OCEANOGRAPHY

Overturning assumptions

The lack of deep mixing in the subpolar North Atlantic Ocean for over a decade has raised concerns that climate warming may already be affecting the ocean circulation. A vigorous convection event last winter shows that the system holds some surprises yet.

Susan Lozier

The deep mixing of ocean waters at high latitudes is important for the heat and carbon uptake of the oceans. This mixing, also known as overturning, is usually triggered by strong heat loss during the winter season. But with expectations of warmer surface waters and an increasing influx of fresh water in the high latitudes in a warming climate, it has been suggested that deep mixing may diminish or perhaps even cease in the near future: both effects, warming and freshening, make the top layer of water less dense and therefore increasingly resistant to deep mixing. Nevertheless, on page 67 of this issue Kjetil Våge and co-authors[1] present evidence for a remarkable overturning event in the subpolar North Atlantic Ocean last winter, surprisingly aided by Arctic sea-ice decline. Their observations challenge oceanographers to shed some simplistic assumptions about how the ocean responds to climate variability and change.

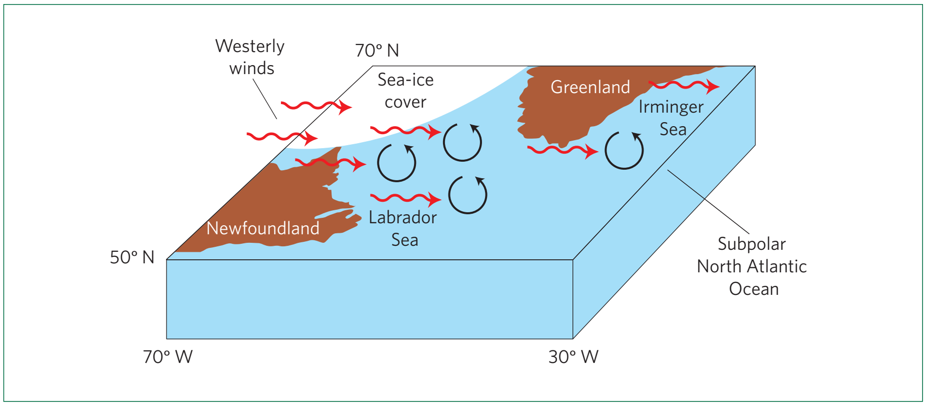

Figure 1 | Deep convection in the subpolar ocean. As reported by Våge and colleagues[1], an unusually extensive sea-ice cover insulated the strong, cold westerly winds from the warmer ocean until they reached the central basin of the Labrador Sea in winter 2007–08. There, the unusually cold winds rapidly cooled the surface water, leading to mixing of the water column to depths that had not been reached in the previous 15 years.

Oceanographers have long been interested in how, where and when surface waters in the high latitudes of the northern North Atlantic Ocean are drawn to depth in convective overturning events. In these instances, the previously layered water column is mixed from the surface to depth in a huge chimney of water that is characterized by a characteristic, homogeneous temperature and salinity, as well as other properties. Once the surface stratification has reestablished itself, the mass of water below the surface layer is no longer in contact with the atmosphere, and the properties of the homogenized water column are preserved in a characteristic water mass. Using these fingerprints of temperature and salinity, individual water masses can be traced as they move away from their source locations: for example, 'North Atlantic Deep Water' formed in the Labrador, Irminger and Norwegian–Greenland Seas can be identified as far away as the Southern Ocean. In fact, most of what physical oceanographers know today about the deep ocean circulation comes from tracking such water properties.

Recently, other climate scientists have become interested in the formation of water masses. As water is removed from the surface it carries not only heat and salinity anomalies to great depths, but also anthropogenic carbon dioxide[2], absorbed when the water was still at the surface. The carbon dioxide, like the other water mass properties, is transported to the deep ocean where it remains for hundreds of years. Therefore, the amount of carbon dioxide that has been — and will be — stored in the deep ocean is critically linked to the production of water masses through deep overturning events.

In recent years it has been suggested that the production of these water masses depends on the state of the North Atlantic Oscillation (NAO)[3], a natural climate fluctuation linked to the strength of the westerly winds across this ocean basin[4]. A high North Atlantic Oscillation index, associated with strong westerlies, is expected to favour the production of deep water masses in the northern North Atlantic Ocean, whereas a low index is believed to hinder deep convection. From prior observations, oceanographers had little reason to expect that deep water production during winter 2007–08 would be any different from the previous 15 winters during which convection had been fairly shallow or even non-existent: the North Atlantic Oscillation index in 2007–08 was lower than in the previous winter, when there had been no appreciable change in the convective depth. In addition, the slow advance of global warming was expected to steadily stabilize the surface waters, through warming or freshening or both.

