and therefore the total warming in the model would be greater than that observed. Better agreement with observations is achieved with lower values of sensitivity, which also underestimate WMGHG warming.

Some of the most directly policy-relevant research is based on simple box models[6,7] and integrated assessment models that incorporate simple climate models. The inability to differentiate between the sensitivities to sulphate aerosols and WMGHGs makes it impossible for these models to provide accurate projections of both long-term future temperature changes (in which WMGHG forcing is expected to dominate) and shorter-term changes (where the effect of cooling aerosols is also important). For longer timescales, relatively high values of sensitivity may be appropriate but this has the effect of overestimating near-term temperature changes. Probabilistic twenty-first century projections based on these models and observational constraints suffer from the same issue highlighted above, thus under-weighting the possibility of high impacts and over-weighting low impacts on multi-decadal timescales.

The scale of the effect in the GCMs varies widely, so there is certainly a need to better understand and quantify it. Future assessments will need to take it into account and previous assessments may need to be revisited. It is worth reflecting, however, that this new estimate for TCR comes about by questioning a widely-made implicit assumption in the application of simple climate models. Climate predictions would generally benefit from increased efforts to understand, rather than reduce, their uncertainties — something that can be in conflict with the remit provided by funders. Greater emphasis on the inherent assumptions could aid both policy interpretation and the advancement of the science. The challenge is to generate cross-disciplinary reflection and debate on the conditionalities of the latest predictions. The robust physical basis for confidence in some results, such as the reality and seriousness of anthropogenic climate change, could then be separated from more speculative, cutting-edge research. This would be valuable for public discourse on the subject and help science focus on those issues most likely to increase understanding, if not necessarily reduce uncertainty. ❐

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OCEANOGRAPHY

Southern Ocean polynya

From 1974 to 1976, an unexpected large hole appeared in the Weddell Sea winter sea-ice cover, a consequence of ocean heat carried to the sea surface by convection. This may have been a window to the past, as model analysis suggests anthropogenic climate change will diminish the chances of a repeat performance.

Arnold L. Gordon

Along Antarctica's continental margins, cold, dense water formed above the continental shelf spills over the edge, cascading to the depths. The resultant water mass, Antarctic Bottom Water (AABW), spreads northwards along the sea floor throughout the global ocean. En route it is modified through ocean mixing and blending with the warmer, more saline North Atlantic Deep Water. It returns to the Southern Ocean as a relatively warm deep layer, closing the circulation loop (Fig. 1). Although this is widely recognized as the predominant mode of overturning circulation, it is not the only Southern Ocean ventilation process: another mode exists, that of open-ocean convective, an exchange of deep and surface water driven by density instability[1]. However, model simulations of the Southern Ocean exposed to anthropogenic climate change indicate that open-ocean convention may be a thing of the past, reports Casmir de Lavergne and colleagues in *Nature Climate Change*[2].

Soon after the era of passive microwave satellites began, a large open-water region in the midst of the winter sea-ice cover, a polynya, 250,000 km^2 in extent, was detected within the Weddell Sea for three consecutive years, 1974 to 1976 (refs 3,4). One might conclude that it was the normal condition, but although small, week-long polynyas are now commonly observed in the Weddell Sea, a persistent, winter-long polynya hasn't formed since the mid-1970s. It was a fortuitous observation, for if the satellite had been delayed by three years, we would know nothing about the 'Great Weddell Polynya'. Ship-based observations from summer 1977 in the area of the polynya found that temperature and salinity stratification was nearly absent, marking a breakdown of the normal situation of cold, fresh water sitting above a warmer, saltier deep water across a stabilized, albeit weak, density gradient — the pycnocline[1]. This suggests that the polynya had been maintained, in the face of an intense winter sea-to-air heat flux, by relatively warm deep water (~1 °C) being brought to the surface, countering descent of the cold surface water (~−1.9 °C) in convective overturning reaching to nearly 3,000 m. Although there is a suggestion that deep-reaching open-ocean convection, and by inference, a Weddell Polynya, occurred in the early twentieth century[5], it is clearly an infrequent event.

During the coldness of winter, slight changes in the surface layer salinity can trigger water column instability, leading to deep-reaching convection and an open-ocean polynya. Should cold, dry polar

