CRYOSPHERE

Warmth from the deep

Unusual wind patterns and the albedo feedback effect played crucial roles in the rapid reduction of Arctic sea-ice cover in recent years. Evidence is now building that a warmer ocean has also contributed to the thinning of Arctic ice.

Eddy Carmack and Humfrey Melling

Earth's climate system, with all its nonlinear thresholds and feedback loops, is packed with surprises. The Arctic Ocean is a pre-eminent example. In September 2007, 2.5 million km^2 of usually ice-covered ocean — an area the size of Mexico and California combined — was exposed for the first time in recorded history by an unprecedented northward retreat of sea ice. This dramatic retreat was part of a longer-term decline in the Arctic Ocean's ice cover over the past two decades — a trend that has huge consequences for the climate system, marine biology, resource extraction, shipping and international security. It is often assumed by the public and in policy circles that sea-ice retreat is simply a consequence of atmospheric warming. Writing in the *Journal of Physical Oceanography*, however, Igor Polyakov and co-authors[1] present a *tour de force* of data and numerical simulations that documents a significant contribution from warm ocean waters that enter the Arctic realm at depths of 200–800 m and originate from the North Atlantic region.

Arctic researchers have long recognized that ocean heat flux plays a role in determining the equilibrium thickness of sea ice[2]. As ice thickens, it becomes an increasingly effective barrier to the upward flux of heat from the ocean to the atmosphere. At some thickness, about 3 m in the present climate, the rate of upward heat loss at the ice–ocean boundary no longer exceeds the rate of heat supply from the body of the ocean, and no further freezing is possible.

There is sufficient heat stored in the warm water that enters the Arctic basin from the Atlantic Ocean to melt the ice cover many times over. However, a layer of relatively fresh, and therefore buoyant, cold water lies above the warm Atlantic water. The layering strongly suppresses the upward diffusion of heat and thereby protects the ice from melting from below. Ice dynamics also play a critical role in determining the thickness of sea ice, because compression and ridge building can quickly result in ice thicknesses up to ten times greater than those achievable by freezing.

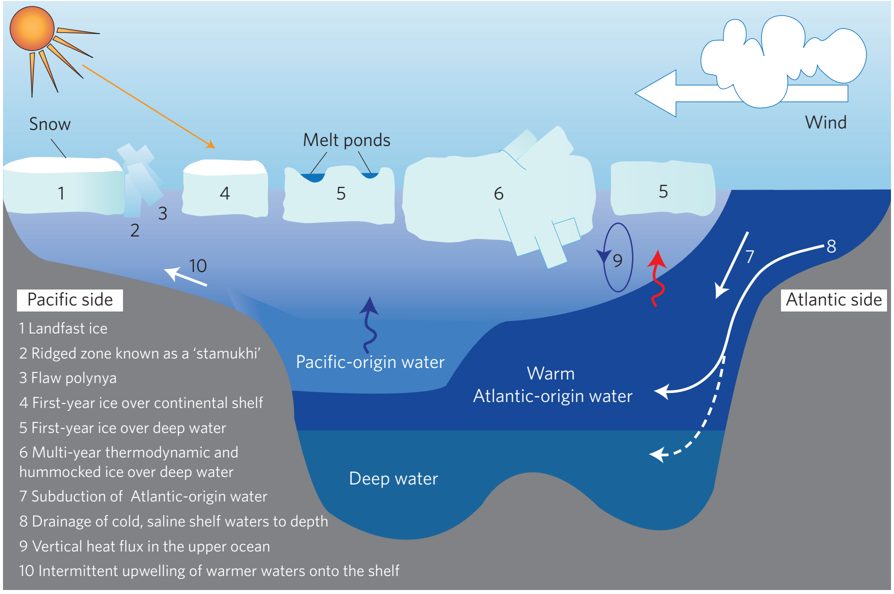

Figure 1 | Schematic cross-section of the Arctic basin showing influences on sea-ice cover. Characteristics of sea ice and underlying water masses, as well as ocean depth, all influence sea-ice cover. Gaps in the ice (3) affect the rate of ice loss by influencing the albedo feedback effect; the type, location and surface properties of ice (1–2, 4–6) affect the way in which it responds to changes in its environment (7–10); and the underlying waters (Atlantic or Pacific origin) affect the degree of melting from below. Polyakov and colleagues[1] show that warming of waters originating in the Atlantic Ocean, combined with lower stability of the upper ocean in the Atlantic sector of the Arctic basin, have contributed to thinning of Arctic sea ice by increasing heat flux from the Atlantic waters to the waters above (red arrow).

Today, change is underway. Over the past few years, sea ice has been retreating and thinning. It has also become less tightly packed, allowing it to move more quickly in response to winds. The rates of these changes are faster than most climate models predict. Thus, it isn't surprising that there is broad debate about the underlying causes of the changes, with researchers identifying a variety of explanations according to their specific expertise.

Polyakov and co-workers[1] set out to investigate the case for an oceanic influence. They focus on observations of a layer of water in the Arctic Ocean that originates from the Atlantic Ocean, referred to here as the 'Atlantic layer'. First, they examined historical data extending back more than 100 years, to a time when temperature was measured with mercury-in-glass thermometers and salinity was determined by titration. They discovered that since the 1970s, the Atlantic layer has warmed by as much as 1 K and shoaled, moving 75–90 m closer to the overlying ice. They also found a substantial decrease in the stability of the upper ocean on the Eurasian side of the Arctic region. This change could potentially have allowed greater heat flux from the Atlantic layer to the overlying water. The researchers also tracked changes in the temperature of the Atlantic water as it moves along its anticlockwise trajectory around the perimeter of the Arctic basin. They found that the Atlantic layer cooled along this pathway, whereas the overlying water warmed, suggesting that heat migrates upwards from the Atlantic layer to the overlying water.

