has been about the evolution of the flight stroke, which can now be seen as having helped proto-birds to escape from terrestrial predators. Ostrom reset this debate in 1974, and its implications continue to resound[15].

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Ocean science

The surprising history of a Southern Ocean current

Natalie J. Burls

Reconstructions of the strength of a powerful current that circles the South Pole reveal that it has undergone no long-term change in the past five million years, even though Earth cooled substantially over that time. **See p.789**

South of human civilization lies the vast Southern Ocean, the waters of which get swept around the globe by the Antarctic circumpolar current (ACC). This formidable current transports more than 100 million cubic metres of water per second. Connecting the Pacific, Indian and Atlantic ocean basins, it has a central role in the global circulation of the world's oceans and in regulating climate[1]. Yet little is known about its history. On page 789, Lamy *et al.*[2] present impressive reconstructions of the strength of the ACC that reveal pronounced variability on the timescale of multiple millennia owing to changes in Earth's orbit (Fig. 1). Interestingly, the records also indicate that the current's strength has remained relatively stable over the past five million years, in spite of the long-term change in Earth's temperature[3–6]. This suggests that the impact of global cooling on the ACC has evolved over time — undergoing mechanistic changes that could reveal how future warming will affect this influential current.

For the past 2.7 million years, Earth's climate has been in a relatively cold state, with ice covering not only Antarctica, but also land in the Northern Hemisphere to varying extents. As Earth's orbit changes over time, so too does the amount of solar energy that the high latitudes receive, and this has led to Earth transitioning between 'glacial' and 'interglacial' states over tens of thousands of years. Glacial states are periods of expanded land and sea-ice extent, such as the Last Glacial Maximum, which occurred approximately 20,000 years ago, when the Laurentide Ice Sheet covered large parts of North America. By contrast, interglacial states are characterized by reduced ice coverage, such as the warm Holocene interglacial state that Earth has been in for approximately 11,000 years.

Scientists have previously[7–11] reconstructed the response of the ACC to fluctuations between glacial and interglacial conditions, using the size of silt particles[12] deposited on the ocean floor as a proxy for ACC strength. The degree and sign of the response has been found to vary depending on the location of the sediment record. But Lamy and colleagues' silt-derived records of ACC strength over several glacial–interglacial cycles show remarkable similarities across five distinct sites in the central South Pacific sector of the Southern Ocean. All of these records suggest that the ACC was weaker during glacial periods than during interglacials. Three of the five sites are from a north–south transect that spans a large latitudinal range of the ACC, and the other two sites straddle a key feature of underwater topography, known as the East Pacific Rise, that influences the ACC.

The overall strength of the ACC is determined by both the strength of westerly winds across the Southern Ocean and large-scale gradients in the density of its waters — northern waters are less dense than southern waters[1,13,14]. The weakening of the ACC during glacial periods was probably the result of changes in both of these factors. During glacial states, the westerly winds are thought to have shifted northwards in terms of where they peak, and to have potentially weakened[15]. Glacial conditions are also likely to have cooled waters in the northern parts of the Southern Ocean, making them denser, whereas the density of near-freezing southern waters would not have changed substantially[16]. Both mechanisms would have led to the ACC being weaker during glacial states than it was in interglacial states.

Given this mechanistic understanding of how the ACC has responded to changing temperatures over glacial–interglacial

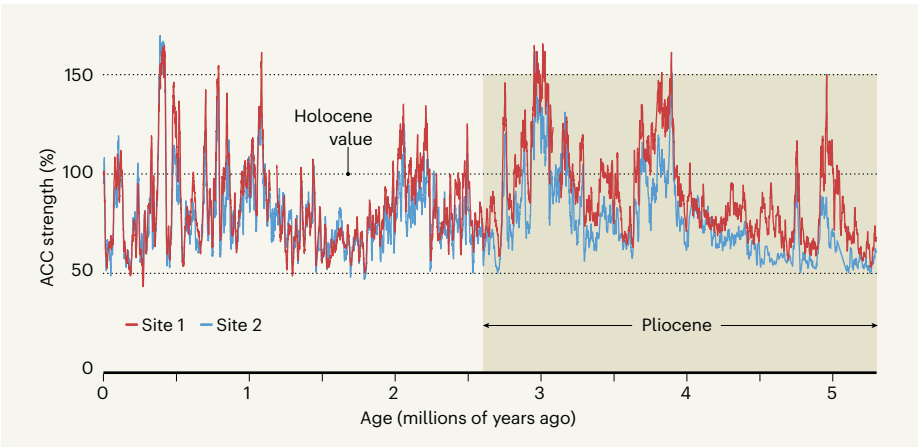

Figure 1 | Changes in the strength of the Antarctic circumpolar current. Lamy *et al.*[2] reconstructed a five-million-year history of the Antarctic circumpolar current (ACC) and found that its strength varied on timescales associated with changes in Earth's orbit, but remained relatively constant over the whole period. Data were similar across five distinct sites. ACC strengths for two sites are shown here relative to the average strength during the present Holocene epoch. A general increase in strength occurred between five million and three million years ago, when Earth was undergoing a period of cooling during the Pliocene epoch. This trend runs counter to the expectation that the ACC is weak during (cool) glacial states and strong during (warmer) interglacial states. (Adapted from Fig. 4d of ref. 2.)

