WCRP REPORT

World Climate Research Programme

Project Report

Report of the 6th Meeting of the CLIVAR/CliC/SCAR Southern Ocean Region Panel and the Workshop on the Upper and Lower Cells of the Meridional Circulation in the Southern Ocean

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ACTION: Search for new panel members (All panel. Speer and England to invite and recruit – with the approval of the SSG via the ICPO)

ACTION: Seek SSG approval for Dr. N. Lovenduski to join the panel (Speer/England/ICPO)

ACTION: ICPO to update the vision document and to reformat the frontiers and research directions as was done for the U.S. Southern Ocean CO_2 plan and to add some decadal predictability topics.

2. Introduction

2.1 Terms of Reference

In 2004 the Scientific Committee on Antarctic Research (SCAR) became the third co-sponsor of the Southern Ocean (SO) region panel. Thus the SO CLIVAR/CliC/SCAR panel is charged with refining and implementing the science plans of CLIVAR, CliC and SCAR in the SO Sector.

The terms of reference (TOR) of the panel are:

1. To design a strategy to assess climate variability and predictability of the coupled ocean-atmosphere-ice system in the Southern Ocean region.
2. To develop and refine an implementation plan for the Southern Ocean region that defines the process studies, sustained observations, and model experiments needed to meet the objectives of CLIVAR, CliC and SCAR.
3. To work in concert with relevant CLIVAR panels (e.g. regional panels, numerical experimentation groups), ACSYS/CliC Panels (DMIP, OPP, NEG) and other groups (e.g. Ocean Observation Panel for Climate, Argo Science Team) to integrate SO observations with those in neighboring regions to ensure the objectives of CLIVAR/CliC/SCAR are met and resources are used efficiently.
4. To enhance interaction between the meteorology, oceanography, cryosphere, biogeochemistry and paleoclimate communities with an interest in the climate variability of the SO region.
5. To serve as a forum for the discussion and communication of scientific advances in the understanding of climate variability and change in the SO region.
6. To work with the CLIVAR, CliC and SCAR data systems on issues related to distribution and archiving of SO observations.
7. To advise the CLIVAR, SCAR and ACSYS/CliC SSGs on progress achieved towards implementation.

For further details see: http://www.clivar.org/organization/southern.php

2.2 Main Aims

The main aims of the CLIVAR/CliC/SCAR Southern Ocean region panel are:

I. To design a strategy to assess climate variability and predictability of the coupled ocean-atmosphere-ice system in the Southern Ocean region.

II. To oversee and coordinate Southern Ocean region process studies, sustained observations, and model experiments needed to meet the objectives of CLIVAR, CliC and SCAR.

Further details can be found at: http://www.clivar.org/organization/southern/southern.php

2.3 Sixth Panel Meeting

The 6th meeting of the Southern Ocean (SO) region panel was held from the 14th to 17th of June 2010 at the National Oceanography Centre, Southampton, UK.

The meeting started with a welcome and introduction from the local host Kate Stansfield and panel co-chair Kevin Speer. Howard Cattle (director of the International CLIVAR Project Office - ICPO) then gave a brief overview and reminder of the remit of CLIVAR and the Panel.

Day one focused on a reminder of the meeting goals, an update on the state of the system, reports from and key research directions.

The science goals of this meeting were to explore the latest ideas for the dynamics of the Upper Cell, taking into account the presence of many of the key investigators being located in the UK, and to discuss missing elements and appropriate future observations needed to fill out our understanding of the Lower Cell, more specifically the inflow of deep water and outflow of bottom water.. These goals were intended to further the objectives of SOOS, and to help plan for collaborative studies with carbon and other groups. The panel meeting consisted of two half days for panel only discussions and three half days of science presentations and discussion. The science sessions were broadly organized by talks on upper cell overturning circulation and processes and talks on lower cell overturning circulation and processes.

The main actions and outcomes from the meeting are summarized here; this is not intended to be a faithful summary of each individual presentation. Where appropriate, relevant updates since the meeting have been highlighted.

We take this opportunity to thank Kate Stansfield and Sandy Grapes for organizing the local logistics so well, and also Alberto Naveira Garabato, Gareth Marshall and the National Oceanography Centre, Southampton for providing us with the venue for the meeting, lunches and refreshments.

3. Panel Meeting Outcomes and Agreed Actions

3.1 SOP6 Monday Morning and SOP6 Thursday Morning (Panel Only)

3.1.1 New Business, Meeting Framework and Goals

The panel were reminded of the forthcoming World Climate Research Programme (WCRP) Open Science Conference (Climate Research in Service to Society) to be held from 24-28 October, 2011 in Denver, USA. The panel asked what the structure of the conference was going to be and whether a Southern Ocean session could be proposed.

ACTION: Investigate the structure for the conference and discuss with co-chairs what could be a suitable contribution from the panel (Stansfield/ICPO, panel co-chairs)

It was announced that the ICPO would have a new director, Dr. Bob Molinari, from the 1st September 2010.

The panel next considered the preparation of a Southern Ocean review article (proposed at the panels 5th meeting in Sydney in 2009). One suggestion is to consider what happens to overturning with future climate change. Another suggestion would be to produce a more focused article with possible topics being freshwater fluxes or CO_2 fluxes in the Southern Ocean and what future changes might be. Alternatively, or in addition, the panel could produce a reference article proposing benchmark tests for global ocean circulation models, which are specific to the Southern Ocean.

3.1.2 Climate Modeling Status, Goals - England, Goosse

The main activities in climate modeling since the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) are: additional analysis of existing simulations (weighting of models); and preparation of the models/simulations for the IPCC Fifth Assessment Report (AR5). Model tests and validation in the Southern Ocean include tests at the process level and reproducing the main characteristics of the observed mean state and recent trends. For example, ozone only models appear to produce slightly better agreement with the sea-ice observations and getting the SAM right does not mean that the model gets the sea-ice coverage correct.

The main aim of the IPPC class models is to get the best projection of climate change. Instead of performing simple multi-model average, the results of the various models could be weighted according to some measure of their performance, for example based on hindcast performance. But how would a specific model be excluded or weighted? Should we continue with model democracy or should some models be removed based on objective/subjective criteria? We do not have a good way to evaluate the models so how do we choose the "right" way to weight the various models.

For example, could we select a set of key observations/diagnostics to make a benchmark of models in the Southern Ocean and/or should we insist on the evaluation of multi-decadal timescales to determine the weighting of individual models. A key point is that where the signal is strong models should reproduce this signal (preferably on multi decadal time scales).

The AR5 simulations begin in haste so the panel should produce a short list of parameters/processes the models need to get right for the Southern Ocean and send this list to the Coupled Model Intercomparison Project Phase 5 (CMIP5) group. Diagnostics could include: the strength of the ACC; sea ice extent; the position of the maximum Westerly's; and basin divergence of heat and freshwater. The list could comprise of a fundamental level of diagnostics (i.e. the models should not get these wrong) and a fine-tuning list (e.g. processes, stratification, mixed layer depth), which could provide targets/benchmarks for processes that are important for the ocean overturning. It is important to produce quantitative metrics that are easy for the modeling community to evaluate.

ACTION: Panel to produce a list of five or six diagnostics for SO to submit to CMIP5 (All)

The panel discussed the use of different timescales in model evaluation (e.g. seasonal/decadal). It was felt that mean and seasonal timescales are already considered as they are such a strong feature of the observations (e.g.

sea ice extent). Decadal timescales, however, are more difficult as there are fewer multi decadal datasets for model evaluation. It was suggested that perhaps ocean hindcasts could provide a “data set”. For example, for sea-ice, perhaps the last 30 years of observations are not enough to address decadal predictability (e.g. the large variability in the Weddell Sea polyna). Of the major oceans the SO has one of the shortest data time series and the question is whether the last 30 years are representative of, say, a 100-year average.

3.1.3 Process modeling status and goals – Naviera-Garabato

Current themes in Southern Ocean process modeling are:

a) Southern Ocean overturning (and carbon system) response and ACC adjustment to perturbed climatic forcing with the aim of understanding how the Southern Ocean MOC and ACC transport respond to changes in wind and buoyancy forcing and in low- and high-latitude mixing and convection.

b) Transport across jets with the aim of understanding the physical controls of eddy-induced mixing across jets, and jet formation itself.

Emerging themes include:

a) Eddy-topography interactions / internal wave radiation / loss of geostrophic balance with a focus on understanding the energy and momentum balances of the ACC and the role of unbalanced motions in the Southern Ocean overturning (lower cell).

b) Upper-ocean physics / subduction in the ACC – present studies overlook the top boundary condition, the role of mixed layer processes, seasonality and other processes in the upper cell.

c) Variability of Antarctic Slope Front (ASF) and shelf-slope processes – knowledge of ASF processes involved in Antarctic Bottom Water (AABW) formation and ice shelf melting rudimentary at best, critical for sea level rise.

d) Subpolar gyre adjustment to perturbed forcing – impact of changes in the wind on AABW export by modulation of subpolar gyre baroclinicity.

