First synchronous retreat of ice shelves marks a new phase of polar deglaciation

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It is now 10 y since field observations and RADARSAT imagery witnessed the breakup of the Ward Hunt Ice Shelf on Ellesmere Island, Canada. This was the largest remaining ice shelf in the Arctic and one of the last fragments of the 8,900-km^2 Ellesmere Ice Shelf charted by the Aldrich 1875–1876 and Peary 1906 expeditions (1). Its breakup has been linked to the polar amplification of climate change being witnessed in the wider Arctic region (2), including the ongoing reduction in the extent and duration of sea ice (3). Similar ice shelf retreats have been reported from the Antarctic Peninsula region (4). The key question is the following: Have the polar ice shelves broken up before under natural conditions, or are these unique events triggered by anthropogenic climate forcing? In PNAS, Antoniades et al. (5) report a marine geological reconstruction of the Holocene history of the Ward Hunt Ice Shelf. They found that the northern coast of Ellesmere Island has been free of a bounding ice shelf through most of the past *ca.* 11,500 y (the Holocene epoch) and that ice shelves have only been present there between 4,000 and 1,400 calibrated radiocarbon years before present (cal. y B.P.) and from 800 cal. y B.P. until the recent break-up event. This has built on previous work on radiocarbon-dated ancient driftwood deposited along the northern coast of Ellesmere Island that could have arrived there either during periods of ice shelf absence or as a result of changes in the configuration of ocean currents and sea ice (6).

Ice shelves are floating bodies of ice. In the Arctic, the remaining ice shelves are typically formed from landfast ice that has become thickened by up to tens of meters by sea ice accretion onto the base and snowfall on the surface. In the Antarctic, they are more commonly floating parts of the continental ice sheet that extend beyond the grounding line into the ocean. These ice shelves are often hundreds of meters thick, with just over 10% being above the ocean surface. The largest are the Ross and Ronne–Filchner Ice Shelves, which are fed by major ice streams.

The study by Antoniades et al. (5) provides evidence that the Ward Hunt Ice Shelf has experienced a number of phases of presence and absence under natural conditions. The first development of the ice shelf occurred several thousand years after the onset of cooling atmospheric temperatures inferred from the nearby Agassiz and Renland ice cores (Fig. 1). Its subsequent breakup was linked to periods of minimum sea ice in the region, inferred from diatom sea ice proxies (IP_{25}, Fig. 1) and the removal of the protective sea ice buttress around the ice shelf. Breakup was also linked to minor warm events seen in the Agassiz and Renland ice cores; however, events of a similar magnitude recorded elsewhere in the Agassiz and Renland ice cores did not trigger an ice shelf response (Fig. 1). Although these links to mechanisms for ice shelf breakup remain qualitative, they are underpinned by recent observations.

