



Fig 3: Potential temperature (A), salinity (B) and neutral density (C) time series of the gridded data for oceanic (middle) and shelf (right) waters. The position of each gridded data can be seen on map (left), where the red color denotes oceanic regions and the blue and green denotes shelf regions.

# Developing a Vision for Climate Variability Research in the Southern Ocean-Ice-Atmosphere System

Kevin Speer<sup>1</sup>, Nicole Lovenduski<sup>2</sup>,  
Matthew England<sup>3</sup>, David Thompson<sup>4</sup>,  
Catherine Beswick<sup>5</sup>

- 1 Florida State University, USA
- 2 University of Colorado, Boulder, USA
- 3 University of New South Wales, Sydney, Australia
- 4 Colorado State University, Fort Collins, USA
- 5 International CLIVAR Project Office, UK

The Southern Ocean region is currently accumulating more heat and anthropogenic carbon than anywhere else in the ocean, which could have global ramifications. Climate models poorly resolve this key region, and produce a wide variety of projected climate states in the future. Ongoing greenhouse gas increases and ozone recovery are both expected to modify Southern Hemisphere wind patterns, with likely implications for ocean heat and carbon uptake (Figure 1). This will exert a strong influence on the global climate system. Much effort has recently gone into improving ocean model representation of the role of eddies, yet these processes are not yet adequately represented in coarse IPCC-class climate models. Improvements to models and our understanding of the role of eddies and air-sea-ice interactions in the Southern Ocean system have been made, but large gaps still exist. To compound this situation, there is a

paucity of observations in the Southern Ocean climate system, including ocean circulation/hydrography, air-sea fluxes, and atmospheric properties. The CLIVAR/CliC/SCAR Southern Ocean Panel (SOP) has had a sustained interest in driving forward the observational programmes required in this region, with some notable achievements (e.g. the Southern Ocean Observing System; SOOS).

During 19 - 21 October 2011, the SOP held its seventh meeting (SOP-7) in Boulder, Colorado, USA. The meeting convened experts from three key areas of Southern Ocean research – Southern Ocean carbon, atmospheric processes over the Southern Ocean, and Southern Ocean physics – with the overarching objective to generate an overview of current understanding in these three main areas. Under each of the three themes, invited speakers highlighted to the panel key open questions and discussed gaps in our current understanding. This will ultimately feed into the vision document being developed by the panel: A Vision for Climate Variability Research in the Southern Ocean-Ice-Atmosphere System. The following three sections summarize in turn the main issues highlighted during the meeting across the above three thematic areas.

## Southern Ocean Carbon

The Southern Ocean is an important regulator of atmospheric carbon dioxide (CO<sub>2</sub>). In this region, old, CO<sub>2</sub>-rich water is ventilated to the atmosphere, and nearly half of the ocean's anthropogenic CO<sub>2</sub> is absorbed and stored. It is therefore important to quantify and understand the processes controlling air-sea CO<sub>2</sub> exchange in the Southern Ocean, given the implications for the global climate system.

Results based on coarse-resolution ocean models suggest that the physical circulation of the Southern Ocean governs the exchange of CO<sub>2</sub> across the air-sea interface, and that changes in the physical circulation have altered the uptake and release of CO<sub>2</sub> from the region (Figure 1). However, the community remains concerned about certain aspects of these modeling studies. Central to their concerns are two questions: (1) Can

coarse-resolution ocean models accurately represent Southern Ocean circulation and CO<sub>2</sub> uptake?; and (2) Do we have enough observational evidence to support these model-based findings?

Learning more about Southern Ocean carbon uptake will require a sustained international effort to observe Southern Ocean biogeochemistry. Such an effort has been proposed by Sarmiento and collaborators (SOBOM; The Southern Ocean Biogeochemical Observations and Modeling Program); they aim to deploy autonomous ARGO floats with biogeochemical sensors in the Southern Ocean region, and to use these observations to better constrain eddy-resolving models of the Southern Ocean.

