Acceleration of Jakobshavn Isbræ triggered by warm subsurface ocean waters

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Observations over the past decades show a rapid acceleration of several outlet glaciers in Greenland and Antarctica[1]. One of the largest changes is a sudden switch of Jakobshavn Isbræ, a large outlet glacier feeding a deep-ocean fjord on Greenland's west coast, from slow thickening to rapid thinning[2] in 1997, associated with a doubling in glacier velocity[3]. Suggested explanations for the speed-up of Jakobshavn Isbræ include increased lubrication of the ice–bedrock interface as more meltwater has drained to the glacier bed during recent warmer summers[4] and weakening and break-up of the floating ice tongue that buttressed the glacier[5]. Here we present hydrographic data that show a sudden increase in subsurface ocean temperature in 1997 along the entire west coast of Greenland, suggesting that the changes in Jakobshavn Isbræ were instead triggered by the arrival of relatively warm water originating from the Irminger Sea near Iceland. We trace these oceanic changes back to changes in the atmospheric circulation in the North Atlantic region. We conclude that the prediction of future rapid dynamic responses of other outlet glaciers to climate change will require an improved understanding of the effect of changes in regional ocean and atmosphere circulation on the delivery of warm subsurface waters to the periphery of the ice sheets.

The Greenland ice sheet is drained by many outlet glaciers, with Jakobshavn Isbræ (Fig. 1) on the west coast being its most prolific exporter of ice into the ocean, draining 7% of the sheet by area[6]. Jakobshavn Isbræ currently transports about 50 $km^3\ yr^{-1}$ of ice to the head of the relatively long and narrow Jakobshavn ocean fjord. The mouth of this fjord lies on Disko Bay, of average depth 400 m, and with two deeper channels that connect the mouth to the outer continental shelf break. At the break, Disko Bay joins the much larger and deeper Baffin Bay, which has a core of warm Irminger water travelling northward at depth, at the break[7] (see Supplementary Information, Fig. S1). This warm, subsurface water can cross the break, and move into Disko Bay. Even though such subsurface waters are warm, they are also relatively saline, originating farther south in the North Atlantic. At cold temperatures, salinity has a controlling influence on density, and hence the nature of the water movement. (Further background information is available in Supplementary Information.)

Airborne laser-altimeter surveys along a 120 km profile in the Jakobshavn ice-drainage basin have been made almost every year since 1991 by the National Aeronautics and Space Administration's Airborne Topographic Mapper[8] (Fig. 2b). Whereas many other glaciers were thinning around Greenland, these surveys revealed that Jakobshavn Isbræ thickened substantially from 1991 to 1997 (ref. 2) at elevations less than 1,100 m. After 1997, Jakobshavn Isbræ began thinning rapidly with peak rates[5] of 15 $m\ yr^{-1}$. Also after 1997, there has been sustained thinning over progressively increasing distances inland from the grounding line[2]. Between 1997 and 2001, Airborne Topographic Mapper surveys showed an approximately 35 m reduction in surface elevations on the 15 km floating ice tongue, implying a thinning of about 320 m at an average rate[5] of 80 $m\ yr^{-1}$. This is far higher than thinning rates of grounded ice immediately upstream, and was probably caused by an increase in basal melting rates[2].

Comparison of Jakobshavn Isbræ velocities during 1992–2003 with earlier measurements showed a decrease from 6.7 $km\ yr^{-1}$ in 1985 to 5.7 $km\ yr^{-1}$ in 1992, and subsequent increases to 9.4 $km\ yr^{-1}$ by 2000 and 12.6 $km\ yr^{-1}$ by 2003 (ref. 3) (Fig. 2c). These changes were consistent with the observations of thickening in the early 1990s (ref. 9) and rapid thinning thereafter. Inland of 40 km from the grounding line, there was no appreciable velocity change over the period of observation, suggesting the change originated at the ice front adjacent to the ocean, and not inland.