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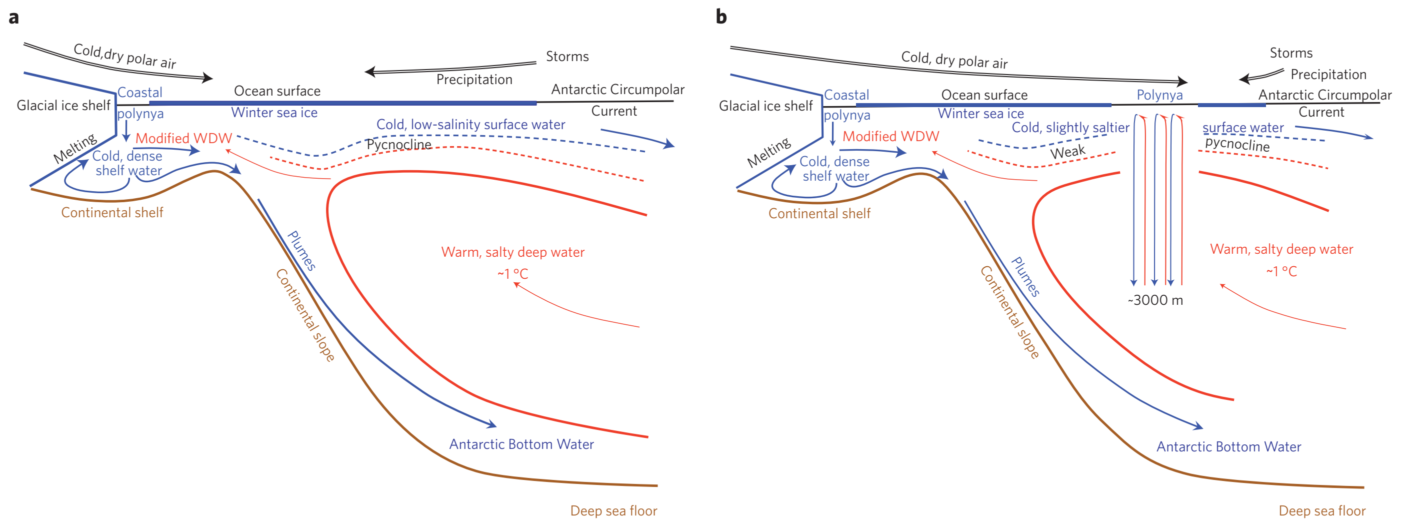

Figure 1 | Southern Ocean convection. **a**, The prevailing conditions of the present-day Southern Ocean is one of low-density surface water resting over warmer, saltier, denser deep water within the winter sea-ice cover. Deep-reaching convection is inhibited by precipitation associated with storms of the circumpolar belt. The predominant form of ventilation is limited to the descent of dense water plumes drawn from shelf water masses formed over the continental slope, through a combination of sea-ice generation within a coastal polynya and ocean–glacial ice interaction[1,5]. **b**, Northward expansion of cold, dry polar air masses of Antarctica, occurring during a negative Southern Annular Mode, reduces precipitation, increasing surface water salinity, causing a break down of the pycnocline, enabling deep-reaching convection cells that transfer deep ocean heat into the surface layer, while cold surface water reaches into the deep ocean, resulting in a winter polynya, and an alternative mode of deep ocean ventilation. WDW — warm deep water.

air spread seawards from Antarctica, the ocean's surface layer would receive less fresh water and a saltier, denser surface layer would ensue. If the polar air remains more confined to the glacial ice sheet, this allows storms of the westerly wind belt to turn polewards, and the surface water becomes fresher and less dense. This sequence reflects, respectively, the negative and positive phase of the Southern Annular Mode (SAM)[6], with the density gradient across the pycnocline separating the surface and deep stratum weakening during negative SAM, and intensifying during positive SAM. If the negative SAM persists over a few years, open-ocean convection develops, and the deep water cools. In the absence of a polynya, there would be a rebound in deep-water temperature, as observed since the Great Weddell Polynya[7].

De Lavergne *et al.* suggest[1] that anthropogenic forcing reduces the probability of deep convection. They report significant freshening of the surface water over the past 60 years within the seasonal sea-ice zone. This long-term freshening of southern polar surface waters is consistent with the positive SAM trends[8], accelerating melting of Antarctic glaciers[9] and warming of deep water[10]. Global climate model simulations, using 36 models of the Coupled Model Intercomparison Project Phase 5, find that deep convection within the Weddell Sea was common under pre-industrial conditions, but becomes increasingly rare under climate change.

The team acknowledge that the models are too coarse to properly simulate the continental shelf processes, including an ocean–glacial ice interaction and AABW spillage over the continental slope, but they do capture changes in precipitation, winds, sea ice and ocean circulation, and can be used to assess the probability of polynya development. Significant deep open-ocean convection is displayed in 70% of the models under pre-industrial conditions, with most exhibiting events at ten-year intervals. When subjected to increasing carbon dioxide concentrations, all convection models show a decrease in the strength of deep convection over the period 1900 to 2100, with 7 models displaying a complete cessation before 2030. Simulations continued to 2300 simulate no return of deep convection.

Polynya-induced convection cannot replace the present-day denser AABW drawn from the continental margin. However, if continental margin AABW is stymied, as it might have been in the glacial age maximum about 18,000 years ago, when sea level was 130 m lower and glacial ice covered much of the continental shelf[11], open-ocean convection would be free to reach the sea floor and become the dominant mode of Southern Ocean ventilation. As the interglacial period proceeded, open-ocean convection continued but at a reduced frequency to be overtaken by dense water formed along the continental margin of Antarctica, finally disappearing as the post-industrial Anthropocene took hold.

The study by de Lavergne *et al.* concludes that the changing hydrological cycle forced by anthropogenic factors reduces the probability of deep open-ocean convection and polynya occurrence within the Southern Ocean winter sea-ice cover, countering the effects of strengthening of the westerly winds[12]. In the twenty-first century, the Great Weddell Polynya, as last observed in the mid-1970s, will become a thing of the past. ❐

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