Analysis of Drake Passage pCO<sub>2</sub> and d14C observations suggests that there has been an increase in the vertical transport of CO<sub>2</sub>-rich and d14C-depleted waters over the past few decades in the region south of the Polar Front. This finding is remarkably consistent with results from coarse-resolution ocean models (Sweeney et al., personal comm.).

Through sustained observations, the Palmer Long-Term Ecological Research (PAL LTER) program has successfully demonstrated the impact of physical climate variability on the Southern Ocean ecosystem. In particular the Western Antarctic Peninsula (WAP) has warmed rapidly over the past few decades, sea ice has dramatically decreased in this region, and phytoplankton productivity has declined in the north WAP and increased in the south WAP (Stammerjohn et al., personal comm.). Such changes have had consequences for all trophic levels.

HIAPER Pole-to-Pole Observations, or HIPPO, an airborne, observational campaign that aims to sample atmospheric O<sub>2</sub> and CO<sub>2</sub>, has completed five missions over the last two years. These data are currently being processed and analyzed. Preliminary results suggest large interannual air-sea O<sub>2</sub> flux variability over the Southern Ocean (Bent et al., personal comm.).

The Community Earth System Model (CESM) is being used to assess variability in Southern Ocean carbon uptake. As a full coupled climate model with a state-of-the-art ocean biogeochemical submodel, CESM has been fairly successful at representing observed CO<sub>2</sub> variability in the region. Results from this model suggest that advection of dissolved inorganic carbon is the dominant control on air-sea CO<sub>2</sub> flux variability in the Southern Ocean, with biological processes playing a smaller role (Long et al., personal comm.).

Wang and Moore (2012) coupled an older version of the Community Climate System Model to a modified ocean biogeochemical model, in order to assess the role of the biological pump in controlling air-sea CO<sub>2</sub> flux variability over the Southern Ocean. The model included an improved parameterization of the iron cycle, an additional phytoplankton group, *Phaeocystis Antarctica*, and an improved representation of Southern Ocean mixed layer depths. This study suggests that biological production and circulation play equally important roles in controlling Southern Ocean CO<sub>2</sub> flux variability.

## Southern Ocean Atmosphere

The Southern Annular Mode (SAM) is the prominent pattern of large-scale climate variability in Southern Hemisphere mid-high latitude circulation. Variations in the SAM influence weather across broad regions of the Southern Hemisphere ocean and land areas (see Thompson et al., 2011, for a recent review). Thus understanding how the SAM will respond to anthropogenic forcing is of key societal importance.

The SAM is believed to be sensitive to both increases in greenhouse gases and decreases in stratospheric ozone. Ozone depletion appears to have played a dominant role in driving low frequency variability in the SAM during the 20th Century; increases in greenhouse gases are expected to play a similarly important role during the 21st Century. But there is considerable uncertainty regarding the underlying dynamical mechanisms. It is unclear for example why the SAM responds to ozone-induced cooling in the polar stratosphere. It is also unclear why the SAM responds to increases in greenhouse gases. In fact, it is arguably unclear why the SAM exists in the first place.

The SOP-7 talks on atmospheric dynamics over the Southern Ocean emphasized the key role of feedbacks between the mean flow and the wave fluxes of heat and momentum in the Southern Hemisphere atmosphere. They explored the role of the SAM in driving changes in the strength and position of the Antarctic Circumpolar Current. They examined the processes that drive variability in the SAM and they explored the mechanisms whereby both the SAM and tropical climate variability influence Antarctic climate.

## Southern Ocean Physics

The Southern Ocean is thus far responding to climate change very differently to the Northern Hemisphere; for example the rapid warming observed over subpolar northern latitudes has not yet materialized over the Southern Ocean. The primary reason appears to be the large uptake of heat by the Southern Ocean, although the precise mechanisms at play remain uncertain. Furthermore, there is inconsistency in model estimates of the magnitude of this anthropogenic heat uptake. Recent progress has been made in formulating eddy parameterizations more appropriately in coarse resolution models, so that to first order the response of the Southern Ocean to wind changes is correctly captured (Gent and Danabasoglu, 2011). Ongoing eddy-permitting and eddy-resolving model development is also targeting this issue, to bridge the gap between IPCC-class climate models and the eddy-rich flow patterns seen in observations and high-resolution models.

