The scientific response to Antarctic ice-shelf loss

Biological communities beneath Antarctic ice shelves remain a mystery, hampering assessment of ecosystem development after ice-shelf collapse. Here we highlight major gaps in understanding of the patterns and processes in these areas, and suggest effective ways to study the ecological impacts of ice-shelf loss under climate change.

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The calving of A-68, a 5,800-km², trillion-tonne iceberg in July 2017 from the Larsen C Ice Shelf was one of more than ten significant ice-shelf-loss events in the past few decades resulting from accelerated warming around the Antarctic Peninsula. Ice shelves are thick, floating platforms of ice ranging from <100 to>1,500 m in thickness, and are formed where glaciers or ice sheets flow on to the ocean. Observations over the past 60 years indicate that the many ice shelves around Antarctica are rapidly thinning, retreating and collapsing[1–4]. Rising atmospheric and oceanic temperatures, which cause shelf thinning and melt, act with wind forcing and upwelling to increase ice-shelf retreat and facilitate crevasse formation and propagation, ultimately leading to calving events. These processes can take years, but once thresholds are passed disintegration can occur within weeks[5]. Antarctic ice shelves are important because they create a buttressing effect, preventing more rapid discharge and melting of the grounded ice sheets and glaciers that would increase global sea levels[6].

Ice shelves fringe 75% of the Antarctic coastline and cover over 1.5 million km² of seafloor, or about 30% of Antarctica's continental shelf. This enormous sub-ice-shelf area has been largely inaccessible to the scientific community. The limitations inherent to sampling from small (and expensive) boreholes through hundreds of metres of ice mean that only a few studies have caught limited glimpses of life beneath ice shelves. These studies support an advective-food hypothesis of energy supply from ice-free areas to the benthic communities living under the shelves. Crustaceans, fish, microbial assemblages and benthic suspension-feeders have been found 12–450 km from open water[7–9]. Assemblages under the ice shelves generally resemble the communities found in the oligotrophic deep sea, which receive a sparse rain of food particles (Fig. 1). This similarity implies that food sources for biotas under the ice shelves must arrive from distances away from the shelf edges and be entrained in currents for delivery to sub-ice-shelf organisms. Fossil evidence reveals a sub-ice-shelf benthic gradient with distance from open waters in response to the intensity of food advection. Sessile suspension-feeders that need abundant particles falling through the water column were found close to the edge of the ice shelf (where marine inflow is high) and deposit-feeders and grazers that can feed on limited benthic food sources were found further away from the shelf edge (where food advection is lower)[10].

The sparsity of sub-ice-shelf studies from boreholes stands in contrast to the number of studies that have addressed physical and ecological questions about the aftermath of ice-shelf collapse. New areas of open water provide increased access, permitting studies with far greater spatial and temporal coverage.

Ice-shelf disintegration opens new habitats in the form of polynyas and sea-ice zones, which in general support rich and abundant life, and productive food webs[11] (Fig. 1). Ecosystem responses can be rapid, with high phytoplankton production and biomass in newly opened areas less than a year after collapse[12]. Ice-shelf collapse has a significant impact on the biological pump through changes in gas exchange, biogeochemical cycling and energy transfer, potentially leading to increased carbon sequestration in benthic sinks[13]. Such changes result in cascading effects on food-web dynamics and altered community composition[14].

At least five years elapsed after the Larsen A and Larsen B ice-shelf collapses before scientists were able to study the resultant ecosystem developments; studies indicated extensive changes in marine ecosystems within this short period. Different ecosystem components responded over different timescales, reflecting mobility and colonization potential. In general, the pelagic system seemed to respond rapidly to the ice-shelf collapse, whereas the benthos showed more gradual succession from an impoverished oligotrophic system to a more diverse shelf fauna[15,16]. Shifts in species distributions and altered phenologies may lead to trophic mismatches[17]. Ice-shelf retreat and the environmental changes that follow such an event are thus expected to weaken synchronization between food availability and food requirements across various temporal and spatial scales, affecting predator–prey relationships and ultimately ecosystem structure and function.

To fully comprehend the ecosystem shifts, more frequent rapid-response research efforts are required. Such prompt responses are now feasible (conditions permitting) — as demonstrated by the mobilization of researchers led by the British Antarctic Survey to the Larsen C area in January–February 2018, just five months after the A-68 calving event[18]. However, because of heavy sea ice the mission was redirected further north to the Prince Gustav Channel, which had been blocked by shelf ice until 1995. South Korean scientists funded by the Korean Polar Research Institute, in collaboration with investigators funded by the US National Science Foundation, attempted to reach the Larsen C region in April 2018, but were also thwarted by thick sea ice. The Alfred Wegener Institute and the international consortium of the Weddell Sea Expedition 2019 are heading there next austral summer.

