

Heat from turbulence in the faster flows becomes significant in melting ice, causing a transition during the middle and late summer to an efficient, low-pressure drainage system of channels¹⁰. Partial drainage of cavities under pressure into the channels reduces water storage and lowers the ice surface. As the ice interacts with more obstacles, ice motion slows down. Drainage through efficient channels after the end of surface melting in the autumn produces the most-drained basal condition and slowest ice velocities. But as the water flow slows and turbulent heat production drops, channel walls creep in faster than they are melted, and the channels eventually close. The slow supply of water from basal melting or any reservoirs then repressurizes the basal system, returning it to the late-winter conditions.

Ian Bartholomew and colleagues⁵ document the evolution of the ice-sheet response to seasonal meltwater input through observations of summer surface temperatures and the locations of four GPS receivers along a ~35 km flowline in western Greenland. They find the ice sheet's behaviour strikingly similar to that of alpine glaciers.

Significantly, the annual rearrangement of the drainage pathways here leads to a net increase in annual ice motion in Greenland, because the spring speed-up exceeds the autumn slow-down in comparison with

the late-winter value. Whereas previous estimates^{1,2} placed this net increase at roughly 5–25%, Ian Bartholomew and colleagues⁵ report a 17–40% increase along their flowline. Although modest when compared with the several-fold increases in ice flow that have been observed from dynamic changes at the ice front¹¹, evolving drainage systems could potentially lead to dynamic feedbacks that activate sliding over a larger portion of Greenland and significantly alter sea-level projections¹².

Because of the complex balance between warming effects on the spring speed-up and autumn slow-down inherent in the evolution of the basal water system, it remains a scientific challenge to predict if future warming will continue to increase flow speeds. Incorporating these processes in ice-flow models is further complicated by limited data. To calculate the percentage of speed up expected for a given volume of water, we need to know not only the amount of water involved, but also the late-winter flow speeds against which summer and autumn values are compared, and the basal conditions over which the ice flows. Obtaining continuous GPS records in Greenland throughout the bitter winter months remains a technological challenge. Furthermore, records across a decade or more of winters are required to help capture

transient processes that might be operating in the system to alter the storage and release of water in winter¹³. Ongoing efforts by geophysicists are continually improving the regional, high-resolution characterization of a surface that is buried beneath hundreds-to-thousands of metres of ice.

The rate of discovery in glaciology, even in the face of daunting obstacles, is exciting, thanks to studies such as the one by Bartholomew and colleagues⁵. As a result, our ability to predict the future evolution of the ice sheets is improving rapidly. □

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GLACIAL CYCLES

Atmosphere and ocean chemistry

Low atmospheric carbon dioxide concentrations during glacial periods must have been accompanied by changes in surface-ocean carbonate chemistry. But it is unclear whether concurrent changes in the deep sea contributed to the glacial carbon dioxide decline.

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During the past eight glacial cycles, atmospheric carbon dioxide levels were consistently about 80 parts per million by volume (ppmv) lower than those of interglacial periods, a difference that has proved challenging to explain. In his quest to solve the ice-age CO₂ puzzle, seventeen years ago Wally Broecker considered a scenario in which the glacial deep sea would have been more alkaline¹. Specifically, an elevation of the carbonate ion concentration of the deep sea by 40 μmol kg⁻¹ or more could largely explain the observed glacial atmospheric CO₂ levels. The scenario was initially supported^{2,3}, but was ultimately shown to be untenable⁴. Broecker finally concluded

that the scenario “appears to have bitten the dust”⁵. Over the past few years, significant progress has been made in reconstructing deep-sea carbonate chemistry. Writing in *Paleoceanography*, Rickaby and colleagues⁶ provide evidence for elevated carbonate ion concentrations in the deep Weddell Sea during the past eight glacial intervals.

On glacial–interglacial timescales, atmospheric CO₂ is slave to the ocean, as the ocean contains about 60 times more carbon than the atmosphere. Hence any explanation of the glacial CO₂ drawdown must invoke changes in the ocean's carbonate chemistry. The carbonate ion concentration [CO₃²⁻] is a useful variable to track changes in

ocean carbonate chemistry. All else being equal, atmospheric CO₂ should be inversely proportional to the ocean's carbonate ion concentration. Deep-sea carbonate ion concentration in turn affects the distribution of calcium carbonate in marine sediments and the chemistry of the shells of benthic organisms — properties that can be measured in sediment cores. Thus changes in deep-sea carbonate ion concentration can be inferred from the sedimentary record.

Reconstructions of deep-sea carbonate ion concentration (Fig. 1) rely on tools including calcareous assemblages, preservation indices, stable boron isotopes, and Zn/Ca and B/Ca ratios from the shells of

seafloor-dwelling protozoans. Based on B/Ca and Mg/Ca ratios, Rickaby and colleagues⁶ suggest that the carbonate ion concentration of glacial waters at a depth of roughly 2.5 km in the Weddell Sea was about $25 \mu\text{mol kg}^{-1}$ higher than during interglacials. This finding is important because today the Weddell Sea, located to the east of the Antarctic Peninsula, contributes to the formation of Antarctic Bottom Water (AABW). Antarctic Bottom Water fills a substantial portion of the abyssal ocean during interglacial periods, and was probably even more prevalent during glacial periods. Thus a large volume of glacial AABW with elevated carbonate ion concentration could have contributed to the lowering of atmospheric CO_2 during ice ages.