In 1997, and earlier, Jakobshavn Isbræ flowed into a 15 km floating ice tongue with ocean waters circulating beneath. From theoretical and numerical results, it is known that an ice tongue has a nonlinear sensitivity to ocean warming[10,11]. A temperature jump in the waters at the base of the tongue would account for the rapid thinning inferred to be 80 $m\ yr^{-1}$ between 1997 and 2001. The subsequent acceleration of Jakobshavn Isbræ began after 1997, with glacier velocities roughly doubling by 2000 and remaining so since. The speed-up occurred after the thinning event, consistent with the ocean controlling the change in Jakobshavn Isbræ dynamics, with increased melting at the base of the tongue initiating a process resulting in glacier acceleration. The tongue itself finally disintegrated in the early 2000s, and the grounding line has continued to retreat (see Supplementary Information, Fig. S2).

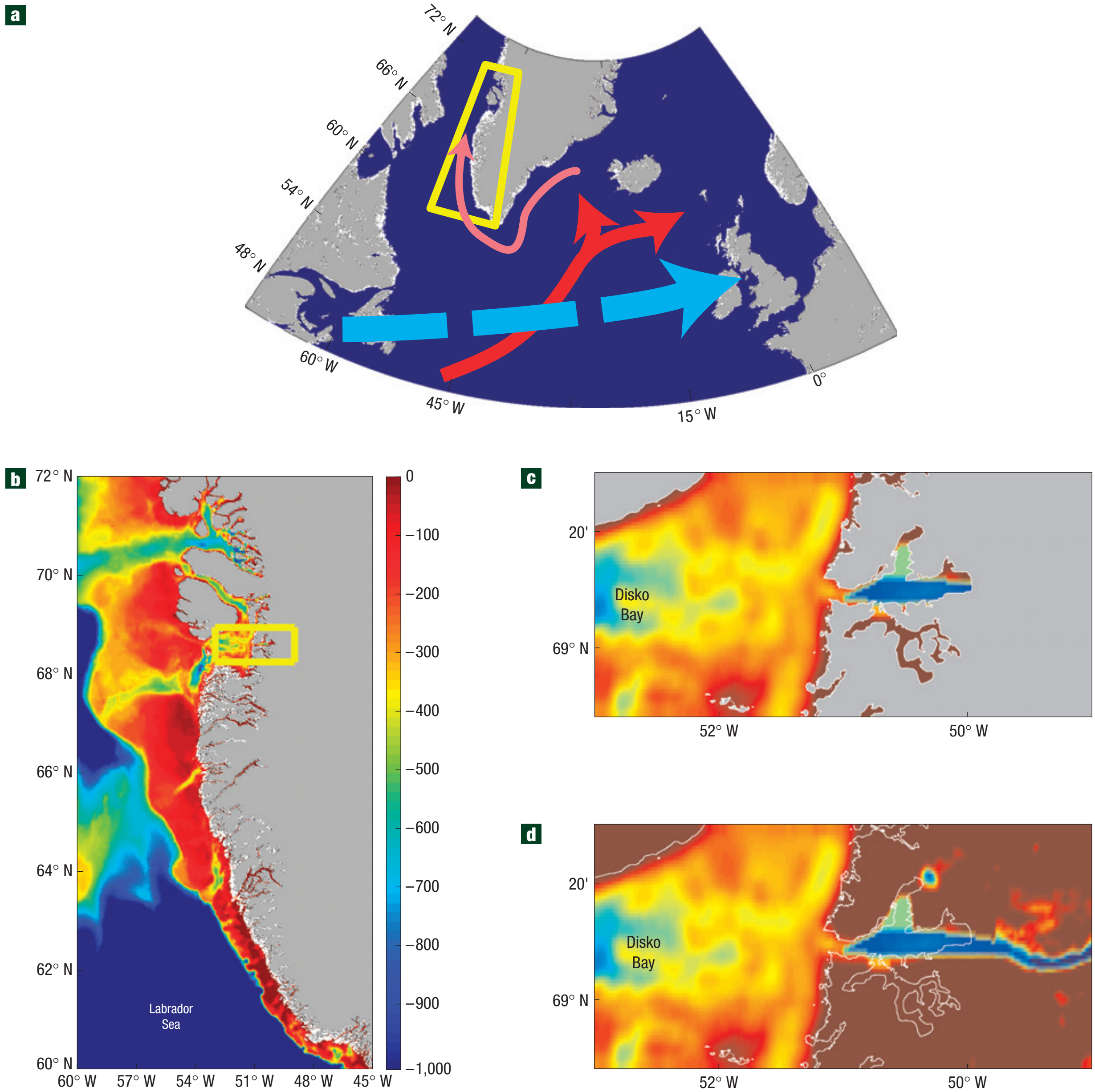

Figure 1 Larger-scale setting and regional-scale bathymetry. a, Schematic diagram of the North Atlantic subpolar gyre showing interactions of the atmosphere, ocean and Greenland ice sheet. The blue dashed line indicates the mean position of the storm track across the North Atlantic Ocean, the strength and position of which are characterized by the NAO. The solid red curve indicates the pathway of the North Atlantic Current, an extension of the Gulf Stream, and the southern boundary of the subpolar ocean gyre. The solid pink curve indicates the pathway of the Irminger Current, the northern boundary of the subpolar gyre. This current extends onto the continental shelf of the west coast of