Many cross-disciplinary questions covering a broad range of spatial and temporal scales remain to be answered. Science–policy discussions at the International Marine Ecosystem Assessment for the Southern Ocean (MEASO) Conference in Hobart, Tasmania, in April 2018 highlighted the need for investment in scientific infrastructure and research to collect long-term observations with enough statistical power to draw robust conclusions. Predictions of how the Southern Ocean and its ecosystems will respond to, and interact with, Antarctica's ice-shelf and ice-sheet dynamics (as well as how the changes will affect Earth's broader climate system) are needed. Future research programmes should work towards illuminating the

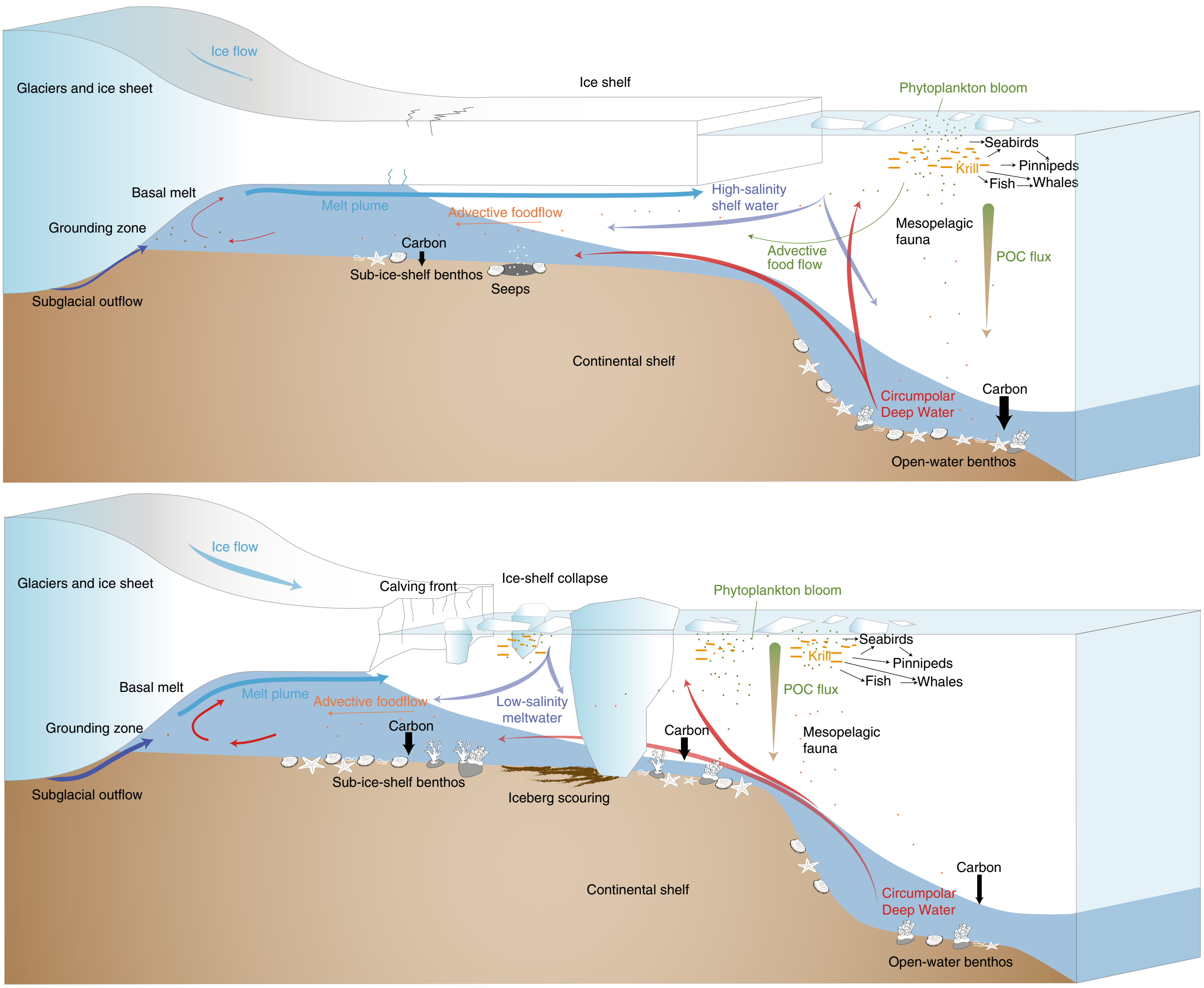

Fig. 1 | Ecosystem properties and processes shown with their responses to ice-shelf collapse. Top, Pre-collapse. Bottom, Post-collapse. Shifts in the spatial and temporal ranges of pelagic and benthic organisms, populations and communities post-collapse lead to changes in trophic dynamics and distribution ranges, altering ecosystem properties, processes and functions of sub-ice shelf areas. Thin black arrows between biota associated with krill indicate trophic interactions. The colour gradient of the particulate organic carbon (POC) flux indicates the change from fresh to more degraded/refractory material. Thicker arrows indicate higher fluxes. Figure adapted from ref. [5], AGU.