Upwelling was identified as a key process at the U.S. Southern Ocean Carbon, Ecosystems and Biogeochemistry meeting but what are key processes that control getting water into the surface mixed layer? Ekman pumping? The seasonal cycle of entrainment?

3.1.4 SOOS Observations, process and sustained status, goals - Rintoul, Fahrbach

When SOOS is fully implemented the Southern Ocean will be the first to have a multi disciplinary observing system. There are still gaps, however, in the number of sustained observations in the plan and also with planned links to the carbon and ecosystem communities.

Bridges need to be built between LTER/ecosystem programs and SOOS and an expansion of observations in the vicinity of ecosystem projects might be considered especially in the light of the retreat of sea ice from the W Antarctic peninsula. If a new LTER-like site were to be proposed where should it be located and what should it measure?

The final SOOS document will be ready for the SCAR meeting in Buenos Aires in August, however there are still some weaknesses in terms of biology and carbon. The biological community is not used to thinking in the “big picture” and typically do not have sensors that as are advanced as say the physics or chemistry groups. The carbon community have been working on their own “global” science plan so it has been hard to get their attention to help strengthen the SOOS plan.

The panel queried the status of O_2 sensors on Argo floats. Currently there are only about a dozen floats with the sensors but 10 more are expected to be deployed in the coming Antarctic field season.

However there are significant stability issues with the sensors. The panel commented that if the community wishes to augment the ARGO floats with biological sensors then what sensors would be required and what would be the correct number of floats?

It was noted that JAMSTEC will be deploying two surface flux moorings: one at 60°S (south of Australia); and one at 47°S. The intention is that the 60°S be subjected to "ice" (rime ice). In addition, an ORION mooring will be deployed at 55°S mooring. These locations should be added to the SOOS diagram.

It was also reported that the LTER project will be deploying 6 moorings and 3 gliders every year (currently summer only) with plans to run the gliders between Palmer and Rothera.

ACTION: Add new mooring locations and make corrections to the SOOS diagram – panel to input updates to Kate (Stansfield/panel)

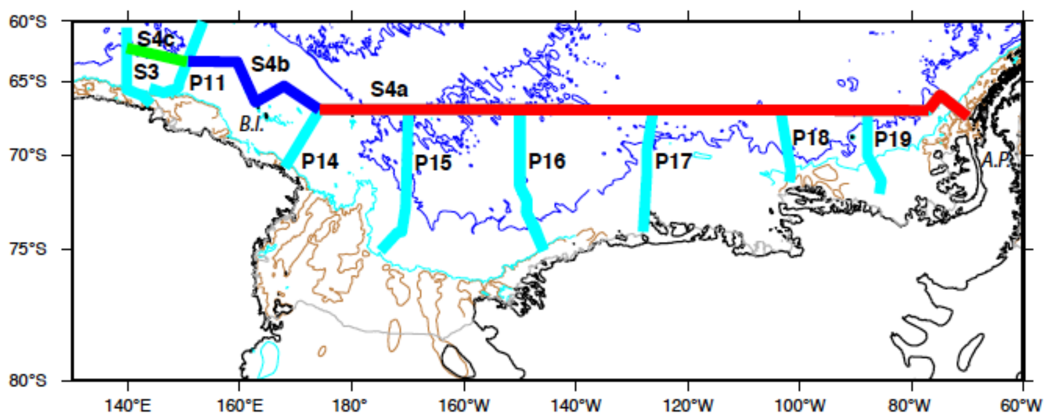

Figure 1: S04 track: "S4P" 2011 on the R/V Nathanial. B. Palmer will sample the red lines, which are drawn schematically here. East of 150°W station spacing will be adjusted so that the easternmost point is reached before running out of time to go to port. Extensions of the sections toward the Continent are meant to reach the continental shelf or water shallower than ca. 400-500 meters.

It was suggested that the ARGO program could be used as a model for the future implementation of SOOS. The SOOS community need to decide whether the observing system will operate in active or responsive mode. The lack of champions for the program is the biggest threat to SOOS - not enough people are really committed at the present time. Currently the load is carried by the research community and there is no single agency to sponsor or support the observing system.

There is an International group for discussing Antarctic base activities; however the ocean component is mostly overlooked. As with SCAR, the SOOS needs a long-term commitment of say 10 to 15 years initially. It was mentioned that should such a commitment be forthcoming it would be possible to host a SOOS secretariat at Hobart.

3.1.5 Vision document revisions for CLIVAR SSG – Speer / All

In 2009 the Southern Ocean panel produced a vision document which was submitted to the CLIVAR SSG (see Appendix B). In light of the transition of WCRP to a new structure by 2013 the panel were asked to review the latest version of the vision document and feedback to the SSG (through the Southern Ocean co-chairs) any places where the proposed WCRP structure does not fit with the Southern Ocean vision.

Kevin Speer also requested that the panel reconsider the vision document especially with regard to future grand challenges for the Southern Ocean (e.g. the ACC and the role of eddies), bearing in mind that major programs (such as DIMES) can take 5 or more years to spin up.

ACTION: Panel to review the vision document with regard to the emerging new structure of WCRP and future grand challenges for the Southern Ocean (all panel)

3.1.6 Panel membership

The panel is down to 10 members (other basin panels have up to 14) and Steve Rintoul and Doug Martinson are rotating off. In addition, Eberhard Farbach (ex-officio) wishes to end his link with the panel and Kevin Speer is due to stand down as co-chair.

In discussions a replacement co-chair from the panel was not forthcoming so Kevin has agreed to stay on until the next panel meeting in 2011. A new co-chair must be recruited before the next panel meeting in 2011.

In addition to replacing panel members the SSG has suggested that the panel should include a representative from the ocean carbon community and also the ocean ecosystem community.

There was concern over where the SO panel now overlapped with the Antarctica and the Global Climate System (AGCS) group and the Joint SCAR/SCOR Oceanography Expert Group (historically AGCS had emphasis on the Atmosphere/cyrosphere/paleo parts of the system only).

Dr. Nikki Lovenduski has agreed to join the panel to represent the carbon community (subject to SSG approval). Panel members are asked to help identify additional names who can then be approached by the co-chairs.

ACTION: Search for a new co-chair. (Speer and England to identify and recruit – with the approval of the SSG via the ICPO)

ACTION: Search for new panel members (All panel. Speer and England to invite and recruit – with the approval of the SSG via the ICPO)

ACTION: Seek SSG approval for Dr. N. Lovenduski to join the panel (Speer/England/ICPO)

3.1.7 Vision document – revisited in light of the meeting

In the panel discussion it was suggested that the vision document that the panel produced in 2009 was too long and would deter program managers from reading it. The suggestion was to delete the introduction and progress sections and reformat the frontiers and research directions bullet points into a table format much as was done for the U.S. Southern Ocean CO_2 plan. It was suggested to remove some Arctic specific topics from the document. In addition the plan lacks any mention of decadal predictability for e.g. the CO_2 sink, greenhouse gases and ozone etc.

ACTION: ICPO to update the vision document and to reformat the frontiers and research directions as was done for the U.S. Southern Ocean CO_2 plan and to add some decadal predictability topics.

The panel wondered whether publication of a "glossy" document of the Southern Ocean imperatives which could be distributed to NSF program managers and NERC theme leaders (for example) might help leverage support for the long term goals outlined in the SO vision? It was hoped that the SO vision would feed into what will follow on from the Antarctica and the Global Climate System program.

3.1.8 Review for submission to Reviews of Geophysics

The panel discussed the structure and focus of this review. There were two possible options:

An "ozone to sea-ice review" from top to bottom including ocean, atmosphere, cryosphere processes or a more targeted paper on SO dynamics, the role of eddies and what the IPCC class models can and cannot reproduce – possibly for submission to the Journal of Climate (or similar).

3.1.9 Date of next meeting

It was proposed to hold the next panel meeting in October 2011 either before or after the WCRP Open Science Conference (Climate Research in Service to Society) in Denver, Colorado.

Since the panel meeting the EOL Atrium in the NCAR Foothills Laboratory has been booked for the meeting (Oct 19-21).

4. Science talks – the Upper and Lower Cells of the Meridional Circulation in the Southern Ocean

4.1 Background

Eddy transport and mixing appears critical to the dynamics of the global Meridional Overturning Circulation (MOC). In the Southern Ocean, deep and intermediate waters are hypothesized to move south and upwell in two cells, an upper cell and a lower cell. At the surface in the upper cell, water masses are carried by the wind to the north and transformed into Subantarctic Mode Waters, which in turn downwell, and spread to temperate latitudes.

In the lower cell, water upwells near the continent and mixes into the dense plumes that eventually produce Antarctic Bottom Water. Since the primary current of the Southern Ocean, the Antarctic Circumploar Current (ACC), is zonally connected above mid-depth bathymetric obstructions, the zonally integrated meridional geostrophic current must vanish above those obstacles. The dominant mechanism for the meridional transport of mass, heat, and potential vorticity above the bounding topography and below the wind-driven Ekman layer at the latitude band of Drake Passage is thus believed to be quasi-geostrophic, mesoscale eddy motions and standing waves.