Polyakov and colleagues then used numerical models to explore the implications of these observations. Using a one-dimensional model, they estimate that the warmer Atlantic layer, combined with the lower stability of the upper ocean, led to an increase in the upward flux of heat from the Atlantic layer by 0.5 $\mathrm{W\,m^{-2}}$. This rise in heat flux is sufficient to thin Arctic sea ice by about 30 cm over 50 years. The crux of their argument is that slow changes in ice thickness linked to increased heat flux from the underlying ocean preconditioned the ice for its dramatic response to summer-time conditions in 2007.

The change in heat flux is small and is based on uncertain estimates of vertical diffusion in the ocean, which — as the researchers readily admit — limits the confidence that can be placed in it. Furthermore, the analysis is specific to the Atlantic sector of the Arctic basin, that is, the deep Eurasian and Makarov basins. In the Canada basin, the other half of the Arctic deep waters, different melting patterns are being observed[3]. Here, the addition of low-density waters from the Pacific Ocean, rivers and melting ice has actually increased the stability of the upper ocean[4].

Nevertheless, these findings provide a valuable prompt to examine the role of oceanic factors in the decline of Arctic sea ice more carefully. This will not be straightforward. For one thing, neither Arctic sea ice nor the underlying ocean is homogeneous. The interactions between different ice types, surface properties, geographical settings and underlying water masses create a variety of circumstances, each of which needs careful study (Fig. 1). The use of a conventional one-dimensional vertical diffusion model by Polyakov and co-authors has also revealed a discomforting lack of knowledge about turbulence and diapycnal mixing in the ocean beneath Arctic sea ice. The general failure of coupled models to replicate the rapid progression of changes observed in the Arctic region is clearly a warning against oversimplification and a call for increased attention to the full range of interacting physical processes that allow sea ice to exist (or not) in the ice–ocean–atmosphere system.

The painstaking data analysis by Polyakov and co-authors[1] supplies a large-scale view of the present state of intermediate-depth waters in the Arctic Ocean, and of the changes in the properties of this layer throughout the twentieth century. Furthermore, the work demonstrates the value of international collaboration under the auspices of the International Polar Year. The state of the Arctic Ocean in 2007 was a surprise. Does it hold more surprises? Given the stakes, we cannot afford not to look. ❐

Eddy Carmack and Humfrey Melling are at Fisheries and Oceans Canada, 9860 West Saanich Road, PO Box 6800, Sidney, British Columbia V8L 4B2, Canada.
e-mail: eddy.carmack@dfo-mpo.gc.ca

References

1. Polyakov, I. V. *et al. J. Phys. Oceanogr.* doi:10.1175/2010JPO4339.1 (2010).
2. Maykut, G. A. & Untersteiner, N. *J. Geophys. Res.* **76,** 1550–1575 (1971).
3. Shimada, K. *et al. Geophys. Res. Lett.* **33,** L08605 (2006).
4. Yamamoto-Kawai, M. *et al. J. Geophys. Res.* **114,** C00A05 (2009).

GEOMORPHOLOGY

Deceptively old Alpine gorges

The timing and origins of Alpine gorge formation are controversial. A high-resolution analysis of the inner gorges of the Swiss Alps suggests that these landforms were carved over successive interglacial periods, and survived the intervening glaciations.

Jean L. Dixon

The deep gorges found in many of the Earth's mountain belts have caught the curiosity of geomorphologists for more than a century[1–3]. These deep scars in the relief of mountains are commonly thought to have formed during an exceptional period in Earth's history. In this framework, the initial relief was shaped by the high erosive power of the glaciers that covered most high mountains until 15,000 years ago. The U-shaped valleys they sculpted would have then been incised even further by fluvial processes in the few thousand years following the melting of the glaciers, superimposing a V-shape on the valleys. However, clear evidence for gorge formation solely since the end of the last glacial period has remained elusive. As they report in *Nature Geoscience*, Montgomery and Korup[4] have demonstrated that deep inner gorges in the Central Alps are not just postglacial in origin.

The relative efficiency of glacial and fluvial erosion is a long-standing and controversial question[5,6]; better constraints on these rates are critical to understanding how climate, erosion and tectonics interact to shape landscapes. Glacial and fluvial erosion each produce distinct landscape morphologies[6,7] under certain climate conditions: the presence of fluvial gorges in a glacial terrain suggests that the inner Alpine gorges are young, postglacial features.

Exposure ages obtained from measurements of the cosmogenic nuclide ^{10}Be suggest that at least some Alpine gorges were rapidly incised following glacier retreat[3,7]. But age estimates can be complicated, as gorges may be carved directly beneath glaciers[1], preventing the accumulation of ^{10}Be in the initial stages of incision, before the glacier receded. Or, if the valleys were perhaps carved slowly over successive interglacial periods[2], evidence of previous exposure would be erased by subsequent erosion. Arguments for or against longer timescales of gorge formation have therefore remained largely speculative.

Using numerous lines of evidence, Montgomery and Korup[4] now make a compelling case for the longevity of these topographic features. They mapped the relief of more than 1,000 inner gorges in the Alps using high resolution digital topography from airborne LiDAR. Based on this topography, they calculate that mean fluvial bedrock erosion rates would need to be 8–18 $\mathrm{mm\ yr^{-1}}$ to carve gorges following the last glacial period. This is much higher than the average Holocene rates of erosion for the region[8]. Rates this high have been recorded over shorter durations. For instance, in one extreme example, metres of relief were carved into limestones within a few days during a recent megaflood[9], which attests to the erosive power of rivers during catastrophic