cycles, one might expect the ACC to be weaker today than it was during an epoch known as the Pliocene (5.3 million to 2.6 million years ago). This is because elevated atmospheric greenhouse-gas concentrations during the Pliocene made Earth much warmer than it is now. Instead, Lamy and colleagues' ACC records show the opposite relationship – the strength of the ACC increased overall as Earth cooled between 5 million and 3 million years ago. The authors attribute this discrepancy to processes resulting from the climatic conditions that characterized the warm Pliocene, before the establishment of a larger ice sheet on Antarctica and increased sea-ice extent at the end of the Pliocene. These processes led to a strengthening of north–south density gradients and Southern Ocean wind forcing in response to the global cooling that occurred throughout the Pliocene.

As well as these million-year ACC trends, Lamy *et al.* also observed 400,000-year cycles, which they ascribe to the impact that Earth's orbital changes have had on tropical atmospheric circulation and, in turn, on westerly winds in the Pacific sector of the Southern Ocean. The authors discuss how their records complement other reconstructions of oceanic and atmospheric changes that have taken place across the past five million years. Together, the combined reconstructions help to establish key connections between the strength of the ACC, the supply of nutrients to the surface ocean, the marine carbon cycle and the storage of carbon dioxide in the Southern Ocean.

Although Lamy and co-authors' reconstructions provide insights into the evolution of the ACC and its relationship with the changes in Earth's climate, questions remain. First, how representative are the South Pacific records of the other sectors of the Southern Ocean? For example, are the 400,000-year cycles common to all sectors? Second, can the relative contribution of changes in wind versus density gradients be more explicitly untangled by using robust reconstructions of the evolution of north–south density gradients across sectors of the Southern Ocean? Finally, to what extent has the depth dependence of ocean current speeds in the ACC changed over time?

Over the past century, human activity has driven a rise in atmospheric greenhouse-gas concentrations from the relatively low values characteristic of the rest of the Holocene to the much higher levels associated with the Pliocene, setting Earth's climate on a trajectory towards Pliocene warmth. This begs the question: will the ACC strengthen with warming, as it does on the timescale of glacial–interglacial cycles, or weaken, as suggested by the long-term Pliocene trend?

There are two important aspects that need to be kept in mind when using past climate change to inform our understanding of the ocean's response to future global warming. The first is the direction of change. Earth's climate is currently going from cold to warm, and not warm to cold, as it did during the Pliocene. The second is the timescale on which the ocean adjusts to climatic changes, which is on the order of thousands of years for the deep ocean.

Taking these points into account, the glacial–interglacial timescale of past changes in ACC strength might be considered the closest analogue for future climate change, suggesting that the current's strength will increase as westerly winds shift towards the South Pole and as Southern Ocean density gradients strengthen. That said, this picture will probably be complicated by mechanisms in the atmosphere, ocean and cryosphere (regions of Earth covered by snow and ice), acting on shorter timescales. These uncertainties aside, it's clear that detailed reconstructions such as the records reported by Lamy *et al.* will improve our understanding of these powerful climatic players.

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Haematology

Powerful imaging shows blood cells made in bone

M. Carolina Florian

A method for imaging the production of blood cells in the bones of mice has revealed the organization of cell lineages, both in a steady state and in response to stressors, such as bleeding and infection. **See p.839**

Blood cells constantly renew throughout life, in a process called haematopoiesis. In adult mammals, blood cells are produced in bone marrow, which is a semi-solid tissue found in most bones in the body. Because haematopoiesis is a dynamic process that can readily adjust to face challenges such as stress and infection, bone marrow must also be dynamic. The tissue is packed with different cells in various stages of development, ready to be released into the bloodstream to maintain homoeostasis of the blood. Given the semi-solid and highly dynamic nature of bone marrow, it has so far been difficult both to tell how cells are organized in the tissue, and to resolve the production of blood cells at a single-cell level. On page 839, Wu *et al.*[1] describe a powerful method for visualizing various steps of haematopoiesis throughout the skeletons of mice.

In 2021, researchers in the same lab as Wu *et al.* established tools for imaging myelopoiesis – the production of myeloid cells, which are a family of immune cells that includes granulocytes, such as neutrophils[2]. In the latest study, Wu and colleagues build on these tools and describe a protocol for imaging the most immature haematopoietic stem and progenitor cells (those that have the potential to give rise to all blood cells); the production of red blood cells (erythropoiesis); and the production of another family of immune cells, which includes dendritic cells and B lymphocytes (lymphopoiesis). The method allows them to see where each of these processes happens in bone marrow, how they intermingle and how they remodel in the face of stress. The detailed images that the authors generate show that bone marrow has a defined architecture with many haematopoietic processes happening in specific anatomical locations.

The authors start by using a technique called flow cytometry to define combinations of five proteins expressed on the surface of bone-marrow cells, referred to as