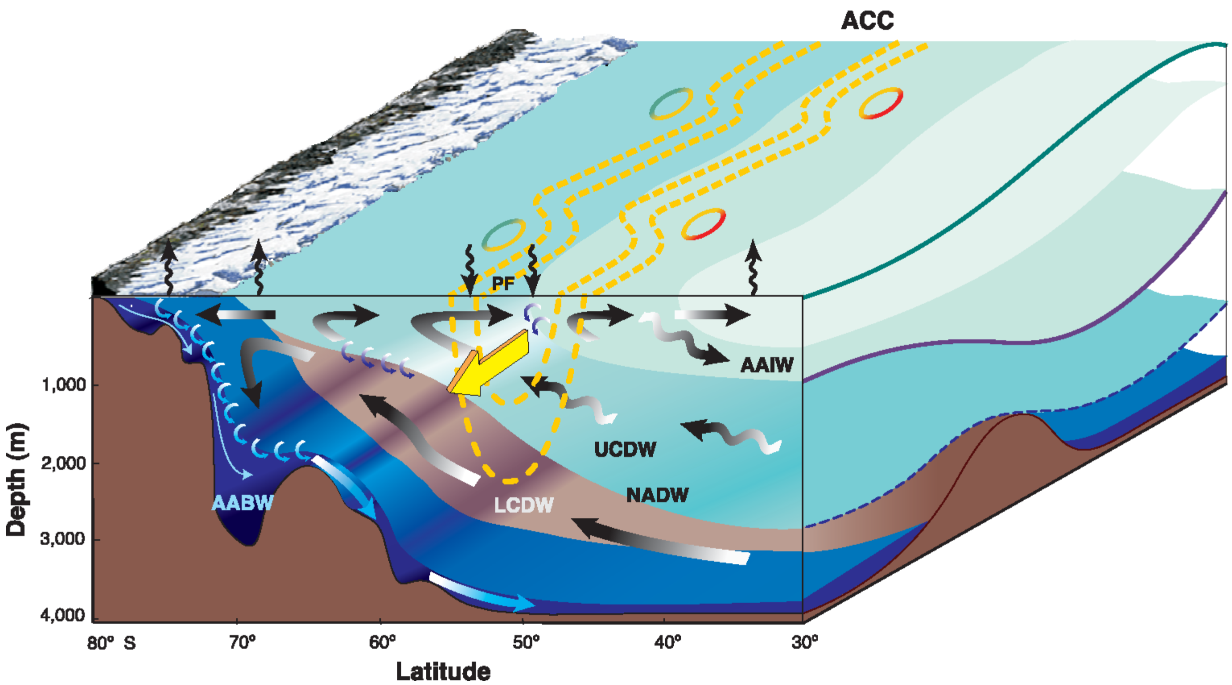

Figure 2: Schematic of the Southern Ocean MOC including the wind-driven Ekman transport, deep and bottom water flow supported by topography, and eddy-driven mass fluxes at mid-depth, adapted from Speer et al., (2000).

4.2 Monday Afternoon - Lower cell

Chair: Kevin Speer

4.2.1 Introduction – Kevin Speer

The strength of the MOC appears to be controlled by the competition between wind and buoyancy forcing. In the Atlantic the strength of the MOC is determined roughly half by subpolar gyre convection and half by the strength of the overflows. The variability of the AMOC seems to be due to the variability of the wind forcing, as the variability of the strength of the overflows appears to be weak.

In the Southern Ocean other factors such as coastal polynas, occasional open ocean polynas, overflow plumes, and entrainment and mixing over topography also need to be considered.

Processes affecting the Lower cell that are as yet not well understood are:

- Deep diapycnal flux(es);
- Cross – ACC pathways;
- Entrainment (plumes and ridges);
- Bottom water evolution; and
- Control by wind and buoyancy flux.

4.2.2 Aspects of the Atlantic sector Deep MOC in recent GO-SHIP sections – Brian King

Estimates of the cumulative transport through Drake Passage on the SR1b section since 1993 indicate that there is a bi-modal pattern in the location of the Polar Front. The exception to this being the intermediate location of the front in the 2005/06 season. The observations in Drake Passage, over the period 1993-2009, also show no significant trend in either volume transport or temperature, hence for this ocean region any trend is either absent, or small and masked by interannual variability.

A comparison of AABW transport at 24^{o}S from a section completed in 2009 with one completed in 1983 implies that there has been an increase in the Northwards flow of the coldest water for both water colder than 0.7^{o}C and water colder than 0.9^{o}C.

At 24^{o}N, on the RAPID moored array section, there appears to be cooling and freshening of the deep waters (2010 relative to 1981) over much of the western basin. The total volume of water on this section with a temperature colder than 1.8^{o}C does not appear to have changed much, however the coldest classes, which had a maximum volume in 1998, now appear to have gone (2010). The question remains as to whether decadal variability can be identified in the deepest water masses. Data from the deepest RAPID mooring (WB6) have shown up to 1.8 Sv variation in bottom water transport over a period of 6 months. Data from the RAPID array over the next few years should provide a better idea of the transients.

4.2.3 Processes at the Antarctic continental slope and shelf; the ocean's interaction with ice –Karen Heywood

It is clear that our ocean climate models do not get the bottom water transport right in the Southern Ocean, however improving the models to include more of the relevant processes is a big challenge as we do not understand the seasonal cycles round the Antarctic.

The Synoptic Antarctic Shelf-Slope Interactions (SASSI) project was designed to deliver understanding of continental shelf and slope processes (a critical contributor to global climate variability), to adequately allow their accurate representation in climate models that could then be used to predict this variability. In addition, interannual and seasonal variability would be documented for the first time in many locations.

So far results have shown: that that an offshore movement of the slope front in Autumn and Spring introduces cold fresh water (shelf water) at 1000 m; that periodic fluctuations in the slope front in summer bring warm, salty water onto the shelf; and that there is high frequency variability in winter at 500 m, implying that the front is inshore.

The SASSI project is yielding a wealth of data which will hopefully allow a circumpolar, multinational syntheses of processes such as continental shelf waves, eddies, instabilities and tides, the magnitude of the seasonal cycle in transport, water mass properties, identifying the mechanisms for transporting heat to melt ice sheets, and the role of undercurrent and forcing mechanisms.

Processes that will (eventually) need to be included in climate models may include:

- Dense water formation on the continental shelf;
- Tides;
- Narrow slope currents (as mechanisms preventing and/or facilitating exchange);
- Topographically trapped waves;
- Ice shelves;
- Accurate seasonal cycles (sea ice); and

- Downslope flows, entrainment and mixing (as mechanisms setting deep/bottom water densities).

4.2.4 Processes influencing the properties of AABW exported from the Weddell Sea into the Atlantic overturning – Mike Meredith

AABW export from the Weddell Sea appears to be controlled by the Weddell gyre's baroclinic adjustment to wind forcing on time scales of several months. Variability in the regional winds seems to be closely linked to the Southern Annular Mode (SAM). There is also evidence to suggest that there may be a causal relationship between the SAM's positive tendency observed in recent decades and the subsequent warming of AABW detected across much of the Atlantic Ocean. This warming is evidence of a major change in the properties of the lower limb of the oceanic overturning circulation, originating in the Weddell Sea and transiting through the Scotia Sea.

4.2.5 Evidence of Decadal Fluctuations in the Water Mass Properties in the Atlantic sector of the Southern Ocean – Eberhard Fahrbach

Data collected as part of the Weddell Sea Convection Control project (WECCON) have shown that there are pronounced variations, on a multi-annual time scale, in the water mass properties of the Warm Deep, the Weddell Sea Deep and the Weddell Sea Bottom Water, the Winter Water, and the winter sea ice thickness. Whereas the overall average temperature and salinity are increasing on the Greenwich meridian over 24 years of observations, the source water is subject to decadal variations.

Whilst Weddell Sea Bottom Water is warming at the Greenwich Meridian, it has been cooling in the main basin of the Weddell Sea since the early 2000s. Regional processes are able to transform the time scales of external forcing into time scales of internal reaction. For example, variations in the gyre circulation affect the water mass properties by controlling the inflow of source water masses. To follow the ongoing variations a Southern Ocean Observing System (SOOS) is needed.

4.2.6 Formation, export and variability of AABW in the Indian and Pacific sectors – Steve Rintoul

Recent simulations of the deep overturning, using a box inverse model and data from the WOCE and CLIVAR hydrographic sections and the gridded ARGO product, have shown a possible weakening in the overturning with a decrease in the outflow of Antarctic bottom water (AABW), and also a decrease in the inflow of upper circumpolar deep water (UCDW).

The results show a continued freshening of Ross and Adelie Land AABW (ALBW). A leading candidate for the cause of this freshening is the addition of glacial melt water from the SE Pacific (and perhaps more local sources), and/or a decrease in sea ice formation for ALBW. In addition there is a warming signature in abyssal waters in all basins. Using the model we have also quantified the seasonal cycle of bottom water properties and export of ALBW. Our results have confirmed that the Kerguelen deep western boundary current carries ALBW and RSBW equatorward and that there is a "spin up" of the barotropic flow where the SAF negotiates a narrow gap in the Macquarie Ridge.