Greenland as a subsurface feature, and into the area marked by the yellow trapezoid, and is shown in greater detail in **b**. **b**, Seafloor elevations (in m) on the southwestern Greenland continental shelf (source National Geophysical Data Center). The yellow rectangle indicates the location of Disko Bay and Jakobshavn ocean-ice fjord, shown in detail in **c** and **d**. **c**, Disko Bay and Jakobshavn ocean fjord bathymetry showing a broad submarine trough (left centre of image) connecting to the mouth of the fjord. **d**, Same as **c**, except the land and ice-sheet mask (grey shading) have been removed, showing the inland ice-fjord bed elevations[28].

Repeat, standardized oceanographic observations are taken in Disko Bay on a nearly annual basis[12], with one such station near Ilulissat, just to the north of the mouth of the Jakobshavn fjord. That standard station, identified as SJA3 (see Fig. 2a for location), has been revisited each summer between 1980 and 2006, but with a gap from 1991 to 1996. We analysed temperature and salinity data from that station, and despite the gap could clearly identify a transition from a cold regime before 1990 to a warm regime since 1997 (Fig. 3a). The SJA3 data show that the timing of the transition in subsurface temperatures in Disko Bay, sometime between 1991 and 1997, precedes initiation of rapid thinning of the Jakobshavn Isbræ ice tongue.

Similar hydrographic time series taken south of Disko Bay, identified as SUK5 and HOL5 (see Supplementary Information, Fig. S3), reveal subsurface temperatures in the period 1996–2000 that are generally above the 1970–1995 values, and remained warm

