Climate science

Southern Ocean heat sink hindered by melting ice

Joellen L. Russell

Simulations show that the melting of Antarctic ice reduces the production of deep water that stores heat at the bottom of the Southern Ocean. Comprehensive models could reveal whether the trend will persist. **See p.841**

The Southern Ocean has an extraordinary role in mitigating climate change: it takes up most of the heat absorbed by oceans across the globe, which itself is an estimated 93% of the total heat trapped owing to the increase in greenhouse gases[1]. This feat is made possible by cold water moving up from the ocean's depths to the surface waters, where it exchanges heat with the atmosphere. The Southern Ocean's deepest water is warming much faster than is the rest of the ocean[2,3], suggesting that there might be an influx of extra atmospheric heat. However, on page 841, Li *et al.*[4] report simulations that attribute this observed warming to reduced production of cold, dense ocean waters near Antarctica.

Strong westerly winds that circle Antarctica are responsible for the upwelling of cold water from the Southern Ocean's depths. Since the middle of the twentieth century, these winds have increased in strength and shifted towards the South Pole[5]. These changes have occurred in response to both cooling in the stratosphere, brought on by the loss of ozone, and warming of the underlying troposphere resulting from an increased concentration of greenhouse gases[6].

However, it's not yet clear how the changed winds have affected the circulation and mixing of the deep ocean. Measurements at the ocean's surface have shown increases in wind speeds[7], wave heights and wave power[8], as well as in the kinetic energy of most of the major ocean currents[9]. Surface measurements have also shown that the mixed layer at the top of the Southern Ocean is both warming and deepening[10].

But the oceanic processes most crucial to climate occur under ice, or in high winds and waves. And the ocean – the Southern Ocean, in particular – is extremely difficult to observe systematically, even under the best conditions. Moreover, technical and logistical hurdles prevent any single method from providing a coherent picture that will determine the specifics of climate change as a new global equilibrium emerges. The ocean is changing everywhere that has been measured, and numerical models are required to understand and reconcile observations. It is in this context that Li and colleagues' study is so important and timely.

The dense ocean water examined in the study is known as Antarctic Bottom Water (AABW) and originates as cold, brine-laden water on the continental shelves around Antarctica. This dense shelf water flows down the continental slope and, as it descends, it mixes in warmer and fresher water to form AABW[11]. The AABW then flows northwards and refreshes the abyssal ocean, which is the layer at depths between 4,000 metres and the bottom.

These small-scale processes are notoriously hard to simulate realistically using 'global coupled' models that bring different aspects of the climate system together, including the ocean, the atmosphere and sea ice. Ice modellers and other climate scientists are working hard to integrate land ice into global coupled climate models, but, unfortunately, none of the current generation of such models (nor those in previous generations) includes the melting of ice sheets on Antarctica or Greenland. For now, these simulations estimate future sea-level rise by calculating the