In the upper limb, the subduction of mode water occurs in "hot spots" and we have inferred a pattern consistent with the distribution of potential vorticity and anthropogenic carbon on isopycnals. In the ACC, the regional pattern of sea-level rise reflects shifts in position of ACC fronts.

4.2.7 Prospects for Determining Antarctic Sea Ice Thickness from Space – Seymour Laxon

Recently, progress has been made in determining the thickness of Arctic sea ice from satellite radar altimetry. The technique involves bouncing a radar signal off the ice surface; although layering in the snow complicates the signal. In the Arctic this method for acquiring sea-ice thickness data has also been validated against submarine data.

Extending the same technique to Antarctic sea ice is complicated because Antarctic sea ice has a number of properties that are significantly different to Arctic sea ice. For example, the surface of Arctic sea ice is typically above sea level and the snow cover typically melts completely during the summer months. In the Antarctic the situation is more complicated as the ice is thinner and its surface is often weighted down by snow, to the point that it is pushed below sea level. This causes the base of the snow layer to flood, complicating the radar signal returned to the satellite.

It is thought that combining laser and radar measurements of sea ice thickness should lead to improvements in our ability to determine sea ice thickness remotely in the Antarctic. However more in-situ data, especially Upward Looking Sonar data and long time series/transects of data, will be needed to validate the satellite observations.

4.3 SOP6_Tuesday Morning Upper Cell, physics, carbon and freshwater fluxes – I

Chair Alberto Naveira-Garabato

4.3.1 Equilibrium and adjustment of the Antarctic Circumpolar Current – David Marshall

The simple two-layer model of Gnanadesikan (1999), which assumes thermal wind balance and weak flow in the abyssal layer, suggests that the ACC transport is determined by Southern Ocean wind forcing, North Atlantic buoyancy forcing, and diapycnal mixing from breaking internal tides (i.e., the moon!).

A simple momentum balance for a tidally-driven ACC might assume that: i) diapycnal mixing deepens the pycnocline; ii) the North-Sourth density gradient induces a density current; iii) the Coriolis force (rapidly) deflects flow to the left; and iv) bottom form stress kills bottom flow.

The main findings from the Gnanadesikan (1999) model are:

- The ACC is driven by both Southern Ocean winds and diapycnal mixing;
- The North Atlantic MOC also influences ACC strength;
- The equilibrium ACC is sensitive to eddy parameterization;
- The relevant wind stress is the integral across the ACC, not at its northern edge, nor at the northern tip of the Drake Passage;
- Adjustment/spin-up time-scale is set by eddy parameterization;
- Adjustment also depends on the area of global oceans to the north (therefore there is a need to be careful interpreting results from channel models over limited latitudinal extent); and
- In the global ocean, seiching modes between basins can also be excited during ACC adjustment.

Questions remain as to how the upper cell changes in response to forcing (especially the Gent-McWilliams eddy parameterisation). Both the equilibrium ACC and its adjustment are determined by eddy diffusivity across the ACC. This has important implications for climate models; as in IPCC class models it is hard to resolve the shorter scale changes in the pycnocline (the models are not eddy resolving). The Hobart group are constructing an "eddy-resolving box model" that can both resolve eddies and be repeatedly integrated to equilibrium (5000 years). It is important to note that thermohaline feedbacks are still important even if they are not a significant energy source, and that as the pycnocline moves up and down and meridional circulation changes, there may be large feedbacks onto atmospheric CO_2. This may have implications for the response of ocean to anthropogenic forcing.

4.3.2 Jet-Topography Interactions in the Southern Ocean – Andy Thompson

The ACC is partitioned into a series of distinct water masses separated by fronts or jets. Topographical steering produces zonal asymmetry; traditional hydrographic definitions identify three circumpolar fronts. Satellite altimetry data and numerical models reveal that the ACC is comprised of an intricate web of fine-scale jets. Hence it is not necessarily possible to track any individual feature circumpolarly.

Spatial characteristics show multiple jets or fronts across the ACC with a narrow, filamentary structure, i.e. not purely zonal features. Temporal characteristics show topographical localization; jets are observed to drift and merge and jets may appear intermittently.

Relevant questions include: what dynamical processes might give rise to the fine scale structure of the ACC? How does this fine scale structure impact mixing and how do mixing properties vary along the path of the ACC?

Jets form when a large-scale gradient of Potential Vorticity (PV) permits wave motion. PV (tracers) is mixed between the jets and the inversion of a sharp PV gradient produces a narrow eastward flow.

Jets persist because: i) the variation of the Coriolis force with latitude generates a zonal flow; ii) baroclinic instability leads to eddy formation; iii) Reynolds stresses force the upper layer; and iv) the system is balanced by form drag and bottom friction.

When jets encounter bottom topography, steering of the flow generates non-zonal mean flows. The eddy kinetic energy rises and eddy length scales grow. When the mixing length exceeds the topographic scale, zonal jets emerge; following this eddy energy decays and jet spacing reduces. Major topographical features are associated with re-organization of the front structure. (Almost) circumpolar homogenization occurs along the 36.50 density surface. Multiple fronts are most evident over flat topography.

It appears that topography contributes to unsteady jets in the ACC (but this is not the only mechanism). Unsteady jets localize mixing in space and time. However topography is also a catalyst for jet re-organization. Incorporation of this along-stream variability is a challenge for ACC modeling and parameterization.

4.3.3 Sea level in the Southern Ocean: What does it tell us? – Chris Hughes

Close to Antarctica, sea level variability is dominated by a barotropic "Southern Mode", which accounts for about 50% of transport variance. To the north, eddies and baroclinic variability become much more important, making it much harder to measure the "Northern contribution" to transport changes. In the ACC itself, variability is a combination of complex, nonlinear baroclinic eddy variability which is swept downstream, and stationary (or near stationary) meanders which are essentially barotropic Rossby lee waves. There remains much more information in sea level than has been fully exploited so far (e.g. kurtosis, vorticity fluxes, Sokolov/Rintoul front identification).

4.3.4 Regional Variation of the Surface Eddy Diffusivity in the Southern Ocean – Emily Shuckburgh

Lyapunov exponents and vectors provide a powerful theoretical and practical framework for the analysis of the instabilities that can develop in a dynamical system. The Lyapunov diffusivity combines the tracer-based effective diffusivity with the particle-based Lyapunov exponent. Hence Lyapunov diffusivities may be a new way to characterise eddy diffusivities from observations (e.g. float trajectories and satellite altimetry, although care must be taken in regions of strong horizontal shear). At the surface of the ocean, the total eddy diffusivity is a combination of the effects of stirring and air-sea interaction, thus different tracers can have different eddy diffusivities. In addition regional diffusivities can be influenced by eddy-mean flow interactions and mixing can be non-local (i.e. some mixing may be advected where as some mixing may be locally generated).

4.4 SOP6_Tuesday Afternoon - Upper Cell, physics, carbon and freshwater fluxes – II

Chair: Gareth Marshall

4.4.1 Buoyancy forcing of an eddy-saturated ACC – Andy Hogg

There is strong evidence that quasi-geostrophic and adiabatic layered models of the ACC are in an eddy-saturated regime but the jury is still out on diabatic models (and the real ocean). The eddy saturation question is relevant mainly because eddies control poleward heat transport across the ACC. An idealised channel model of the ACC, with both buoyancy forcing and wind stress, appears to be completely eddy saturated, on the other hand, ACC transport also appears to be sensitive to the strength of the buoyancy forcing! The true driving mechanism of the ACC is still unclear, but it seems that surface buoyancy forcing cannot be discounted. However, how the buoyancy flux is applied (in both time and space), and how the buoyancy forcing and wind stress are applied spatially, could alter the results.

4.4.2 Update on the Southern Ocean source/sink for atmospheric CO_2 – Andy Watson

The temporal and spatial variability in surface water CO_2 concentrations make it challenging to evaluate global fluxes based on in situ measurements alone. The latest global flux climatology, based on approximately three million measurements collected between 1970 and 2007, gives a net ocean uptake of 1.4 ± 0.7 GT-C yr^{-1} (Takahashi *et al*., 2009). This figure has been revised downwards from the previous estimate of GT-C yr^{-1} (Takahashi *et al*. 2002). Measurements of carbon in the Southern Ocean are sparse, especially in winter, with the exception of the Southern Indian Ocean. This makes it difficult to assess whether the Southern Ocean is a source or sink of CO_2 to/from the atmosphere.

The Polar Southern Ocean is the region where North Atlantic Deep Water (NADW) returns to the surface. The NADW takes atmospheric CO_2 into the interior as it sinks, so we would expect it to outgas when it returns to the surface (more generally, upwelling regions are sources, downwelling regions are sinks). For "natural" (pre-industrial) carbon we would expect the Southern Ocean to be a source but for "anthropogenic" carbon (the perturbation due to increasing CO_2) it is a strong sink because the surface water is rapidly ventilated. However the decomposition into pre-industrial and anthropogenic is only valid so long as the circulation does not change. It is thought that there was more upwelling in the recent past and that the overturning circulation is currently more vigorous than it was. Overall therefore, today it is (probably) a weak sink for atmospheric CO_2. Except in a few well-studied regions (e.g. the Southern Indian Ocean) we do not have sufficient data to answer the source/sink question by observation, in particular more wintertime observations are needed. It is also uncertain whether the CO_2 sink is increasing in time or is nearly constant. If a stronger phase of the Southern Annular Mode (SAM) leads to increased upwelling (due to stronger winds) then the sink should be nearly constant. Such observations as there are suggest that this is the case.