linkages between Antarctica's cryosphere and its ecosystems in a comprehensive, collaborative and interdisciplinary fashion, while acknowledging the importance of long-term studies and assessments in concert with research conducted on shorter timescales. Such programmes could also provide a scientific network that allows rapid, collaborative responses to abrupt events, including ice-shelf loss. The resulting studies should aim to document ecosystem responses at all levels of biological organization — from the genome to continental scales — and the mechanistic linkages among climate, cryosphere dynamics, biogeochemical processes, food web structure and population and community dynamics[19].

Advances in marine technology will be key to achieving these aims. Reaching and documenting pristine sub-ice-shelf ecosystems before dramatic change occurs will require an international scientific infrastructure collaboratively utilized to cover large spatial scales with high temporal resolution. Oceanic and through-the-ice moorings with equipment capable of shallow-to-deep sampling, weather- and climate-recording systems, and automated underwater vehicles are but a few of the technologies that are needed for a comprehensive understanding of ice-shelf collapse and ecosystem consequences. The Southern Ocean Observing System (SOOS), an international initiative that facilitates the collection and delivery of observations across different platforms, provides a framework for such international collaborations. For example, the SOOS-endorsed Network for the Collection of Knowledge on Melt of Antarctic Ice Shelves (NECKLACE) project aims to measure ice-shelf melt across the entire Antarctic through collaborative developed instruments, illustrating the potential role of SOOS in studying responses to ice-shelf collapse.

In recent years, and especially for the Larsen C collapse, scientists have been making increased efforts to share knowledge, identify important research priorities and knowledge gaps, and outline strategic plans to advance our understanding of the continent-wide implications of climatic warming. Building on long-established networks within organizations, including the Scientific Committee on Antarctic Research (SCAR) and its working groups, newer international efforts such as Integrating Climate and Ecosystem Dynamics (ICED) and MEASO could provide a platform to connect multidisciplinary researchers investigating ecosystem responses to ice-shelf collapse and disintegration. Antarctic and Southern Ocean science is inherently collaborative as a consequence of the logistical challenges of working there and the cooperative nature of the international Antarctic Treaty System (ATS), its various bodies and national Antarctic programmes. The Council of Managers of National Antarctic Programs also facilitates connections, as does SCAR, which provides independent advice to the ATS on science related to the conservation and management of Antarctica and the Southern Ocean, and the role of the Antarctic region in the Earth system.

Research on ice-shelf collapse and ecosystem responses can be used to inform Antarctic conservation and management policies through SCAR and the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), also embedded in the ATS. Science–policy interfacing is high on the agenda for the region, most recently illustrated by the aim of MEASO 2018 to spear-head a quantitative ecosystem assessment that enables managers to reach consensus in adapting their management strategies. The newly exposed marine area in the Larsen C region was the first to benefit from designation as a 'special area for scientific study in newly exposed marine areas following the collapse or retreat of ice shelves across the Antarctic Peninsula region' under CCAMLR's conservation measures, providing a time window for investigating ecosystem responses without confounding effects from fishing activities. International proposals are being developed to designate marine protected areas (MPAs) along the western Antarctic Peninsula, in the Weddell Sea and off East Antarctica; they will be discussed during the 37th CCAMLR meeting in Hobart in October 2018. The MPAs would be part of a system of protections that already includes the large sanctuary that shields roughly 1.6 million km^2 of the Southern Ocean adjacent to the Ross Ice Shelf since 2016 and the South Orkney Islands MPA (94,000 km^2) established in 2009. All of these protected areas provide important context for studies of the consequences of ice-shelf collapse.

To understand the complex responses of various ecosystems components, and to distinguish changes driven by ice-shelf disintegration from natural variability, the research community needs to increase its efforts to ascertain marine ecosystem conditions pre- and post-ice-shelf collapse. Accurate projections of future conditions around the Antarctic margin can only be achieved through internationally coordinated, multidisciplinary research that includes long-term measurements and the integrated analysis of physical, biological and biogeochemical processes. Such projections will be of great value to policymakers as rapid environmental change continues, both in Antarctica and around the globe. ❐

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