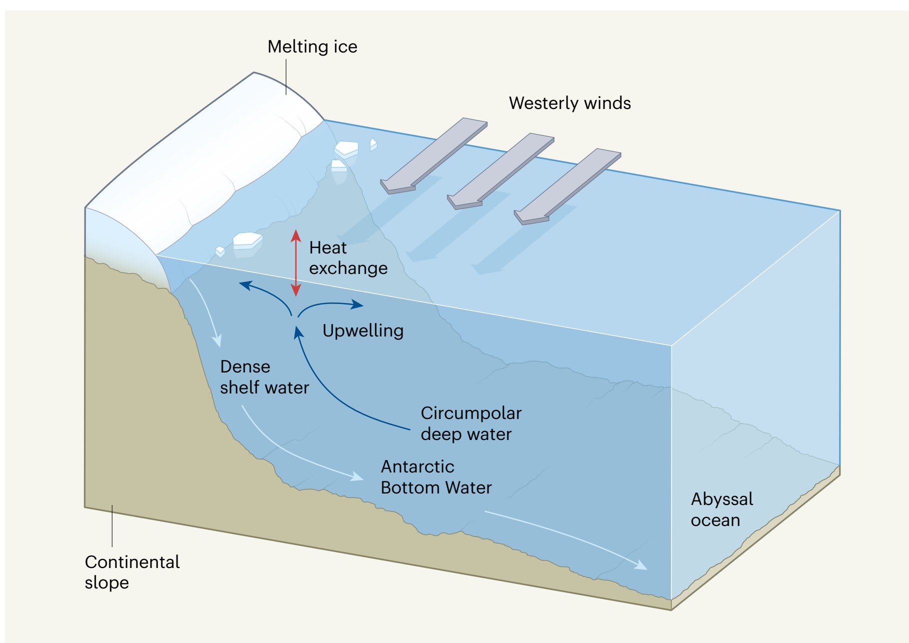

Figure 1 | Ice–ocean interactions in the Southern Ocean. Westerly winds pull cold 'circumpolar deep water' to the surface of the Southern Ocean, where it can absorb heat from the atmosphere. Some of this fluid mixes with dense water along the Antarctic shelf, flows down the continental slope and mixes with more circumpolar deep water to form Antarctic Bottom Water (AABW). AABW refreshes the abyssal ocean (the layer between 4,000 metres and the bottom), which is warming faster than the rest of the global ocean, and the source of this heat is unclear. Li *et al.*[4] simulated AABW formation and the abyssal ocean circulation in response to past and projected changes in wind, heat and meltwater. They found that increased meltwater from Antarctic ice inhibits AABW formation and reduces abyssal refreshing, suggesting that the observed warming is a repartitioning of old ocean heat, not a result of new, atmospheric heat.

volume of ice that would melt owing to warming, and by ignoring potential feedbacks that might occur if the meltwater were put back into the ocean.

Li *et al.* are not the first to address this shortcoming in a modelling study (see, for example, refs 12 and 13). However, they are the first to examine whether meltwater from Antarctica is directly or indirectly causing the observed temperature increase at the bottom of the ocean (Fig. 1).

The authors used a model that accurately simulates ocean–ice interactions, and that reproduces the observed volume and characteristics of AABW along the edge of the Antarctic in the correct geographical locations[14]. They first imposed changes in the wind, heat and meltwater that were measured[15] between 1991 and 2019, to see how the formation of AABW and the circulation of the abyssal ocean would respond. They then modelled the response to changes that are projected to occur between 2020 and 2050 according to the current global climate models.

Two hypotheses have been proposed previously to explain some or all of the observed deep warming. The first holds that AABW forms at the same rate as it did previously, but at a slightly higher temperature[2]. The second suggests that production of AABW has decreased, allowing other (warmer) water to intrude on its former territory[3]. These two mechanisms affect climate in different ways – the first actively sequesters 'new' heat (from the atmosphere) in the deep ocean, whereas the second repartitions 'old' heat in the deep ocean.

Li and colleagues' study supports the latter hypothesis: increased meltwater inhibits the formation of cold AABW, which reduces its volume, thereby warming the abyssal ocean and decreasing its ventilation. The authors' simulations suggest that this trend will continue, and that the combination of wind and warming perturbations have little effect on the abyssal ocean.

Studying the deep waters of the ocean might seem remote from everyday concerns, but these waters are crucial for distinguishing between transient and equilibrium climate change. The former relates to the temperature change that results from increases in atmospheric heat and carbon dioxide before the deep oceans have had time to equilibrate[16] (as well as heat, oceans sequester around 25% of anthropogenic CO_2 emissions[17]). The depth at which atmospheric heat and CO_2 are stored influences the time it will take for the ocean to come into equilibrium with the 'new' atmosphere, and therefore defines the timescale of transient climate change.

Taken together with the results of other studies[12,13], Li and colleagues' simulations indicate that atmospheric heat is not making it down to the deepest ocean and that only intermediate depths are currently available to buffer the anthropogenic effects on climate. The timescale associated with transient climate change will probably be shorter rather than longer, which is bad news for humans in this century.

The convergence of models of global climate, the Earth system and weather enhances scientists' ability to make accurate predictions[18]. Such predictions are essential to better prepare society to withstand extreme events such as droughts and floods, heatwaves and wildfires[19]. Li and colleagues' study takes a step in the right direction by highlighting the ocean's influence, from top to bottom, on the global climate.