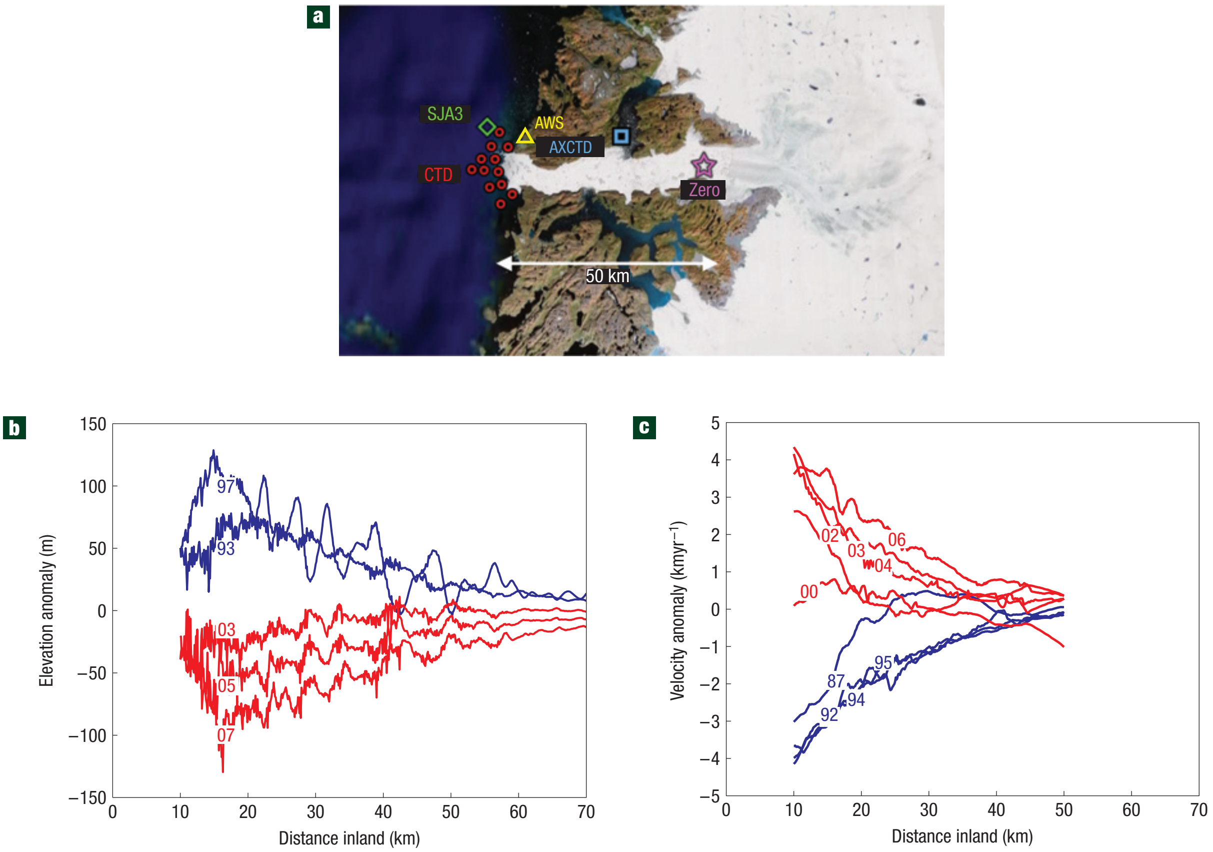

Figure 2 Elevation and velocity changes in Jakobshavn Isbræ. a, Satellite image of Jakobshavn ocean-ice fjord from the early 2000s (source Google Earth). Positions of various reference features are noted. Glacier elevation (**b**) and velocity (**c**) are presented as a function of distance inland from a reference position (marked by a star and labelled 'Zero'). **b**, Elevations of Jakobshavn Isbræ along a flight line starting from the 'Zero' reference position have been measured with airborne laser altimetry[8]. Data for the years 1993, 1997, 2003, 2005 and 2007 are presented in terms of anomalies of the mean. Blue curves show higher than average elevations during 1993 and 1997; red curves show lower than average during 2003, 2005 and 2007. Thinning rates from these curves imply that Jakobshavn Isbræ began to thin after 1997. **c**, Velocities of Jakobshavn Isbræ during nine specific years over the period 1987 to 2006 as a function of distance from the 'Zero' reference position[3]. Data are presented in terms of velocity anomalies of the mean. Blue curves show lower than average velocities for 1987, 1992, 1994 and 1995; red curves show higher than average for 2000, 2002, 2003, 2004 and 2006.

since without cold interruptions. These data are in agreement with findings[13] of changes in the oceanic heat and volume transport of Irminger water entering the southwest Greenland coast, post 1995. As for meteorological time series, air temperatures at the nearby Ilulissat meteorological station[14] show no abrupt transition in 1997, but rather a gradual change through the 1990s and up to the present (Fig. 3c). Although the oceanographic data from SJA3 are suggestive that a jump in subsurface temperatures is temporally correlated with the change in behaviour of Jakobshavn Isbræ, we cannot rule out the possibility of the ocean–air system surrounding Jakobshavn Isbræ exceeding a threshold temperature, explained by the more gradual increase as indicated from SUK5 and HOL5.

