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 channels\(^5\). 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 lowest 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 colleagues\(^5\) document the evolution of the ice-sheet response to seasonal meltwater input through observations of summer surface temperature 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\(^1\) placed this net increase at roughly 5–25%, Ian Bartholomew and colleagues\(^5\) 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 front\(^1\), evolving drainage systems could potentially lead to dynamic feedbacks that activate sliding over a larger portion of Greenland and significantly alter sea-level projections\(^1\).

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 winter\(^5\). 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 colleagues\(^5\). As a result, our ability to predict the future evolution of the ice sheets is improving rapidly.

Byron R. Parizek is at Penn State DuBois, College Place, DuBois, Pennsylvania 15801, USA. e-mail: parizek@psu.edu

References


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.

Richard E. Zeebe and Thomas M. Marchitto, Jr

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 CO\(_2\) puzzle, seventeen years ago Wally Broecker considered a scenario in which the glacial deep sea would have been more alkaline\(^1\). 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 CO\(_2\) levels. The scenario was initially supported\(^2,3\), but was ultimately shown to be untenable\(^4\). 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 Paleoclimatology, Rickaby and colleagues\(^6\) provide evidence for elevated carbonate ion concentrations in the deep Weddell Sea during the past eight glacial intervals.

On glacial–interglacial timescales, atmospheric CO\(_2\) is slow to the ocean, as the ocean contains about 60 times more carbon than the atmosphere. Hence any explanation of the glacial CO\(_2\) drawdown must invoke changes in the ocean’s carbonate chemistry. The carbonate ion concentration [CO\(_3^{2-}\)] is a useful variable to track changes in ocean carbonate chemistry. All else being equal, atmospheric CO\(_2\) 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 colleagues\(^5\) suggest that the carbonate ion concentration of glacial waters at a depth of roughly 2.5 km in the Weddell Sea was about 25 μmol 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 ~25 μmol 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 sediments\(^7\) 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 ~10 μmol kg\(^{-1}\) (Jimin Yu, personal communication).

Because Weddell Sea deep waters have the lowest carbonate ion concentration found in the modern ocean, a 25 μmol 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.

There is no shortage of alternative scenarios proposed to lower atmospheric CO\(_2\) down to glacial values, which work in simple box and advection–diffusion models and some intermediate-complexity models. Many of these scenarios are consistent with little or no change in 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 colleagues\(^5\) 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 valid\(^5\).

Richard E. Zeebe is in the School of Ocean and Earth Science and Technology, Department of Oceanography, University of Hawaii at Manoa, 1000 Pope Road, MSB 504, Honolulu, Hawaii 96822, USA; Thomas M. Marchitto, Jr is in the Department of Geological Sciences and INSTAAR, University of Colorado, Boulder, INSTAAR, Campus Box 450, Boulder, Colorado 80309-0450, USA. E-mail: zeebe@soest.hawaii.edu, tom.marchitto@colorado.edu

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