4.4.3 Southern Ocean Air-Sea Fluxes: Recent Developments – Simon Josey

In the Southern Ocean the annual mean heat exchange is close to zero (although the individual terms in the heat budget are large), thus it is unclear whether the ocean gains or loses heat over much of the region (dataset dependent). There is also a strong seasonal variation and attempts to estimate air-sea exchanges in Southern Ocean are plagued by the lack of observations. All available flux fields have significant sampling problems including the reanalysis datasets. Measurements of the sea surface temperature from ships and floats give reasonable coverage of the Southern Ocean however, calculating the latent and sensible heat fluxes also requires wind speed, air temperature and near surface humidity measurements. There is some coverage in the Southern Ocean of latent heat flux observations in summer, but virtually nothing in winter. New surface flux moorings offer the potential for accurate evaluation of reanalysis fields at specific locations and the results may be more widely applicable. Of course the annual mean field never actually occurs, instead there is strong seasonal variation resulting from the changing balance between the latent / sensible / longwave heat loss and the shortwave gain.

In March 2010 a Southern Ocean Flux Station (SOFS) was installed at 46.75 ^{o}S, 142 ^{o}E, 350 nautical miles Southwest of Tasmania in the Sub-Arctic Zone, a region with strong biological activity. This station is funded through the Integrated Marine Observing System for Australia (IMOS). Details of the flux station and the instrumentation can be found at: http://www.cawcr.gov.au/projects/imos/sofs/index_.php.

Preliminary analysis by Josey of data kindly supplied by Eric Schulz shows surprisingly good agreement between NCEP and SOFS turbulent heat loss terms but this is for an extremely short period, Mar 17 - June 5, 2010, so no conclusion should be drawn from this result - subsequent research will examine a longer time period spanning the austral winter and only then will it be possible to make a definitive statement on the quality of NCEP in this region.

The Japan Agency for Marine-Earth Science and Technology (JAMSTEC) are also planning a flux buoy for 60°S, 140°E just north of seasonal sea-ice edge. It was commented that moving the buoy North to 55 °S might provide a more interesting contrast with the SOFS site as NCEP infer a significant net heat gain according in this region.

To gain the maximum benefit from these two new flux stations it is vital that the data are not assimilated into the reanalysis products for the time being. Advances in precipitation sensor technology could also lead to major improvements in the freshwater flux estimates for the region (and hence the buoyancy exchange).

4.4.4 Southern Ocean CO_2 Fluxes and Acidification: Recent Changes and Future Projections - Nikki Lovenduski

Models and observations find that the Southern Ocean is a sink for atmospheric CO_2. The magnitude of the sink is model dependent and a function of physical and biogeochemical parameterizations. A number of model studies have shown that the Southern Ocean CO_2 sink has weakened over the past few decades as a result of stronger winds (at about 55 °S due to the SAM being in a more positive phase) and overturning. These same changes have enhanced acidification in the high latitudes. There is some observational evidence to support the idea of a weakening CO_2 sink. The CO_2 sink is expected to weaken with changes in the stratification.

4.4.5 Twentieth century behaviour of the Southern Annular Mode – Julie Jones

Century-length SAM reconstructions have been produced using observations of sea level pressure from meteorological stations (Jones *et al*., 2009). These reconstructions have now been used to evaluate the SAM in IPCC AR4 model simulations (Fogt *et al*., 2009). The SAM reconstructions were compared with 17 coupled atmosphere-ocean GCM simulations, 11 of which employ time-varying ozone forcing. It was found that models underestimate the persistence of strong historical SAM anomalies. Only in December/January/February is there a clear anthropogenically forced component in the SAM trend (forced by ozone and Greenhouse gases - GHG). March/April/May trends may have a forced component, but there are peaks and stronger trends earlier in the reconstruction, which are not captured by the models. For June/July/August, both models and reconstructions show no significant trends. The models demonstrate forced trends in September/October/November (which Arblaster and Meehl (2006) find is in response to GHG forcing), while the observations do not, so caution must be used when interpreting model results in this season. Finally, March/April/May and September/October/November observations indicate perhaps that tropical-extratropical interactions, and/or tropospheric-stratospheric coupling is not well resolved by the models.

The SAM reconstructions imply that there was a switch around 1945/50. It should also be pointed out that the SAM is not really annular. It has been shown that the wave number three pattern is important over the Southern Ocean. It is likely that recent changes in the wave number three pattern reflect natural decadal variability in the long wave patterns over the Southern Ocean rather than anthropogenic forcing, however no studies of this are known. The time series of observations is very short so it is hard to say definitively what is causing the variability, for example local/regional wind forcing may also play a role. The implication is to beware of over-interpreting changes in the SAM.

4.5 SOP6 Wednesday Morning

Chair: Matthew England

4.5.1 Ocean Heat Along the West Antarctic Margin: Unstoppable Glacial Melt? - Doug Martinson

Winter air temperature, measured at Faraday/Vernadsky, is increasing at a rate of 0.107˚ C/year, which is ~5.4 times the global average temperature increase. In the 20 years from 1979 to 1999, perennial ice along the Western Antarctic Peninsula has virtually gone and the winter sea ice season has shortened by 3 months. Of all the marine glacier fronts on the peninsula and associated islands, over the past 61 years, 87% have retreated. In addition, the Adelie penguin colonies in the region have seen a decrease in breeding pairs from15,200 in 1974 to 3,500 in 2007.

Fundamental here is the change of air temperature occurring in winter, when the sun is low and the atmosphere – even on the best days is frigid – suggesting that the only significant source of heat capable of contributing to these trends is the ocean.

Fortunately there has been a Long Term Ecologic Research (LTER) project situated in the heart of this change since 1992, sampling a 900 km by 200 km regional grid every Austral summer, and numerous non-summer months as well, allowing the role of the ocean to be investigated. Details of the sampling undertaken along with data and result from the project can be found at: http://pal.lternet.edu/

A Temperature-Salinity diagram from the surveys so far shows that of the four fundamental water masses in region, Upper Circumpolar Deep Water is the only source of "hot" water. The ACC is primary transporter of warm deep water responsible for the dramatic change (UCDW). It circles the entire Antarctic, so why, assuming the ocean is responsible for the heating, is the Antarctic western margin (continental shelves of Amundsen, Bellinghausen Seas: ABS) so unique? The ABS shelves are so different in the Antarctic because they are only location where the ACC lies close to the broad continental shelf. Elsewhere the shelves are buffered by the expansive polar gyres (and as a consequence of this isolation, the waters on those shelves have the opportunity to cool and grow saltier from brine release during sea ice formation, to form the global Antarctic Bottom Waters).

Most of our understanding of the ocean heat effect comes from sampling in the LTER grid, BUT, because the primary drainage region of the Western Antarctic Ice Shelf (WAIS) has a similar continental shelf, and is downstream of where the ACC meets the shelf break, it is assumed that the LTER processes are representative of the WAIS processes.

The open question is whether this system is representative of that operating at the first location where the ACC makes contact with the continental shelf, near Pine Island Glacier, where the glacial melting is a major concern.

4.5.2 CLIVAR GoodHope, IPY BONUS-GoodHope & South Atlantic MOC (SAMOC) – Sabrina Speich

The Southern Ocean and subtropics are characterized by a highly nonlinear dynamics. South of Africa these dynamics affect:

1. Water masses dynamics and interbasin exchanges (exchanges through ACC jets, slope currents, eddies and filaments);
2. Air-sea exchanges, that are highly impacted by mesoscale dynamics (eddies, fronts);
3. Biogeochemical budgets via eddies, filaments, and slope currents;
4. The observing platform – made of in situ data, bottom moorings, and satellite observations – gives access to time series of the upper and interior ocean states.

Clivar GoodHope is a monitoring system for the exchanges of heat, fresh-water, and mass transports at the crossroad of the South Atlantic, Indian, and Southern Oceans as a component of the Meridional Overturning Circulation. Anticyclonic Agulhas rings detached from the Agulhas Current retroflection are usually found in the South tropical area north of the South Atlantic Front. During IPY, the BONUS-GoodHope program completed one transect including full geochemistry, biogeochemistry, and atmosphere observations, and deployed two long-term bottom mooring Current-Pressure Inverted Echo Sounders in the first part of the transect on the African slope (at 1000 m and 4000 m) for long-term monitoring of inter-ocean exchanges.

