CLIMATE CHANGE

Changes in the Southern Ocean

Strengthening and poleward movement of the Southern Westerlies, and increased melting of the Antarctic ice sheet play a primary role in changes observed in the Southern Ocean over the past few decades, according to measurements and modelling.

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The Southern Ocean occupies less than one-third of the global ocean, but it absorbs 43% of the total oceanic anthropogenic CO_2 and 75% of the heat[1]. Oceanic heat stored in the Southern Ocean is the main source of melting of the Antarctic ice sheet[2]. Changes in the Southern Ocean can therefore have global consequences, both in terms of global warming and sea-level rise. Observations in the Southern Ocean have shown rapid physical and biogeochemical changes in the past few decades. However, it is unclear what caused these changes as it is challenging to collect measurements from this remote part of the world and to model a region where ice, ocean and atmosphere interact with each other. Writing in *Nature Geoscience*, Bronselaer et al.[3] present measurements from ships and floats and simulations with a state-of-the-art Earth system model to show that warming, deoxygenation, acidification, and increases in ocean carbon content and nutrients can be explained by two main processes: the poleward shift and intensification of westerly winds, and increased melting of the Antarctic ice sheet.

The wind system in the Southern Ocean is characterized by westerly winds centred at about 50° S and easterly winds closer to Antarctica. The divergence between the Westerlies and Easterlies allows upwelling of Circumpolar Deep Water, a warm, salty, oxygen-poor, carbon- and nutrient-rich water mass that originates in other ocean basins to the north. Near the surface of the Southern Ocean, two branches of the overturning circulation develop: an upper, northern branch where Circumpolar Deep Water is transformed into less dense waters, and a lower, southern branch where Circumpolar Deep Water reaches the Antarctic continental shelf and is then transformed into denser Antarctic Bottom Water (Fig. 1a). The upper branch is the primary agent of global oceanic uptake of heat and carbon on decadal timescales[4], whereas the lower branch is responsible for bringing ocean heat toward the Antarctic ice sheet and renewing the water in the abyssal ocean[2].

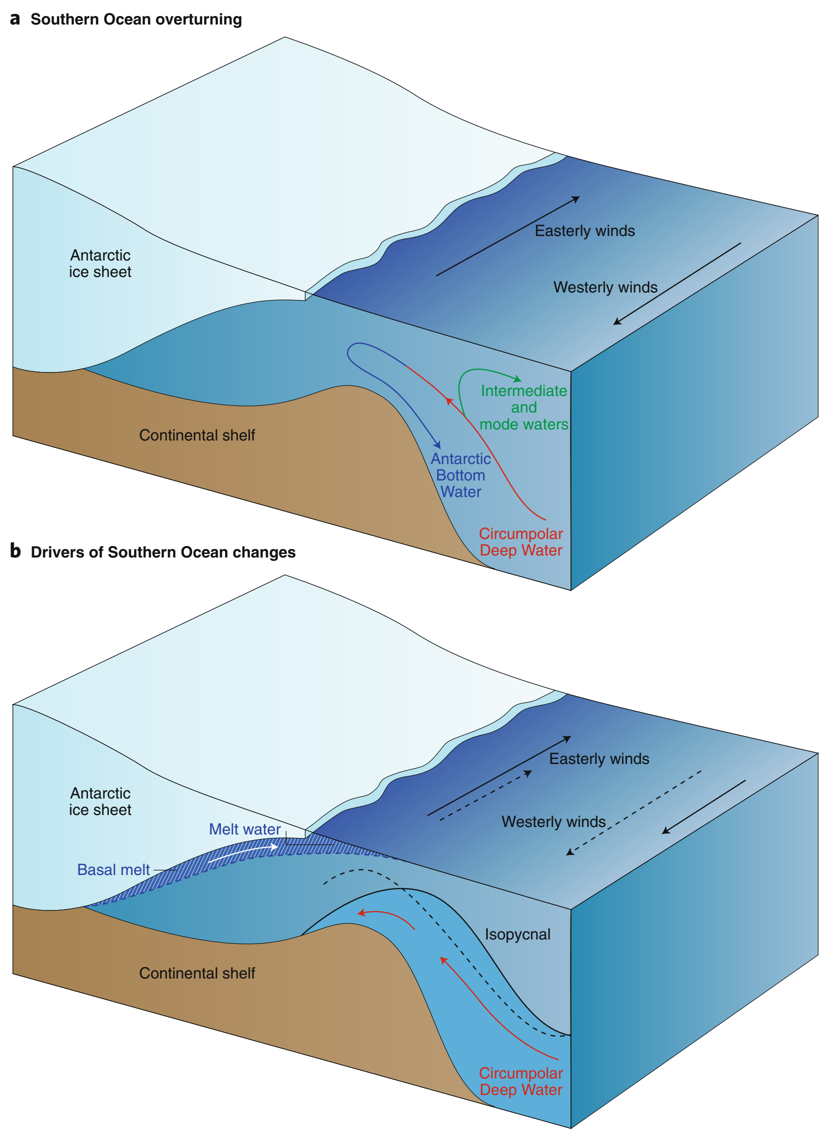

Fig. 1 | The Southern Ocean in a changing climate. a, Divergence between westerly and easterly winds drives upwelling of Circumpolar Deep Water, which upon interaction with atmosphere is transformed into either lighter intermediate and mode waters (upper overturning) or denser Antarctic Bottom Water (lower overturning). **b**, The strengthening and poleward shift of westerly winds, concurrent with a weakening of easterly winds (see dashed arrows), cause isopycnals to shoal near the Antarctic coast and deepen further offshore (see dashed line). Increased meltwater discharge from the Antarctic ice sheet enhances ocean stratification near the surface (see hatched area). Bronselaer et al.[3] show how these mechanisms can help explain observed decadal changes in physical and biogeochemical properties of the Southern Ocean.