Kjetil Våge and colleagues[1] analysed drifting floats in the subpolar basin that measure temperatures from the surface down to 2,000 metres. They found unusually deep mixed layers, particularly in the Labrador and Irminger Seas, indicative of very strong overturning. The overturning considerably cooled the waters of the Labrador Sea at intermediate depths, disrupting a recent warming trend[5]. The authors partially attribute the strong overturning to an indirect impact of global warming arising from a chain of events (Fig. 1). First, the unusually high export of sea ice from the Arctic Ocean in the summer of 2007 created a freshwater cap in the northern part of the Labrador basin.

This freshening prevented the overturning of the surface waters with the onset of autumn, aiding the local formation of sea ice from these very cold surface waters. The resulting extensive ice cap insulated the cold air blowing eastward off the American continent from the relatively warmer ocean water. The air was therefore unusually cold when it reached the interior of the Labrador Sea, where it caused tremendous heat loss from the ocean and instigated massive overturning.

Therefore, in an ironic twist, the increased flux of Arctic sea ice, which has been attributed to global warming[6], contributed to the strong overturning of subpolar North Atlantic surface waters. An additional contribution to the 2007–08 deep convection event came from unusually strong westerly winds over the Labrador and Irminger Seas that not only supplied the cold continental air to these regions, but also created weather patterns favourable for ocean mixing[7]. These local wind changes — not captured by the basin-scale North Atlantic Oscillation index — along with the unusually cold air and extended sea-ice cover conspired to create a deep overturning that could not have been predicted from the relatively simple measure of the North Atlantic Oscillation index.

Not all is turned upside down. Oceanographers can still rely on the familiar narrative that very cold winters produce deep convection in the northern North Atlantic and that, in general, the colder the winter, the greater the overturning. Temperatures this past winter were indeed unusually cold, about 5–6 °C colder than the previous seven winters[1], and so it makes sense that deep mixing followed. On the other hand, oceanographers have tended to assume that deep convection is preceded by preconditioning of the surface waters — such as cooling in the previous year — and that global warming will inhibit convection. Neither of these two assumptions held true during the winter of 2007–08. These heuristics therefore need to be replaced by a more sophisticated understanding of how water mass formation responds to climate variability and climate change.

Våge and colleagues provide a timely reminder that the climate system in the high northern latitudes is ruled by intricate feedbacks between the ocean, ice and atmosphere. At the same time, the familiar assumption of oceanographers of a direct causal link between local production of water masses at high latitudes and the export of those waters at depth as part of the global ocean circulation is no longer a certainty, but rather a focus of current research[8]. As this research evolves, many more of our assumptions about the workings of the deep ocean may very well be overturned. ❐

Susan Lozier is in the Division of Earth and Ocean Sciences, Nicholas School of the Environment at Duke University, Box 90230, Durham, North Carolina 27708, USA.
e-mail: mslozier@duke.edu

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PLANETARY SCIENCE

Tidal flows in satellite oceans

Sub-surface oceans probably exist on several large satellites of Jupiter and Saturn. An analysis of Europa's tides suggests that some of the Rossby waves are resonantly enhanced by the obliquity, producing sufficient heat and flow to keep the ocean liquid.

Bruce G. Bills

Most of what we know, or think we know, about the influence of tides throughout the Solar System comes from two disparate sources: the first, observational and theoretical work on tides within Earth's oceans[1], is mostly aimed at appropriate solutions to the governing system of equations that Pierre-Simon, Marquis de Laplace, worked out in 1776; the second, a much smaller but still substantial, body of work, focuses on the dissipation of energy by tidal processes in other planets and satellites, mostly assuming that dissipation occurs only in solid (effectively viscoelastic) regions of these bodies. This dichotomy of understanding tidal effects in solid and liquid regions is particularly acute when applied to Jupiter's satellite Europa — widely believed to contain a subsurface liquid ocean[2] that is prevented from freezing by tidal heating in the surface ice layer[3] (Fig.1). Conversely, Robert Tyler[4] proposes that resonantly enhanced tidal flows in the fluid oceans of Jupiter and Saturn's icy satellites could represent a significant heat source within these bodies.

The idea that tidal heating in other planets occurs mostly in their solid regions is based largely on a model developed for the Moon[5] and then used to predict volcanic eruptions on Jupiter's satellite Io[6], a week before such eruptions were discovered[7]. The usual excitation mechanism for satellite tides is simply the change in gravitational potential experienced by the satellite as it moves on an eccentric orbit. The eccentricity tide acts to change the shape of the body. In a synchronously rotating satellite — one that always shows the same face to its parent body with only a small sideways wobble — the tidal bulge moves back-and-forth along the equator, rather than circulating round the equator as it does on Earth. Such a movement can generate a significant amount of dissipation in both the solid and liquid regions of the satellite. However, because the predictive model for Io was so successful based on the solid regions, planetary researchers have focused primarily on this aspect.

Regardless of the excitation mechanism for a uniform-depth ocean on a rotating spherical body, the response of the ocean is a superposition of a large number of different characteristic spatio-temporal patterns or wave types[8]. At wavelengths of the order of metres, where planetary rotation is not important, the primary restoring forces are gravity and surface tension; the resulting patterns of motion are the gravity waves and capillary waves we know from Earth's oceans.