans? Will other radiatively important gases be affected by global warming? Both questions are very relevant to the Southern Ocean

Discussion of the future developments of ocean carbon models. Southern Ocean has high nitrate concentrations in the surface water, which means there is a potential to stimulate the biological pump and increase CO_2 uptake. Southern Ocean is an important uptake region of CO_2, which is connected to ocean dynamics, and the uptake is sensitive to climate change. The Southern Ocean is the first region where aragonite becomes unstable in the surface ocean under rising CO_2 levels. The Southern Ocean phytoplankton have the potential to impact ocean dynamics. Changes in Southern Ocean sea-ice may affect phytoplankton production and ecosystem structure. In the Southern Ocean, DMS production is an important contributor to CCN - CCN doubles at 3x CO_2 atmosphere SO circulations changes are evident in BGC fields like dissolved oxygen. Present carbon models are insufficient to deal with important global warming impact questions such as (1) ecosystem impact of elevated CO_2, (2) potential changes in the structure and production of marine foodwebs. Future carbon models will incorporate a foodweb based approach (multiple phytoplankton functional groups and multiple elemental cycles). Such models will be more complex with many parameters. Increased model complexity will require the development of metrics to assess the model and targeted observations to monitor the ocean carbon system. Models can help design observing strategies.

Robbie Toggweiler (NOAA/GFDL, Princeton, USA): Origin of the 100,000-Yr Glacial-Interglacial CO2 Cycle in the Southern Ocean

Dr Toggweiler's summary of his presentation is as follows: Atmospheric CO_2 has varied over the last half million years with a sawtooth shaped cycle and a period of roughly 100,000 years. It is widely believed that the 100,000-yr cycle is linked to variations in the eccentricity of the Earth's orbit and that CO_2 is acting in some way to amplify the eccentricity forcing. Here, an alternative is presented in which the 100,000-yr glacial-interglacial cycles are internal to the Earth's CO_2/climate system.

The main feature of the proposed mechanism is a climate threshold associated with the westerly winds over the Southern Ocean. The threshold is a position or strength of the westerlies in relation to the position of the Antarctic Circumpolar Current (ACC). The southern westerlies in the warm interglacial of the present day are located relatively far to the south where they tend to overlie the ACC. Strong westerlies in this position cause a large volume of deep water to upwell to the surface between the ACC and Antarctica. The upwelling maintains a vigorous overturning circulation around Antarctica, which maintains, in turn, a high level of CO_2 in the atmosphere. The westerlies during cold glacial climates, on the other hand, were located relatively far to the north where they did not cause as much upwelling and as much overturning. The latter condition leads to a build-up of CO_2 in the deep ocean that reduces the level of CO_2 in the atmosphere. The tendency of the westerlies to shift/ strengthen in warm and cold climates becomes a positive feedback when linked to the ocean's carbon system. I argue in this talk that the intermediate state between the warm interglacial and cold glacial extremes is destabilized by this feedback so that the intermediate state is effectively a climate threshold.

I claim that the big glacial-interglacial cycles of the last half million years owe their existence to the fact that long-term mean pCO_2 of the atmosphere set by volcanoes and weathering happens to overlap with the intermediate pCO_2 associated with the threshold. This overlap explains why the climate system periodically finds itself back at the threshold where it is subsequently driven off to the next glacial or interglacial extreme. Climate excursions, like those associated with Heinrich Events, also play a major role in this idea. Interactions between these short-term excursions, the threshold, and the long-term geochemical constraints give rise to the particular shape and repeat time of the 100,000-yr cycle. In this way, the biggest natural climate changes of the last million years are not forced "top down" by changes in the Earth's orbit, rather they "bubble up" from interactions that are internal to the CO_2/climate system.
Annex A Schedule of Speakers

Nov 9: Observations and Dynamics

0845-1000: Steve Rintoul (CSIRO-Hobart): What can inadequate observations tell us about incomplete models?

1010-1125: David Webb (SOC): Ekman Transport and the Southern Ocean

1135-1250: Dirk Olbers (AWI): The circulation of the Southern Ocean - processes, dynamics and models

1300-1415: Lunch at CSIRO

1430-1545: John Marshall (MIT): Theories and models of the ACC and its associated meridional overturning circulation

1600-1715 : Aike Beckmann (Finland): The South End: Modelling of the Antarctic Marginal Seas

1730-2000: Dinner at CSIRO

Nov 10: Processes and climate change

0845-1000: Nathan Bindoff (UTAS): South of the Polar Front, modelling the Antarctic slope front, polynyas, eddies, icebergs, ice shelves and southern hemisphere climate

1010-1125: Matthew England (UNSW): Southern Ocean water-masses in climate-scale models

1135-1250: Rudiger Gerdes (AWI): Sensitivity of the ACC transport in IPCC and CORE simulations

1300-1415: Lunch at CSIRO

1430-1545: Richard Matear (CSIRO-Hobart): The future of ocean carbon modeling in the Southern Ocean

1600-1715: Robbie Toggweiler (NOAA/GFDL): Why is the Southern Ocean so Important for Climate Change?

International CLIVAR Project Office
National Oceanography Centre, Southampton
Southampton University Waterfront Campus
European Way, Southampton SO14 3ZH
United Kingdom
Tel: +44 (0) 2380 596777
Fax: +44 (0) 2380 596204
email: icpo@noc.soton.ac.uk