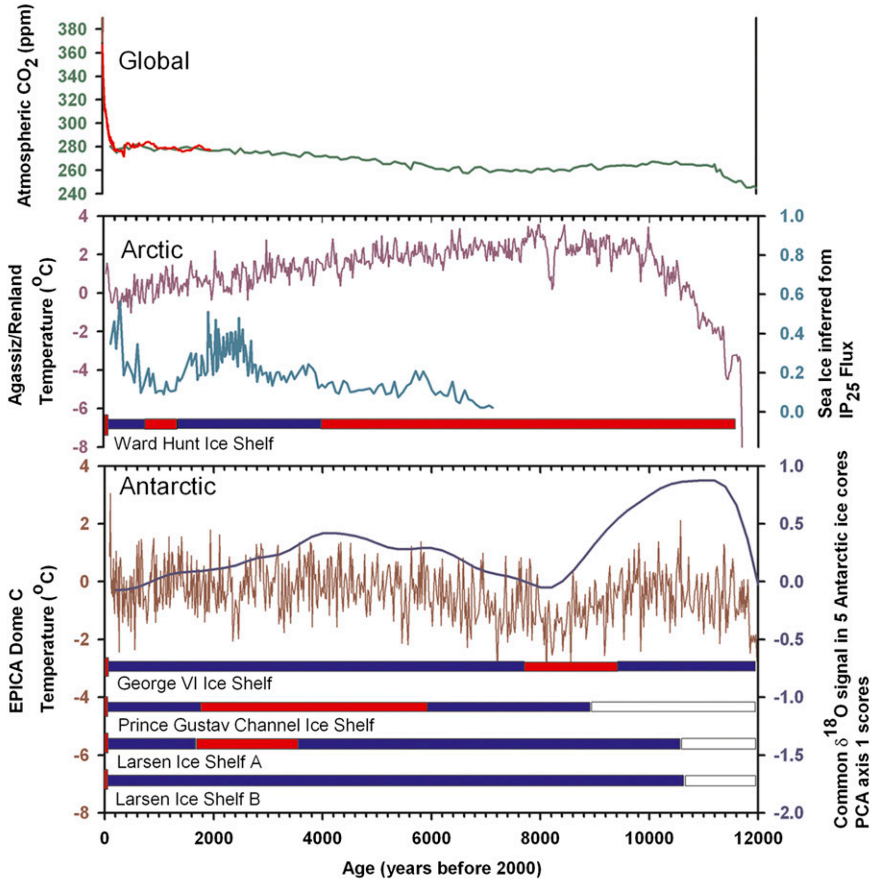

Fig. 1. Holocene reconstructions of the presence and absence of polar ice shelves that have broken up or retreated in the past few decades. Solid blue bars show periods when the ice shelves were present, red bars show periods of absence or retreat, and empty bars show where a grounded ice sheet was present. These are compared with potential forcing factors: a global CO_2 composite record from the European Project for Ice Coring in Antarctica (EPICA) Dome C ice core (22), the Law Dome ice core (23), and the Mauna Loa instrumental record (24); a composite coastal temperature record from the $\delta^{18}O$ data in the Ellesmere Island and Greenland coastal Agassiz and Renland ice cores (25); a proxy sea ice record derived from the sea ice diatom-derived biomarker IP_{25} in Victoria Strait in the Canadian Arctic Archipelago (26); the Antarctic EPICA Dome C deuterium-based temperature reconstruction (27); and a principal components analysis (showing axis 1) of the common and residual signals in five Antarctic $\delta^{18}O$ records (28).

Just as the Ward Hunt Ice Shelf has undergone previous natural periods of ice shelf loss that are at least equal in terms of ice mass loss to that experienced in the past few decades, studies in the Antarctic have shown that many of the ice shelves in the Antarctic Peninsula region, that are currently in retreat or have broken up completely, have also experienced natural

Author contributions: D.A.H. wrote the paper.

The author declares no conflict of interest.

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breakup events during the Holocene. These breakup events have been attributed to periods of atmospheric warming and changes in ocean currents. For example, marine geological evidence shows that the George VI Ice Shelf, west of the Antarctic Peninsula retreated between 9,600 and 7,730 cal. y B.P., immediately following a period of maximum Holocene temperatures inferred from ice cores (Fig. 1) and at the same time as warm circumpolar deep water penetrated onto the continental shelf (7) and open water conditions were detected in nearby fjords (8). On the northeast side of the Antarctic Peninsula, the Prince Gustav Channel Ice Shelf broke up between 6,000 and 1,900 cal. y B.P. (9) and the Larsen Ice Shelf A experienced periods of instability at 3,800, 2,100, and 1400 y B.P. (10) during a known period of Holocene warmth (11). In contrast, the Larsen Ice Shelf B has not broken up before in the Holocene (12).

When plotted together, what is clear is that although many of these polar ice shelves have retreated before in the past 12,000 y, none of the retreats so far identified have been synchronous (Fig.1) and no single forcing mechanism has been identified as providing a tipping point for ice shelf retreat. For example, on Holocene time scales, the relationship between ice core inferred temperature and ice shelf stability does not appear to have consistent thresholds or thermal limits for ice shelf stability. This irregular pattern of natural ice shelf retreat is in marked contrast to the past few decades, which have witnessed a synchronous (past *ca.* 50 y) retreat of ice shelves in both polar regions

Antoniades et al. report a marine geological reconstruction of the Holocene history of the Ward Hunt Ice Shelf.

(including those in Fig. 1). In some areas, marine geological evidence shows ice shelves have already retreated beyond previous Holocene minima (e.g., Larsen Ice Shelf B), whereas in most others, they are still within Holocene natural variability. This synchronous retreat has been accompanied by enhanced regional warming (in both the Arctic and the Antarctic Peninsula), which is expected to increase in the coming decades (13), as well as accelerated glacier discharge (14) and the retreat of sea ice (Arctic). Because these breakups are occurring in "real time," scientists have been able to identify the mechanisms of collapse, including surface (15) and subsurface melting (16).

This first synchronous retreat of ice shelves is significant, not because of ice shelf contributions to global sea level, which are relatively minor (e.g., 17), but because it is linked to wider changes in the cryosphere, the configuration of ocean currents, and both atmospheric and ocean temperatures. In the Arctic, the loss of the remaining ice shelves appears to be part of the long-term 12% per decade decline in sea ice extent, which is having wide regional impacts (18). The loss of unusual ice shelf microbial ecosystems has also been reported, including an extraordinary stratified microbial ecosystem in the Disraeli Fjord (19). In the Antarctic, the stakes are higher. There, the majority of the ice shelves buttress glaciers and ice streams that are vulnerable to accelerated discharge when they disappear, particularly where the sea bed deepens upstream of the grounding line (15). Current increases in discharge of these vulnerable areas of the Antarctic ice sheet were preceded by ice shelf collapse, and the same pattern of ice retreat in the past is supported by ice sheet models (20). Together with contributions from the Arctic, this mechanism is considered responsible for the majority of the postulated natural +6.6-m (21) rise in sea level experienced in the most recent interglacial period between 118 and 127,000 y ago.

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