Although the data discussed above are intriguing, convincing evidence that subsurface ocean temperatures did experience a sudden jump that temporally coincided with the Jakobshavn Isbræ acceleration comes from yet another source. By serendipity, bottom temperatures at trawl sites were recorded during surveys for northern shrimp conducted by the Greenland Institute of Natural Resources from 1991 to 2006 over nearly the entire western Greenland continental shelf (Fig. 4). These data indicate a striking, substantial jump in bottom temperature in all parts in the survey area during the second half of the 1990s. There is some delay in the northernmost regions, consistent with a northward propagation of warming waters. The mean value for the entire survey area increased from 1.7 °C in 1995 to 3.3 °C by 1998 and remained around this level thereafter[15]. In comparison with the modest size of Jakobshavn ocean fjord itself, these bottom data show that the areal scale of the jump in subsurface temperatures was enormous, spanning the entire western continental shelf. The temporal aspect of the data shows that a warm water pulse arrived suddenly on the continental shelf on Disko Bay in 1997. The arrival coincided precisely with the rapid thinning and subsequent retreat of Jakobshavn Isbræ. The warm water mass remains there today (Fig. 4) and Jakobshavn Isbræ is still in a state of rapid retreat (see Supplementary Information, Fig. S2).

Using the subsurface ocean temperature data presented, we outline an ocean-driven acceleration mechanism consistent with the recent (1990–present) behaviour of Jakobshavn Isbræ. A warm water pulse travelled along the west Greenland coast during the 1990s as observed from demersal fisheries data, and brought an increase in subsurface water temperature over the continental shelf. That pulse arrived at depth in Disko Bay in 1997, as observed not only from the demersal fisheries data but also from a standard hydrographic station at Ilulissat. The bathymetry of the Jakobshavn

