

# Underwater ice boosts production of the world ocean's densest waters

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**Waters cooled below freezing point adjacent to Cape Darnley, Antarctica generate subsurface ice and produce dense waters that flood the global ocean abyss.**

The seas around Antarctica are central to the global ocean circulation, forming the key nexus of the Atlantic, Pacific, and Indian Oceans. They also host a vigorous vertical circulation, where old water last in contact with the atmosphere before the Industrial Revolution rises from great depth (1 to 2 km) to reach the surface. Here, this water interacts with the atmosphere and the ice, before sinking back into the ocean interior. This allows the ocean to absorb very large amounts of heat and carbon from the atmosphere, slowing the rate of global warming elsewhere in the Earth System (1). The coldest water that is formed this way—Antarctic Bottom Water (AABW)—is the densest water in the global circulation; it sinks to the seabed and floods across most of the global abyss (2).

The growth of sea ice (e.g., Fig. 1) is central to this AABW formation, because it injects salt into the water, increasing its density. Understanding where and how this sea ice grows is thus critical. Writing in this issue of *Science Advances*, Ohshima *et al.* (3) report unexpected findings concerning the method of sea ice growth in a key AABW production site, with potential implications elsewhere around Antarctica.

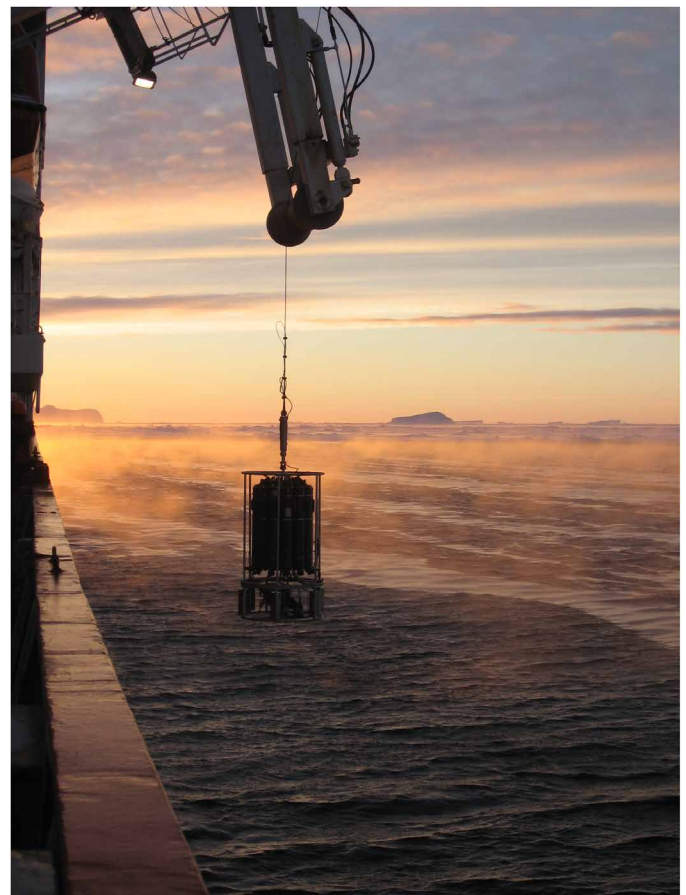
Because of AABW's global importance, many studies have examined how and where this water forms. Although measurements around Antarctica are among the most challenging to obtain, because of its remoteness and hostile conditions, processes occurring on the continental shelves are known to be key, especially sea ice production. Here, interactions with the floating part of the Antarctic Ice Sheet can also supercool the waters, i.e., reduce their temperature below the surface freezing point. Such processes lead to the very cold and yet comparatively saline AABW,

giving it its high density and allowing it to spread at depth around the world.

Despite decades of progress, much remains unknown about AABW production. The traditional view held that three key sites dominated its formation, with these sites characterized by broad continental shelves, floating parts of the Antarctic Ice Sheet, and/or enhanced sea ice production in frequent polynyas (waters kept open during winter). Recently, a fourth region was identified close to Cape Darnley, which does not feature a broad shelf region but where intense sea ice production occurs (4). Much has been learned, but the exact processes behind the dense water production in the Cape Darnley Polynya have remained elusive.

Using satellite observations and data from year-round oceanographic moorings, Ohshima *et al.* (3) demonstrate the importance of underwater frazil ice to dense water production. Frazil ice is well known to Antarctic oceanographers; it forms as irregularly shaped crystals where the temperature of seawater is reduced below its typical surface freezing point. This can happen where water is cooled by the underside of floating

ice shelves, and intense pressure keeps it liquid. Frazil ice can form near the surface where the water is in a turbulent state, with the heat exchange between the atmosphere and ocean allowing supercooling to occur, and it was recently noted that supercooled waters are far more widespread across the Southern Ocean than previously thought (5). The



**Fig. 1. Making oceanographic measurements during vigorous ice formation in the Bellingshausen Sea, Antarctica.** Strong winds and air-sea fluxes drive frazil ice production, which aggregates at the surface into streaks of grease ice. Photo credit: Paul Holland, British Antarctic Survey.

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moorings data used by Ohshima *et al.* (3) reveal repeated occurrences of supercooling in the Cape Darnley polynya, and by monitoring the interior of the ocean acoustically, they observe that frazil ice dominates ice production here. It was noted that strong wind events (gusts exceeding  $15 \text{ ms}^{-1}$ ) were critical in causing frazil formation and that it can occur to unexpected depths (80 m or more). These results echo previous findings from the Arctic (6) and elsewhere around Antarctica (7), but critically, they here relate to an area where the shelf waters connect strongly with the abyss, so the shallow processes can have a deep and pervasive impact.

This discovery has important implications. It had long been presumed that the sea ice production involved in AABW formation was predominantly a surface process and hence could be easily monitored by direct observation. The fact that a major process is occurring underwater means a key part of the system has been at least partially obscured from view. Active frazil formation at depth will also inhibit the formation of a “lid” of sea ice on the ocean surface; this will keep the ocean surface clearer for longer, enhancing the role of the polynya as an ice production “factory.”

A further aspect is that many ocean models do not deal comfortably with frazil ice. This represents an additional challenge for those seeking to use computer simulations to investigate dense water production. The climate and Earth System Models used to project the future of the planet already struggle to incorporate AABW realistically; this

new feature adds additional complexity to that challenge. This process could be important at coastal polynyas other than Cape Darnley, where strong winds can drive supercooling and frazil ice formation. Ohshima *et al.* (3) provide an initial assessment of this using their satellite data, but direct measurements will be needed to verify the level of importance at multiple other locations.

The implications of this finding transcend the physical/climate system. Shelf sea sediments are known to be important sources of nutrients such as iron; these are critical for fertilizing plankton blooms in the Southern Ocean, leading to the Antarctic shelves being biologically highly productive (8). Frazil ice that reaches close to the seabed may incorporate sediments and nutrients, which can then be raised in the water and released as the ice melts. Further, the frazil ice itself can induce strong algal blooms. Incorporating these processes into understanding of Southern Ocean biogeochemistry and carbon drawdown is an important next step.

Overall, these are unexpected and intriguing findings, which shed light on key processes in one of the most remote and inaccessible locations in the world, and yet one known to be globally important. It raises questions about the importance of these processes around other locations, and the level to which their inclusion in predictive models is required or currently possible. Significant fieldwork and research will be required to address these issues more widely around Antarctica.

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