Bronselaer et al.[3] present observations collected by recently developed biogeochemical floats, which reveal stronger and more complex patterns of change than previously detected. These floats are part of the Southern Ocean Carbon and Climate Observations and Modeling project (SOCCOM). Near the Antarctic coast, Bronselaer and colleagues observe warming, salinification, deoxygenation and acidification, as well as increasing levels of dissolved inorganic carbon and nutrients. North of 60° S, the authors note warming and freshening, but changes in biogeochemical properties are less apparent than to the south and become insignificant below 500 m depth. Bronselaer et al. use an Earth system model to understand the causes of these changes. They find that the model more accurately captures the observed oceanic changes in the region when the known changes in winds and Antarctic ice sheet melting are accounted for.

More specifically, Bronselaer and colleagues link changes near the Antarctic coast to a combination of weakened Easterlies (concurrent with a southwards migration of the Westerlies) and increased meltwater input from the Antarctic ice sheet (Fig. 1b). Near the Antarctic coast weaker Easterlies reduce downwelling, causing shoaling of ocean density surfaces (isopycnals) and stronger access of Circumpolar Deep Water to the coastal regions. Increased input of Antarctic meltwater enhances ocean stratification near the surface and thereby insulates subsurface waters — including Circumpolar Deep Water — from the atmosphere. Changes north of 60° S can be mostly ascribed to strengthening and poleward migration of the Westerlies, causing isopycnals to deepen (Fig. 1b). As surface waters north of about 60° S are warmer and fresher than the underlying Circumpolar Deep Water, isopycnal deepening implies warming and freshening. On the biogeochemical side, stronger winds strengthen the upper cell of the overturning circulation, affecting oceanic carbon uptake and causing oxygenation in some regions of the Southern Ocean. Bronselaer and co-authors conclude that continued acceleration of Antarctic ice sheet melting and poleward-intensifying westerly winds driven by anthropogenic forcing will further amplify these changes. This may lead to nutrients being trapped in the Southern Ocean and leave the rest of the global ocean to starve.

The difficulties of working in the Southern Ocean are exemplified by the range of hypotheses put forward to explain Southern Ocean changes, including changes in sea-ice transport[5], and changes in heat and freshwater surface fluxes[6]. The different results arise because different datasets and/or models are employed. The interplay between winds, sea ice, surface fluxes and ice-sheet melting in shaping the Southern Ocean overturning and its temporal changes therefore remains poorly quantified.

To improve our understanding of the Southern Ocean and its role in Earth's climate, two key strategies need to be pursued by the scientific community: the development and implementation of technologies that are capable of monitoring the Southern Ocean in its entirety and for long periods, such as satellites and the SOCCOM floats; and the improvement of Earth system models that couple physics and biogeochemistry, with the ultimate goal of reproducing the interaction between different components of the climate system. Bronselaer et al.[3] have made important steps forward in both directions. By combining the observations with modelling work, they revealed how the Southern Ocean has been and continues to be affected by poleward-intensifying winds and increasing meltwater discharge from the Antarctic ice sheet. ❒

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CARBON CYCLE

What goes down must come up

Differential cycling of carbonate and organic carbon in the mantle may link the Great Oxidation Event and the subsequent increase in carbon isotope values, according to a model that links the Earth's surface and interior.

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Approximately 2.5 billion years ago, the concentration of oxygen in the atmosphere rose rapidly. The sediment layers that were deposited after this Great Oxidation Event[1] show a pronounced change to highly positive carbon isotope values for hundreds of millions of years during a period that has been termed the Lomagundi event[2]. The coincidence of these two events, which were followed by a comparatively quiescent period in Earth's history, has long intrigued geoscientists. Writing in *Nature Geoscience*, Eguchi et al.[3] provide an elegantly simple model that mechanistically links both events to differential cycling of carbon in the mantle. They suggest that it is necessary to account for mantle storage, transport and the release of different forms of carbon to accurately interpret Earth's carbon isotope record.

Carbon isotope compositions (expressed as $\delta^{13}C$) in sediments have been interpreted to reflect the balance between carbon burial as carbonate and as organic matter. For most of Earth's history, the $\delta^{13}C$ of carbonates has varied little around 0‰, which is representative of 20% of carbon buried as organic matter and the remainder as carbonate[4]. In comparison, the $\delta^{13}C$ of carbonate rocks is 8–15‰ across the Lomagundi Event. These anomalously high values require an enormous amount of organic carbon burial relative to carbonate burial. However, as organic carbon production generates oxygen, burial of this quantity of organic carbon would mean oxygen production in volumes that are far greater than the concentrations even in today's relatively oxygen-rich atmosphere.