4.5.3 General Discussion - All

Observations imply that the strongest signal of water mass property changes due to climate in the ocean interior occurs in the mode waters. However it is still unclear as to the "right" mixing coefficient for the upper overturning cell and indeed there may be many different mixing coefficients depending on the problem. The upper cell exists so there has to be some transfer of properties including across ACC barriers. Rossby waves that become unstable can generate jets (behind topography), so there may also be mixing at different vertical levels. Perhaps there is pure compensation of Ekman transport with eddy mass transport? This is unlikely as the situation is probably more complicated. An open question is whether there is a difference if we resolve fine scale mixing or simply apply an "average". Is there enough information in the mean flow to work out what value of K to apply parameterisations to approach the eddy resolving case in the models (if that is the right answer)?

Alternatively perhaps the mean flow approach is not sensible at it appears that most action is through near topography interactions with eddies and Rossby waves. So do the regions between the topography have any role at all?

If the ACC is eddy saturated then how does this interact with the upper cell? The eddy energy is still linearly related to the wind strength, however eddy saturation and eddy compensation are not the same processes so what is the relationship between them? To resolve this question using simple models would require long integrations of order 1000s of years, however improvement in model resolution could provide more insight in perhaps 5 to 10 years.

PV and PV fluxes may also be important. At a recent CLIVAR Ocean Modeling Group eddy workshop it was proposed that the PV flux is almost constant across baroclinic jets and only when the flow gets close to topography is there high gradient in PV on isopycnals and high diffusivities, hence most of the action appears to occur in specific regions. But how should we think about PV fluxes in the down-gradient sense in the presence of sloping topography?

The DIMES project has been looking at isopycnal mixing rates in the intermediate layers. Preliminary results from microstructure measurements show that diapycnal mixing is small away from topography, which is similar to the effect of topographic regions out of the ACC.

The panel asked how or if variations in rates of mixing could control the ACC and how we should start to think about trying to understand this. For example:

- Is the mixing rate a limiting process?
- What is the adjustment to surface fluxes?
- Changes in mixing could conceivably change the circulation (e.g. deeper ocean tides weaker).
- Is vertical mixing at base of mixed layer rate limiting process?
- Strong buoyancy effect on the overturning forced from the interior?
- Are frontal dynamics important?
- What is the link between mixed layer dynamics and upwelling?
- Does the buoyancy set the overturning circulation (in the surface layer)?
- How will a change in the buoyancy forcing alter the overturning circulation (all else remaining the same how does it happen)?
- Can we simply use the surface forcing??
- What are the roles of horizontal mixing, vertical mixing, surface fluxes? Most of the time one of these terms is ignored.

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Appendix A. Agenda

SOP6 Agenda FINAL

Last revision Friday, June 11th, 2010

General Scope of the Panel Meeting

- Upper Cell
- Lower Cell
- Panel business.

SOP6 Meeting Outline

Day 1 - June 14th

MORNING 09:00 - 12:30 Panel only meet

09:00 - 09:30 New business, meeting framework and goals

09:30 - 10:00 Reports from national CLIVAR and related activities, e.g. SO Scoping workshop and Carbon Cycle Science Implementation Plan - Speer

10:00 - 10:30 *Climate modeling status, goals* - England, Goosse

10:30 - 11:00 Tea/Coffee (panel only)

11:00 - 11:30 *Process modeling status and goals* – Naviera-Garabato

11:30 - 12:00 Observations, process and sustained status, goals - Rintoul, Fahrbach

12:00 - 12:30 Vision document revisions for CLIVAR SSG – Speer / all

12:30 - 14:00 Lunch (panel only)

AFTERNOON Lower Cell 14:00 - 17:30 *chair Kevin Speer*

14:00 - 14:20 Brian King, Aspects of the Atlantic sector Deep MOC in recent GO-SHIP sections

14:20 - 14:40 Karen Heywood, Processes at the Antarctic continental slope; the ocean's interaction with ice

14:40 - 15:10 Mike Meredith, Processes influencing the properties of AABW exported from the Weddell Sea into the Atlantic overturning

15:10 - 15:40 Tea/Coffee

15:40 - 16:00 Kevin Speer, *Interaction with Polar Gyre*s

16:00 - 16:20 Steve Rintoul, *Pacific Sector Deep MOC*

16:20 - 16:40 Seymour Laxon, Prospects for determining Antarctic sea ice thickness from space?

16:40 - 17:00 Matthew England, Simulations of the Deep Overturning?

17:00 - 17:30 Discussion/Listing of any actions - all

Day 2 - June 15th

MORNING 09:30 - 12:00 Upper Cell, physics, carbon and freshwater fluxes – I (Roughly organized here by physics am and more interdisciplinary pm) *chair Alberto Naveira-Garabato*

09:30 - 10:00 David Marshall, Adjustment and equilibrium state of the Antarctic Circumpolar Current

10:00 - 10:30 Andy Thompson, Jet-Topography Interactions in the Southern Ocean

10:30 - 11:00 Tea/Coffee

11:00 - 11:30 Chris Hughes, Sea level in the Southern Ocean: what does it tell us?

11:30 - 12:00 Emily Shuckburgh, Regional Variation of the Surface Eddy Diffusivity in the Southern Ocean?

12:00 - 12:30 Andy Hogg, Buoyancy forcing of an eddy-saturated ACC

12:30 - 14:00 Lunch

AFTERNOON 14:00 - 17:00 Upper Cell, physics, carbon and freshwater fluxes – II *chair Gareth Marshall*

14:00 - 14:30 Andy Watson, Observing change, or lack of it, in the Southern Ocean sink for atmospheric CO_2

14:30 - 15:00 Simon Josey, *Air-sea fluxes*

15:00 - 15:30 Nikki Lovenduski, Southern Ocean CO_2 Fluxes and Acidification: Recent Changes and Future Projections

15:30 - 16:00 Tea/Coffee

16:00 - 16:30 Ted Maksym, Sea ice processes and variability

16:30 - 17:00 Julie Jones, Twentieth Century behaviour of the Southern Annular Mode

17:00 - 17:30 Discussion/Listing of any actions - all

Day 3 - June 16th

MORNING 09:30 - 12:30 Panel and speakers meet to discuss the following topics with a view to revising the vision document and outlining a review paper: *chair Matthew England*

Left over business from Monday

Synthesis of Lower Cell talks, outstanding questions written summaries

Synthesis of Upper Cell talks, outstanding questions written summaries

New modeling recommendations, e.g. parameterizations, mixed layers, ice melt, carbon cycle ...

New observational recommendations, sustained, exploratory, and process

Desired/future technology

How to improve leverage of international collaborations for future observations and the SOOS etc.

12:30 - 14:00 Lunch (at own cost as free afternoon)

AFTERNOON 15:00 - 16:30

Opportunity to get a guided walking tour of Southampton's old city walls and vaults

http://www.stga.org.uk/medieval-walls-walk.html

18:30 - ? Panel and guest speakers "no-host" dinner at Mango Thai Tapas bar in Portswood, Southampton (Taxi/bus or lift from those with cars will be needed) http://www.mangothai.co.uk/.

Day 4 - June 17th

MORNING

09:30 - 12:30 Panel only – discussion topics

09:30 - 10:30 SOOS evaluation, strategy, new observational recommendations - all

10:30 - 11:30 New SO climate review article - all

11:30 - 12:00 Panel Membership - all

12:00 - 12:30 Panel wrap-up, Vision document - all

12:30 - 14:00 Lunch and end of meeting

14:00- ? Panel co-chairs to meet with local hosts and ICPO staffer for final wrap up on the actions list.

Appendix B: Pre-meeting Vision document for the SO Panel

A Vision for Climate Variability Research in the
Southern Ocean-Ice-Atmosphere System

by

The Southern Ocean CLIVAR/CliC/SCAR Panel
May 2009

Contents:

Introduction

The variability of the Southern Ocean at various time scales has been documented from observations of hydrography, sea-surface height, and direct measurements of currents. The Argo network has dramatically increased the total, and importantly, the seasonal hydrographic coverage in the upper 2000m of the water column and has helped to provide evidence for significant warming and freshening (Gille 2008; Böning *et al.* 2008; Helm *et al.* 2008). Bottom water variations have been observed as well (Aoki *et al.* 2005; Rintoul 2007; Jacobs 2004, Jacobs 2006; Johnson *et al.* 2008; Fahrbach) and point to large-scale warming.

Ocean – ice shelf interaction has been linked to ice shelf collapse and faster-than-expected dynamical response of the ice sheet, with significant implications for sea-level rise (Rignot and Jacobs 2008). Recent results suggest that ocean heat input, from upwelling warmer deep waters, will play a significant role in determining the future of the Antarctic ice sheet and therefore future sea-level rise. Ice sheet models within climate models are rudimentary at present, and as a result, projections of future sea-level rise are very uncertain. In IPCC AR4 a major source of uncertainty in sea-level rise prediction is dynamic change to ice sheets.

Sea-ice is a major factor in the Earth's albedo. While evidence suggests that the sea-ice coverage is retreating near the Antarctic Peninsula, it is marginally increasing in the Amundsen Basin. However, in order to link sea-ice with evolving freshwater fluxes under climate change, it is crucial to determine ice thickness changes. Recently, first estimates of large-scale Antarctic sea ice thickness (Worby *et al.* 2008) have been made. Cryospheric satellites are making measurements of circumpolar sea-ice properties for the first time, but there is a critical need for further in situ validation. First estimates of sea ice formation rates in the open pack, derived from winter salinity changes measured by elephant seals with CTD sensors (Charrassin *et al.* 2008) show promise for future observational needs.