Scientists at Australian institutions – including the authors, as well as many others – have long been acclaimed for their expeditionary oceanography and climate research. It is our good fortune that they live on the doorstep of the Southern Ocean, the most influential and least-understood player in the Earth system's response to anthropogenic climate change.

Joellen L. Russell is in the Department of Geosciences, University of Arizona, Tucson, Arizona 85721, USA.
e-mail: jrussell@arizona.edu

1. Rhein, M. *et al.* in *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. *et al.*) Ch. 3 (Cambridge Univ. Press, 2013).
2. Purkey, S. G. & Johnson, G. C. *J. Clim.* **23**, 6336–6351 (2010).
3. Purkey, S. G. & Johnson, G. C. *J. Clim.* **26**, 6105–6122 (2013).
4. Li, Q., England, M. H., Hogg, A. McC., Rintoul, S. R. & Morrison, A. K. *Nature* **615**, 841–847 (2023).
5. Swart, N. C. & Fyfe, J. C. *Geophys. Res. Lett.* **39**, L16711 (2012).
6. Thompson, D. W. J. *et al. Nature Geosci.* **4**, 741–749 (2011).
7. Young, I. R. & Ribal, A. *Science* **364**, 548–552 (2019).
8. Reguero, B. G., Losada, I. J. & Méndez, F J. *Nature Commun.* **10**, 205 (2019).
9. Hu, S. *et al. Sci. Adv.* **6**, eaax7727 (2020).
10. Sallée, J.-B. *et al. Nature* **591**, 592–598 (2021).
11. Orsi, A. H., Johnson, G. C. & Bullister, J. L. *Prog. Oceanogr.* **43**, 55–109 (1999).
12. Bronselaer, B. *et al. Nature* **564**, 53–58 (2018).
13. Bronselaer, B. *et al. Nature Geosci.* **13**, 35–42 (2020).
14. Purich, A. & England, M. H. *Geophys. Res. Lett.* **48**, e2021GL092752 (2021).
15. Tsujino, H. *et al. Ocean Modelling* **130**, 79–139 (2018).
16. Nijsse, F. J. M. M., Cox, P. M. & Williamson, M. S. *Earth Syst. Dyn.* **11**, 737–750 (2020).
17. Friedlingstein, P. *et al. Earth Syst. Sci. Data* **14**, 1917–2005 (2022).
18. Harris, L., Xi, C., Putnam, W., Zhou, L. & Chen, J. H. NOAA Tech. Memo. OAR GFDL; 2021-001 (NOAA, 2021).
19. NSTC. *Earth System Predictability Research and Development Strategic Framework and Roadmap* (US National Science Technology Council, 2020).

The author declares no competing interests.

Molecular biology

Inheritance of epigenetic marks scrutinized

Serge McGraw & Sarah Kimmins

There is debate about how epigenetic marks, such as methyl groups on DNA, can be passed down from parent to offspring. A mouse model involving targeted DNA methylation will better equip researchers to study this process.

Parental obesity, nutrient-poor diets or stress can compromise the health of children, and potentially grandchildren, through inheritance of 'epigenetic modifications'[1]. These biochemical changes to DNA or associated histone proteins – the addition of methyl or acetyl groups, for instance – affect gene expression, cell type and more, without altering DNA sequence. Epigenetic modifications can arise in response to environmental cues and are passed down to subsequent generations in eggs and sperm[2]. Writing in *Cell*, Takahashi *et al.*[3] present a mouse model in which methylation is induced at targeted sites in DNA, and demonstrate that this approach can be used to address pressing mechanistic questions about such transgenerational epigenetic inheritance (TGI).

There are two windows in a mammal's life during which most epigenetic marks are removed, then reset to ensure proper cell regulation – a process called epigenome reprogramming. The first is in developing sperm and eggs, beginning with precursors called primordial germ cells (PGCs), and the second is in embryos immediately after fertilization[4]. For TGI to occur, genes must 'remember' the epigenetic marks they previously had, enabling them to escape complete erasure during epigenome reprogramming. So far, only a handful of studies[5–8] have provided evidence for TGI.

DNA sequences at which cytosine and guanine bases are found side by side (known as CpG sites) are common sites of DNA methylation. These can be clustered