Other recent work was also highlighted during the meeting. Drake Passage transport was monitored as part of the cDrake study using pressure sensors and echo sounders and bottom velocity sensors. Results show sustained high velocities 50 m off the ocean floor. A significant challenge for climate models is to match these velocities at the bottom, in the presence of bottom topography that controls flow configuration.

Eddy models as well as direct observations have shown that as the Southern Hemisphere subpolar westerly winds increase, so too does eddy activity, producing a greater eddy-

driven component to the MOC. This poleward eddy-driven flow mostly balances the wind-driven Ekman increase in the MOC. In contrast, there is unlikely to be such compensation in the net meridional heat flux in response to wind changes, as eddies and Ekman fluxes both modulate heat transfer with different depth profiles. Correct resolution of the poleward eddy heat transport is thus an important consideration in getting the correct temperature and sea ice response to anthropogenic climate change. The eddy response appears to be too weak in current models; consequently the response to Southern Hemisphere wind shifts might not be correct.

Sea ice extent in the Arctic has broadly decreased over the last 30 years, whereas Antarctic sea-ice has shown opposing trends over the western and eastern regions. Kirkman and Bitz (2011) have investigated why no net trend has been observed in the Antarctic. Antarctic warming over the last 50 years has been more prevalent in the west, as compared with the east. Warming is also occurring at depth in the Southern Ocean. Loss of sea ice in the Bellingshausen Sea appears to be via tropical teleconnections and/or changes in the SAM. But there are multiple theories for the expansion elsewhere, including 1) SAM trends (driven primarily by ozone) and 2) freshwater flux trends (either via precipitation changes or ice melt). Warming could be shrinking the overall thickness of Antarctic sea ice but observations are thus far insufficient to detect this.

It is unclear why models do not capture observed Antarctic sea-ice trends. A serious problem for future prediction is that the models show quite large disagreement. This is a key issue as it hampers predictions of future change, even to the extent that the sign of the change is unknown in some cases. One major uncertainty is the contribution from sea ice to salinity budgets in the Southern Ocean. Evidence suggests that sea ice is thinning in some areas; where this occurs, the ice will persist less, resulting in longer periods of open water. This trend could be inferred from water isotopes. However, direct sea-ice measurement systems are one of the most difficult observational programs to sustain on a large-scale. Remote sensing offers some hope of regular measurement.

Fig 1. Schematic response of the ocean to the high-index polarity of the Southern Annular Mode (from Thompson et al., 2011). Solid arrows indicate meridional and vertical motion in the atmosphere and ocean. Warm colors correspond to increases in temperature or heat content, and cooler colors to decreases. MLD refers to the ocean mixed-layer depth. All other responses are labeled on the figure or in the legend. All results indicate the climate response to the SAM on timescales less than a season with the exception of the oceanic eddy field, which indicates the response on timescales of 2–3 years. The ocean carbon response indicated remains uncertain; such a response would be considerably weaker if oceanic eddies compensate Ekman fluxes at the near-surface. (taken from Thompson et al. 2011)

Progress in other areas includes the incorporation of observations into a statistical estimate of ocean circulation; e.g. the SOSE (Southern Ocean State Estimate) program (Mazloff et al., 2010). As sensors for biogeochemistry become available they are being integrated into Argo profiles, and these might in turn be incorporated into ocean biogeochemistry state estimates. For SOSE going forward, there is a need for better geoid products and mean dynamic topography products in order to improve the mass balance of ocean volume. State estimates based on a dynamical model such as SOSE provide a basis for evaluating and calibrating climate models. Without adequate observations, no such state estimate is feasible. A concerted community effort is required to bring together the vast array of measurements needed to improve global climate prediction.

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