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Introduction

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The Southern Ocean, carbon and climate

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The Southern Ocean fascinates us. It retains an aura of mystery from the time of the early European explorers, when to sail through the Straits of Magellan or around Cape Horn was to leave the known world behind. Then, as now, the waters of the Southern Ocean earned a reputation as the roughest and most challenging on the Earth, a test for the bravest of mariners. Many that sailed there never returned.

It is no longer a life-threatening adventure to set sail in the Southern Ocean, but it is an adventure nonetheless. To modern oceanographers, the region is still full of mystery and unanswered questions. It is central to the climate of the planet, but we still struggle to understand its dynamics. It is the main source of much of the deep water of the world's oceans, and also the place where much of that deep water upwells to the surface and is converted into shallower waters that flood the rest of the global ocean. Its unique geometry—an open channel, joining and blending the waters of the Indian, Pacific and Atlantic Oceans—has confounded the theories developed by the pioneers of twentieth-century oceanography to explain the gyre circulations that characterize the oceans elsewhere. The lack of observations over huge areas, coupled with this deficit in our understanding, has laid bare the weaknesses in our simple theories, so that the nature of the circulation there and its drivers remain controversial.

The papers in this issue of *Philosophical Transactions A* arose from a two-day meeting at the Royal Society's Kavli Centre, on 16–17 July 2013, entitled 'New models and observations of the Southern Ocean, its role in global climate and the carbon cycle'. The meeting brought together researchers of the physical climate system, particularly physical oceanographers, with carbon cycle scientists, to discuss their mutual interests.

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The resulting papers cover aspects of many of the unresolved issues relating to the Southern Ocean.

Many of the uncertainties relate to the ventilation of the deep ocean, and the upwelling of the subsurface waters into the surface, which constitutes the meridional overturning cells. The paper by Waugh [1] discusses ventilation and recent changes, as detailed using transient tracer data. We now recognize that there are two overturning cells, separate but linked. The deep cell is formed by dense water formation near the Antarctic continent and over the continental shelf, driven by processes specific to the coastal shelf, ice shelves and sea ice formation occurring there. Dense water flows down the continental shelf into the deep sea, entraining ambient water as it descends, and leading to the formation of Antarctic bottom water (AABW). This floods northwards, mixing intensely in the process, to cool and ventilate the ocean abyss. Above the northward-travelling bottom waters are the circumpolar deep waters (CDW). These move upwards along the sloping isopycnals that rise to the south in the vicinity of the Antarctic Circumpolar Current (ACC), eventually outcropping towards its central and southern areas. The deep overturning cell is formed from the AABW moving north and mixing upwards, and the CDW moving south. A new look at the processes influencing this deep circulation is presented by Hogg & Munday [2], whereas the complex processes associated with the continental shelf and slope are outlined by Heywood *et al.* [3]. Key regions for the formation and export of the AABW that penetrates the lower limb of the Atlantic overturning circulation are the Weddell and Scotia Seas; the processes that control the efflux of waters from these regions are discussed by Meredith *et al.* [4], with new data to construct a freshwater budget of the region presented by Brown *et al.* [5].

Some of the CDW that upwells to the surface moves north. At the northern boundary of the ACC, it encounters a region of convergence where subduction and formation of subsurface waters occur, forming Antarctic intermediate water (AAIW). The upwelling of CDW and formation and subduction of AAIW form the upper overturning cell. The upper and lower overturning cells are the sources of the deep and intermediate waters found through most of the rest of the oceans, and therefore the processes that sustain them and how these are affected by changing forcing are of intense interest and relevance to the study of the global climate. The representation of the Southern Ocean in the current generation of IPCC-class coupled climate models is reviewed by Meijers [6].