New insights into the structure, dynamics and variability of the Antarctic Circumpolar Current have been obtained showing the ACC to consist of multiple frontal jets, which can be tracked using altimetric SSH. The fact that the detailed structure of the ACC can be tracked in altimetry allows the variability of the ACC, and its relationship to SSH changes, to be determined (Sokolov and Rintoul 2007b; Sokolov and Rintoul 2007aSokolov and Rintoul 2009a,b; Sallee *et al.* 2008).

A variety of models, observations and theory suggest that the ACC may be "eddy-saturated", with implications for the response of the ACC, overturning and carbon uptake to changes in the winds (Straub 1993; Hallberg and Gnanadesikan 2006). New work has begun to expose the key time scales for the interaction between eddies and wind forcing (Meredith and Hogg 2006; Hogg *et al.* 2008.;Screen *et al.* 2009). Böning *et al.* 2008 suggest that while a significant net poleward shift in the ACC has occurred, this is not accompanied by stronger isopycnal slopes, consistent with the eddy saturation regime.

A much better understanding of the formation, subduction, circulation, and variability of Subantarctic Mode Water and Antarctic Intermediate Water has grown over recent years, and in particular the greater role that eddies play in the evolution of mode water has emerged (Talley *et al.,* SAMFLOC experiment; Sallée *et al.* 2006, 2008, 2009; Herraiz-Borreguero *et al.* 2009). Analyses of IPCC AR4 models suggest that observed changes in mode and intermediate water properties are broadly consistent with "fingerprint" of anthropogenic climate change (Meijers *et al.* 2007; Downes *et al.* 2009a). IPCC models suggest mode and intermediate water migrate to lighter densities with climate change, but the range between models is very large (Downes *et al.* 2009b).

Trends in the SAM have been associated with ozone depletion (and eventual recovery) at high latitudes and tropical ocean surface warming. In the southeast Pacific these trends interact with ENSO and give rise to the dominant low frequency variability. The impact is different in summer and winter and the resulting seasonal climate signal is important to distinguish. Regional processes control the local impact of atmospheric forcing and determine the nature of the ocean-ice response to changes in forcing, including feedbacks. Significant differences exist in current SAM reconstructions and any conclusions on the significance or otherwise of recent trends set in the context of these datasets needs to be treated with caution. Empirical and model efforts should go hand in hand in addressing this question.

The Southern Ocean has been shown to contain large amounts of anthropogenic CO2 and the question of the future of this carbon sink for the atmosphere is being debated. Air-sea CO2 fluxes may decrease in years to come if the SAM trends continue and more natural carbon upwells. This saturation of the carbon sink (Le Quéré *et al.* 2007) is a topic of current debate (Lovenduski and Ito 2008; Law 2008; Lovenduski *et al.* 2008). A related matter is the rising acidity levels and the susceptibility of certain regions to species decline resulting from the dissolution of carbonate skeletal material (Orr *et al.* 2005; McNeil and Matear 2008). Some polar regions, e.g. the Ross Sea, may be the first to suffer from ocean acidification.

The analysis of data and model simulations are required to understand the variability of the Southern Ocean System, and the first high-resolution state estimates for Southern Ocean (Mazloff *et al.,* 2009) and first multi-decadal coarse resolution ocean state estimates for global ocean (e.g. ECCO, SODA) have been achieved. The dynamics of atmospheric modes and their impact on the ocean-ice system, the influence of the ocean and ice on these modes, the dynamics of the ACC, and the stability of the Southern Ocean overturning, or upwelling circulation are key topics for Southern Ocean climate research. In this framework, a better estimation of heat, moisture fluxes and wind stresses at the ocean surface is of great importance. Model representations of deep-water formation in the ocean, of ocean-ice shelf interactions, and of fast ice streams should be priorities. These goals could in part be achieved through regional reanalyzes, eventually using coupled atmosphere-ocean-sea-ice models.

One of the main troubles when addressing the behavior of the Southern Ocean system is the paucity of long time series compared to other oceans. There is an absolute need to maintain the current observations system together with some expansion into under-sampled locations in order to permit the analysis of long-term trends: water masses, sea-ice concentration, sea surface elevation, and the grounding line of ice sheets.

The community should engage a synthesis of observations collected during the 20th century in the Southern Ocean, beginning with physical parameters but extending to ecosystems. Surface temperature (ocean and land), deep-water characteristics, carbon content, and sea ice extent are a priority. Innovative methods should be designed to combine observations and model results to be able to estimate the magnitude and variability of the changes over the 20th century and understand their causes.

Ultimately, we should evaluate the quality of Earth system models in the high latitudes of the Southern Hemisphere and propose improvements in order to provide better projections of future Southern Ocean carbon uptake, water-mass trends, changes in Antarctic sea ice, the stability of the Antarctic ice sheet, and the response of the ecosystem to acidification. The quality of future SAM predictions made using current AOGCMs without a well modeled stratosphere and chemistry included (e.g. many AR4 models) is questionable, and similar criticisms can be made for the ocean and ice components of climate models. Much work needs to be done to improve the representations of key climate physics, biology, and chemistry, and to link these together into Earth systems models.

Significant progress achieved over the past few years

i) Oceans

- Real-time monitoring of Drake Passage transport by sea level (Woodworth *et al.* 2006)
- Under-ice Argo measurements in the Weddell Sea (Klatt *et al.* 2007)
- Adelie Land Bottom Water transport estimated by a mooring experiment (Williams *et al.* 2008)
- Kerguelen DWBC transport estimated by a mooring experiment (Fukamachi *et al.* 2009)
- The confirmation that the Southern Ocean is warming and that this warming is consistent with the response of the climate system to the anthropogenic forcing (Böning *et al.* 2008). Observations have resolved important new aspects of the regional circulation of the Southern Ocean. The first direct measurements of the Kerguelen deep western boundary current transport (Fukamachi *et al.* 2009),
- The ACC transport through gaps in Macquarie Ridge observed (Williams *et al.,* 2008)
- ACC dynamics in Drake Passage (*Chereskin, Donohue & Watts*; Provost moorings; Dong *et al.,* Drake Passage ADCP time series?);
- Weddell gyre circulation under sea ice determined from floats (Klatt *et al.* 2007);
- Adelie Land bottom water outflow quantified (Williams *et al.* 2008; Rintoul *et al.,* moorings);
- Newly recognized bottom water source at Cape Darnley (Fukamachi *et al.,* moorings and CTD).
- Refinement of ideas linking overturning (residual) circulation to buoyancy forcing (e.g. Treguier *et al.* 2007; Marshall and Radko 2006; Radko 2007).
- The importance of the interaction of isopycnal and diapycnal mixing in the ACC and overturning (Naveira Garabato *et al.* 2007*,*)
- Progress on the interaction of the oceanic mesoscale with bottom topography (and subsequent loss of geostrophic balance) and the implication for a significant physical coupling between the upper and lower cells of the Southern Ocean overturning.
- Realization that the 'eddy saturation limit' may apply (Hallberg and Gnanadesikan 2006; Meredith and Hogg 2006; Böning *et al.* 2008)
- Ocean acidification impacts will occur sooner than expected (McNeil and Matear 2008) which implies the need to develop a SOOS to monitor these changes (e.g. Ross Sea focus PULSE BGC time series)
- Argo data has been used to resolve the seasonal cycle of mixed layer depth evolution and to examine heat budgets quantitatively (Dong *et al.* 2008; Sallée *et al.* 2008), and a larger role of eddy heat fluxes has been found.
- Development of a Southern Ocean State Estimate (SOSE) data synthesis, publicly available, for 2005-2007
- Cerovecki *et al.* 2008 have used the SOSE model output to show that water mass transformation is strongly influenced by salinity, and that the major transformation occurs at different densities in each ocean basin.