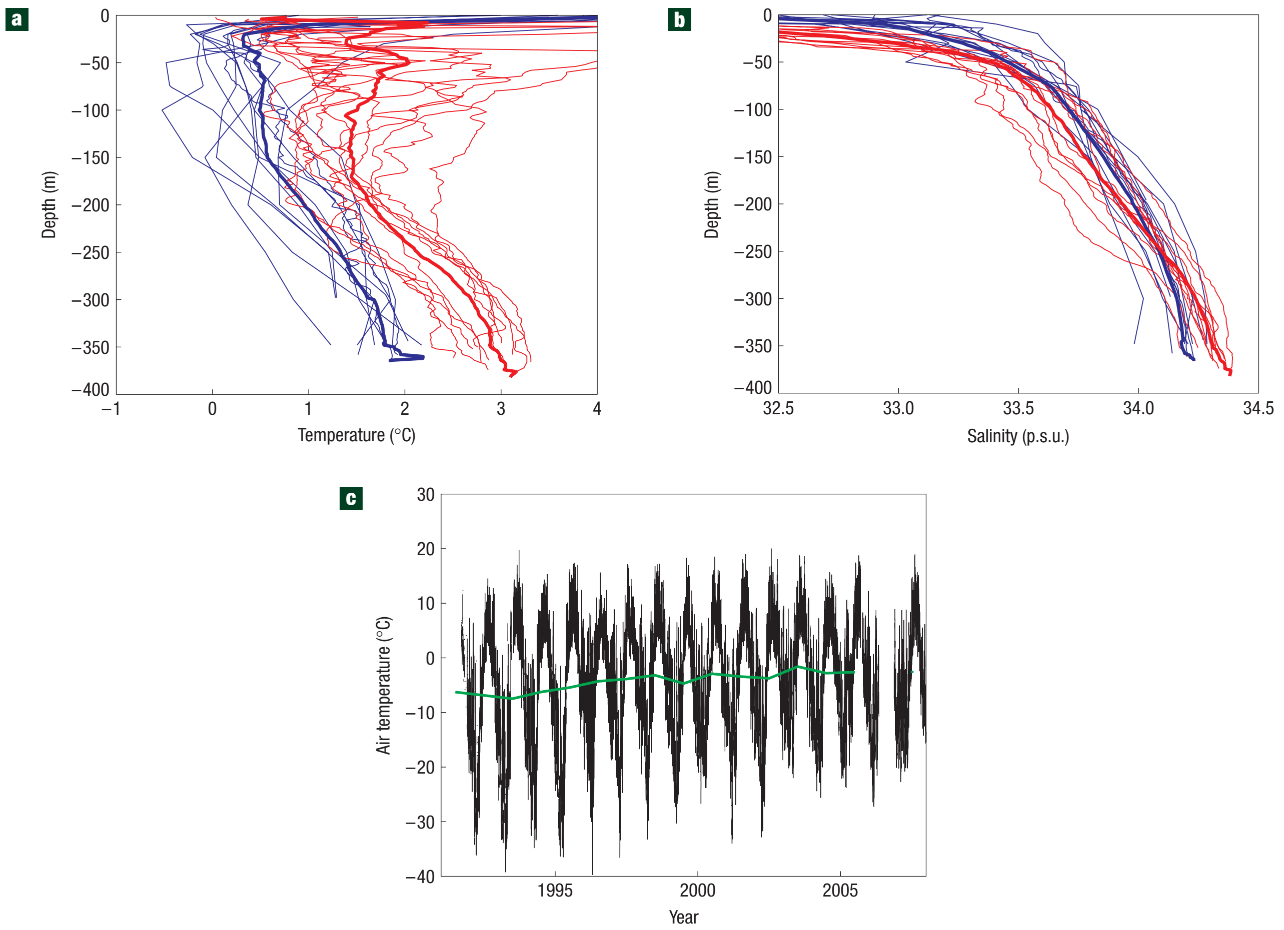

Figure 3 Oceanographic and meteorological observations near Jakobshavn. a, Depth profiles of ocean temperature (in °C) at station SJA3 (marked by the diamond in Fig. 2a) during June–August, 1954 to 2007. Thin blue profiles are taken during 1954 and 1980–1990 (thick blue profile is the average). Thin red profiles are from 1997–2007 (thick red profile is the average). **b**, Same as **a** but for salinity. **c**, Daily air temperatures[14] (in °C) taken at the Ilulissat airport (marked by the triangle in Fig. 2a) during 1991–2008, shown as the black curve. Data for 2006 are missing. The annual average temperatures, given by the green curve, show a gradual increase since the early 1990s.

ocean fjord is uniformly deep at 800 m (see Methods section), and the only obstruction to warm, subsurface waters getting into this fjord is the ∼350-m-depth sill at the mouth of the fjord. On the basis of observations we made during the summer of 2007, warm water is observed above sill depth and actually in the fjord itself (see Supplementary Information, Fig. S4). We argue that the 1997 warm, subsurface pulse in Disko Bay flooded the Jakobshavn ocean fjord, and that warm bottom waters have been there since.

A number of mechanisms have previously been proposed to explain this sudden acceleration of an already fast moving glacier. A time series of velocity measurements on nearby, slow-moving ice showed a strong correlation between velocity and periods of intense surface melting[4], suggesting enhanced lubrication of the ice–bedrock interface due to the rapid migration of surface meltwater to the base. There is, however, little evidence of the seasonal changes in Jakobshavn Isbræ velocities that would be expected if this process significantly affects rapidly moving ice, and a recent study[16] concluded that several fast-flowing outlet glaciers, including Jakobshavn Isbræ, are relatively insensitive to surface-meltwater-enhanced basal lubrication.

It has also been suggested[17] that changes in atmospheric temperature during the 1990s influenced the change in Jakobshavn Isbræ behaviour. Analysis of such air temperature data does show gradual changes in air temperature on decadal timescales, but no abrupt change that would explain the Jakobshavn Isbræ 1997 event. Our analysis of other atmospheric, sea-ice and surface ocean temperature records did not reveal any change particular to 1997. Moreover, a review of the measured elevation-change rates at many locations around the coast of Greenland[18] shows comparatively slow thinning on nearby glaciers with shallower beds than Jakobshavn Isbræ, despite experiencing similar warmer air temperatures and enhanced summer melting. In contrast, two other deep-bed glaciers—Helheim and Kangerdlugssuaq on the east coast—have also undergone massive recent thinning[18].