Recent decades have seen a considerable strengthening of the westerly winds over the Southern Ocean, with the polar vortex centred over the continent strengthening due both to the increasing concentration of greenhouse gases in the atmosphere and the loss of stratospheric ozone over the Southern Pole, with natural variability superposed. However, the effect of the increased winds on the overturning circulation is controversial: the 'residual' circulation, the net upwelling in the polar zone, is the balance between an Ekman-induced upwelling flux responding to the wind stress at the surface and an opposing eddy-mediated flux. It is not clear to what extent this net overturning is sensitive to the wind strength, and its sensitivity may not be adequately captured by existing models. There is a complex mix of changes occurring in the Southern Ocean environment, partly but not entirely owing to human-caused climate change, and involving ocean, atmosphere and carbon cycle components of the Earth system. The asymmetric response of the north and south polar regions to climate change is discussed in the paper by Marshall *et al.* [7], whereas the potential for changes in the latitude of the ACC is investigated by Gille [8].

Physical oceanographers and climate scientists are not alone in intensively studying the Southern Ocean; biologists and biogeochemists are equally engaged. In carbon cycle studies, it has been found that the region is central in setting the natural concentration of atmospheric CO_2, that it is a major route for the penetration of anthropogenic CO_2 into the ocean, and that biological productivity in the region is iron limited. The effect of the Southern Ocean on the global carbon budget is intimately related to the physics which ultimately controls the meridional overturning circulation there. Because the main reservoir of carbon dioxide in the Earth system is the deep ocean, which connects with the surface and the atmosphere principally in this Southern Ocean, the physics, chemistry and biology of the region have a first-order influence on the concentration of atmospheric CO_2. Hence, they affect the climate of the entire planet. There is potential for strong feedbacks, whereby climatically induced changes in the Southern Ocean alter atmospheric CO_2, which feeds back to further alter the climate. Such changes are thought to have played a crucial part in the Quaternary climate cycles of ice ages, which have dominated natural climate change over the past million years. The paper by Anderson *et al*. [9] shows new evidence for the rapid shifts in the biota of the Subantarctic, correlated to dust input. The sensitivity to dust input provides evidence for an important role for the Subantarctic iron fertilization in modifying atmospheric CO_2 during natural climate variations of the Quaternary.

The present Southern Ocean is the biggest ocean sink region for atmospheric CO_2. The fate of this sink will be of great interest in the coming decades as humanity faces up to the challenge of climate change: the oceans as a whole are presently taking up one quarter of our emissions of carbon dioxide, and on time scales of hundreds of years, most of the CO_2 we emit will end up in the deep sea. Majkut *et al.* [10] estimate that $1.1 \pm 0.2\,\mathrm{PgC\,yr^{-1}}$, about 50% of the total ocean uptake at present, is taken up south of 30° S. The rapid uptake of CO_2 from the atmosphere occurs because the formation of subsurface waters, both bottom and intermediate water masses, removes surface water that has taken up CO_2 from the atmosphere, and sequesters it in the deep ocean. The process of uptake into the deep waters of the Weddell Gyre, classically thought to be a major source of bottom water, is studied and quantified in the paper by van Heuvan *et al.* [11].

It has been proposed [12], on the basis both of atmospheric observations and models, that the Southern Ocean sink for atmospheric CO_2 is becoming saturated. These authors suggested this should occur as increased meridional overturning owing to strengthening winds brings high-CO_2 subsurface waters to the surface. However, as discussed above, the connection between wind strength and overturning is not straightforward. Clarification of the physics of the circulation is therefore of great importance to our understanding of how the Southern Ocean carbon sink will evolve over the coming decades. Majkut *et al.* [10] show that the majority of latest IPCC-class models agree that a decrease in the uptake of CO_2 has probably occurred in recent decades. Using a model simulation of a carbon observing system based on floats able to measure carbon parameters, they suggest that a realizable observing system based on profiling floats could constrain the uptake of CO_2 by the region to within $0.1\,\mathrm{PgC\,yr^{-1}}$, a very significant improvement in the uncertainty currently assigned to this uptake.

These papers provide a snapshot of the vigorous and exciting research now centred around the Southern Ocean. Significant challenges remain: until we have a good understanding of the circulation (both vertical and horizontal) of the region, and good models of its role in the carbon cycle and in controlling atmospheric CO_2, we will not be able to say we understand the Earth's climate, how and why it changed over recent glacial cycles, or how it will respond to human-induced greenhouse warming. The papers illustrate rapid progress, but also a long way to go on the voyage of discovery into this ocean at the end of the world.

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