If the inferred carbonate ion concentration rise of $\sim 25 \mu\text{mol kg}^{-1}$ in the Weddell Sea was representative of glacial deep water on a global scale, this could prove to be a show stopper. But this seems unlikely for two reasons. First, estimates of the deep-sea carbonate ion concentration in other ocean basins would have to show a similar rise, which they don't (Fig. 1). Second, if global deep-sea carbonate ion concentration rose so substantially, the depth above which carbonate minerals are preserved in sediments⁷ would have dropped by 1–1.5 km during glacials, which it didn't. Rather, the evidence suggests little change in the globally averaged deep-sea carbonate ion concentration during glacial intervals: changes in the Atlantic Ocean above and below ~ 3 km seem to cancel, and there was little or no change in the deep Pacific Ocean (Fig. 1). The existing evidence for the Pacific Ocean is supported by the very latest results, suggesting that the carbonate ion concentration of the deep Pacific changed by less than $\sim 10 \mu\text{mol kg}^{-1}$ (Jimin Yu, personal communication).

Because Weddell Sea deep waters have the lowest carbonate ion concentration found in the modern ocean, a $25 \mu\text{mol kg}^{-1}$ rise there during glacial intervals would not necessarily translate into a similar rise in other basins. When AABW expanded further into the deep Atlantic during glacial intervals, it almost certainly displaced a deep-water mass with a higher carbonate ion concentration. In the Pacific Ocean, it may have displaced waters with only slightly lower carbonate ion concentration. At any rate, the carbonate chemistry of the ocean's big deep reservoir seems to have been quite similar during glacial and interglacial stages^{8–11}, in spite of the inferred changes in the Weddell Sea (Fig. 1). Indeed, it now seems pretty clear that the principal factor influencing the glacial–interglacial CO_2 shift is not simply the carbonate ion concentration of the deep sea.

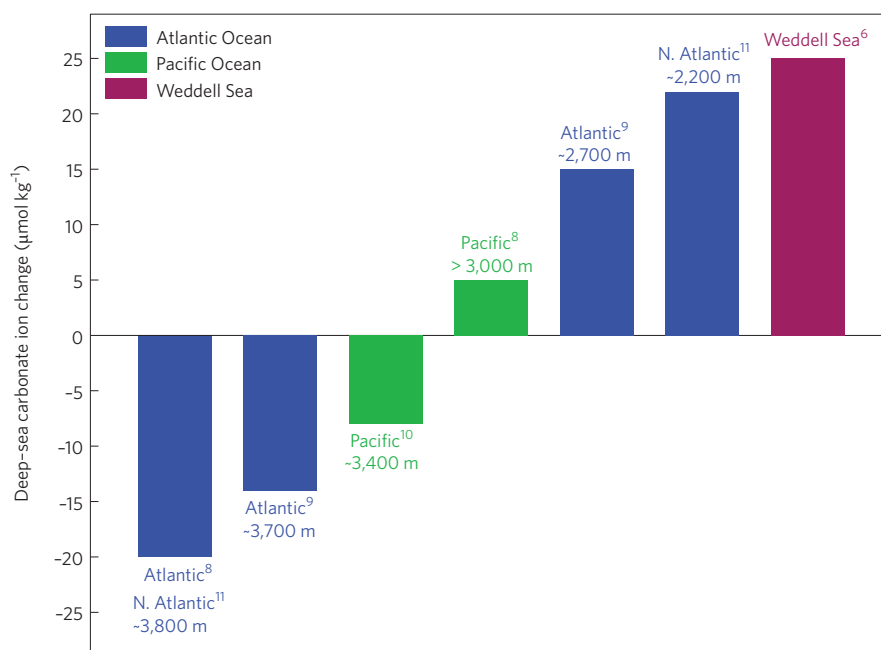


Figure 1 | Glacial–interglacial changes in deep-sea carbonate ion concentration. Rickaby and colleagues⁶ show that the deep-sea carbonate ion concentration in the Weddell Sea was higher during glacial periods than interglacial periods. Although a global ocean-wide rise of this magnitude could explain much of the low glacial levels of atmospheric CO_2 , the corresponding change in the Pacific deep ocean was much smaller, whereas changes in the deep Atlantic Ocean seem to cancel. Thus changes in deep-sea carbonate chemistry are unlikely to explain the full magnitude of the atmospheric CO_2 drop between interglacial and glacial periods.

There is no shortage of alternative scenarios proposed to lower atmospheric CO_2 down to glacial values, which work in simple (for example, box and advection–diffusion) models and some intermediate-complexity models. Many of these scenarios are also consistent with little or no change in global deep-sea carbonate ion concentration during glacials, with significant excursions being limited to the brief glacial–interglacial transitions. However, it is difficult to achieve glacial CO_2 in complex models, such as general-circulation models. If the general-circulation models are right, then something is wrong with the simple models and we may still be missing important processes. Alternatively, we may have identified the processes a long time ago, but something is wrong with the general-circulation models.

Despite the new evidence from Rickaby and colleagues⁶ for increased carbonate ion concentration in deep waters of the glacial Weddell Sea, the balance of evidence speaks against a significant rise of the average deep-sea carbonate ion concentration during glacial periods on a global scale. Hence Broecker's conclusion that the glacial CO_2 drawdown was not a result of globally elevated deep-sea carbonate ion concentration seems to remain valid⁵.

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