ii) Atmosphere

- A better description of the patterns of interannual variability of sea ice cover and a better understanding of the impact of the changes in atmospheric circulation (related to SAM and ENSO in particular) on the ice-ocean system
- Realization that increased winds may transport more heat poleward through the eddy heat flux
- SAM relationship with temperature and precipitation across southern high latitudes is not temporally stable: this may reduce the utility of many potential SAM proxies.
- Climate-chemistry models indicate that a future ozone recovery will produce a decline in the SAM (weakened circumpolar westerlies) during austral summer. This is in contradiction to the mean model response of the IPCC AR4 models, several of which do not have ozone and/or ozone recovery.
- SAM reconstructions using principal component regression techniques indicate that the recent positive trends in austral summer are greater than anything observed during the 20th century and thus are highly likely due to anthropogenic activity. Trends in austral autumn exceeding those in the recent period are seen in the reconstruction and hence we can be less certain in ascribing a human cause to these.
- Southern Ocean response to a positive SAM trend is complex with opposing trends; natural carbon opposes anthropogenic; heat and freshwater opposes the winds.
- Recognition of the importance of the Southern Ocean as a sink for CO2 and heat from the atmosphere and recognition that this sink may change as a result of a changing wind field and altered stratification
- Several studies have noted that the available flux products differ substantially (e.g. by 100s of W/m^2 for heat flux), and the data fields appear to show small eddy-scale variability that is not reflected in the NWP flux products (e.g. Dong *et al.* 2007; Cerovecki *et al.* 2008; Bourassa, 2009).
- Diagnosis of the impacts of the SAM on the coupled ocean-ice-atmosphere system, including the role of air-sea fluxes, ocean dynamics, and eddy fluxes (Sen Gupta, England, Hogg, Meredith, Sallee, Vivier)

iii) Ice

- Sea-ice models including melt ponds
- Recent satellite derived estimates of the mass balance of both Greenland and Antarctica confirm the IPCC AR4 assessment that they are adding to sea level
- Much of the increased loss from both the Greenland and Antarctic ice sheets is due to accelerated discharge from outlet glaciers and ice shelves – not just enhanced surface melt.
- In-situ measurements for satellite validation of some sea-ice variables – especially snow thickness (AMSR_E) (?) that have improved global products – but still require additional calibration, validation, and development**:**

Imperatives

- Absolute need to maintain Argo, hydrographic (water sampling), and extend sampling or observational techniques to the under-ice-covered ocean, up to grounding line.
- Better assessment of the role of eddies on transport and mixing; investigation of the eddy saturation limit.
- Better estimates of air-sea fluxes of heat and moisture, CO2, wind stress, and boundary layer parameterization near continent.
- Broader evaluation of the impact of acidification and the ecosystem response.
- More accurate diagnoses of the freshwater and moisture transfers among the coupled ocean-ice-atmosphere system, and associated feedbacks.

Frontiers

- What is the future of Antarctic ice?
    - Sea ice (albedo and surface heat flux feedbacks)
    - Ice shelves (effect of enhanced CDW upwelling, and warming oceanic waters)
    - Land-ice (sea-level).
        - Improve model representation for key Southern Ocean processes: upwelling, eddy processes, overturning, convective mixed layers, and interactions with the shelf.
- What is the impact of acidification? How will the Southern Ocean store of CO2 change in the future?
- Carry out reanalyses using coupled models with biochemical representations of the carbon cycle: syntheses of ocean/ice/atmosphere data and models.
- How will the ongoing projected trend in the SAM impact on air-sea heat, moisture, and carbon fluxes, and what will be the impact on Southern Hemisphere regional climate?
- What is the future of the Antarctic continental margin? Evaluation and improvement of Earth system models in the high latitudes of the Southern Hemisphere, including runoff from ice shelf lakes.

The most pressing research issues/questions for the next 3-5 yrs.

Data issues

- Direct measurement of AABW transport (e.g. Weddell, Ross, through the Princess Elizabeth Trough), and simultaneous direct measurements of AABW transport and sea-ice production.
- A synthesis of observations collected during the 20th century in the Southern Ocean.
- Development of radar and laser altimetry and in-situ methods for global ice and snow thickness.
- Add biochemical sensors to Argo

Process Issues

- Do eddies compensate the Ekman drift over the Southern Ocean?
- Role of diabatic processes in offsetting eddy saturation hypothesis
- What are the long-term feedbacks on ocean stratification?
- Model and process studies of the interaction of isopycnal and diapycnal mixing in the ACC and overturning, and their vertical structure.
- Assessment of the subtle physics shaping isopycnal and diapycnal mixing in the ACC and ultimately the Southern Ocean overturning.
- Investigating the robustness of the eddy saturation limit (is it truly intrinsic to any conceivable state of the ACC, and if not, under what forcing conditions does it kick in?) and its implications for stability of Southern Ocean overturning.
- A well-validated parameterization of melting and refreezing beneath ice shelves, fast ice-streams
- An accurate, semi-empirical law for iceberg calving, and its implementation in coupled models
- An accurate, numerically robust treatment of grounding-line migration on a fixed grid
- A challenge for the next decade remains to better understand quasi-geostrophic eddies, their vertical structure and interaction with the surface mixed layer.
- Why has there been no trend in Antarctic sea-ice extent over the last 30 years? Has the sea-ice extent decreased during the last 50-100 years and will it decrease during the next few decades as projected by the present generation of global climate models?

Climate model process representation and parameterization

- Better assess the representation of dense water convection in climate models
- What will happen to the SAM? - i.e. fundamental discrepancy between the IPCC models and the models with more sophisticated treatment of ozone recovery.
- What is the long-term response of the SO to changes in the SAM? Does the absence of explicit eddies fundamentally change this response? How do we handle this in the next round of IPCC models?

Dynamical questions

- Dynamics of atmospheric modes and their impact on the ocean-ice system.
- Dynamics of the ACC and response of the ACC system to a changing climate. The quantification of eddy impact and dynamics (meso and submesoscale).
- Analysis of meridional shifts in rainfall and winds associated with modulations in the Southern Annular Mode - effects of GHG's, ozone and other large-scale trends.
- Analysis of the stability of the Southern Ocean overturning, including stability of mode, intermediate and bottom water overturn (wind, eddy saturation; buoyancy; basic T-S feedback, carbon uptake impacts).
- Stability of the Antarctic ice sheet and future contribution to sea level rise.
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Appendix C: Attendees

Panel members

Matthew England (co-chair)	University of New South Wales, Sydney, Australia
Kevin Speer (co-chair)	Florida State University, Talahassee, USA
Hugues Goosse	Université Catholique de Louvain, Louvain-la-Neuve, Belgium
Gareth Marshall	British Antarctic Survey, Cambridge, UK
Doug Martinson	Lamont Doherty Earth Observatory, Palisades, USA
Alberto Naveira Garabato	National Oceanography Centre, Southampton, UK
Steve Rintoul	Commonwealth Scientific and Industrial Research Organisation, Hobart, Australia
Sabrina Speich	University of Bretagne Occidentale, Brest, France
Eberhard Fahrbach	Alfred-Wegener Institute, Bremerhaven, Germany

Invited guests

Karen Heywood	University of East Anglia, Norwich, UK
Andy Hogg	Australia National University, Canberra, Australia
Chris Hughes	National Oceanography Centre, Liverpool, UK
Julie Jones	University of Sheffield, Sheffield, UK
Simon Josey	National Oceanography Centre, Southampton, UK
Brian King	National Oceanography Centre, Southampton, UK
Seymour Laxon	University College London, London, UK
Nikki Lovundenski	Colorado State University, Fort Collins, USA
Ted Maksym	British Antarctic Survey, Cambridge, UK
David Marshall	University of Oxford, Oxford,UK
Mike Meredith	British Antarctic Survey, Cambridge, UK
Emily Shuckburgh	British Antarctic Survey, Cambridge, UK
Mike Sparrow	Scientific Committee on Antarctic Research, Cambridge, UK
Andy Thompson	University of Cambridge, Cambridge, UK
Andrew Watson	University of East Anglia, Norwich, UK

ICPO

Kate Stansfield	National Oceanography Centre, Southampton

(Note that the list of attendees in the science sessions was much higher as it included other local and visiting scientists and students)

Appendix D: Panel Members

The members of the SO panel at the time of the meeting were:

Matthew England (co-chair)	University of New South Wales, Sydney, Australia
Kevin Speer (co-chair)	Florida State University, Talahassee, USA
Yasushi Fukumachi	Hokkaido University, Sapporo, Japan
Hugues Goosse	Université Catholique de Louvain, Louvain-la-Neuve, Belgium
Gareth Marshall	British Antarctic Survey, Cambridge, UK
Doug Martinson	Lamont Doherty Earth Observatory, Palisades, USA
Alberto Naveira Garabato	National Oceanography Centre, Southampton, UK
Steve Rintoul	CSIRO, Hobart, Australia
Sabrina Speich	University of Bretagne Occidentale, Brest, France
Dave Thompson	Colorado State University, Fort Collins, USA

Ex-Officio members:

Eberhard Fahrbach (representing the SCAR/SCOR Oceanography Expert group)
Alfred-Wegener Institute, Bremerhaven, Germany

Alex Orsi (representing iAnZone) Texas A&M University, College Station, USA

Appendix E: National representatives

There are also several national representatives who keep the panel – and SO community as a whole – up to date with their country's work in the SO region and act as a contact point in their country.

Argentina - Alejandro Bianchi

Australia - Steve Rintoul

Belgium - Hugues Goosse

Brazil - Mauricio Mata

Chile - Dante Figueroa

China - Zhaoqian Dong

Finland - Aike Beckmann

France - Sabrina Speich

Germany - Eberhard Fahrbach

Italy - Enrico Zambianchi

Japan - Yasushi Fukumachi

Netherlands - Michiel van den Broeke

New Zealand - Mike Williams

Norway - Svein Osterhus

Russia - Alexander Klepikov

South Africa - Chris Reason

Spain - Damià Gomis

United Kingdom - Alberto Naveira Garabato

USA - Kevin Speer