A more likely explanation is the effect of rapid basal melt-induced thinning, and the subsequent break-up of the floating ice tongue. Such thinning reduces buttressing effects that provide a back pressure on upstream parts of the glacier, reducing rates of longitudinal stretching. Break-up of the floating tongue would result in an immediate increase in longitudinal stretching, and therefore velocities[5]. In following this scenario, ocean conditions beneath the tongue hold the controlling influence over glacier behaviour.

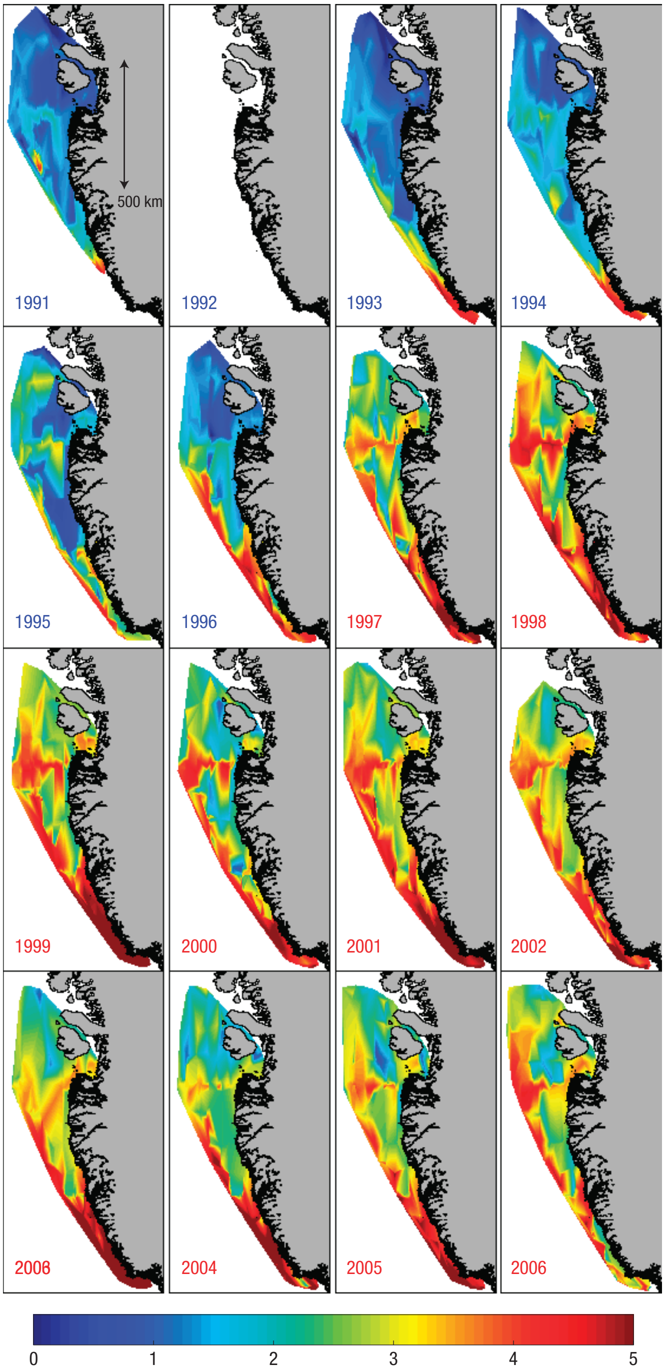

Figure 4 Subsurface ocean temperatures over the west Greenland continental shelf. Data were recorded by the trawl fisheries[15] (150–600 m depth-averaged) during the period 1991–2006. Wherever water depth is less than 150 m, the temperature (in °C) is interpolated from the nearest neighbour with water depth of 150 m, or deeper. Data for 1992 are missing. The survey region corresponds to the area outlined by the yellow trapezoid in Fig. 1a. Cold water years in Disko Bay are numbered in blue (1991–1996); warm water years in red (1997–2006). A jump in subsurface water temperature occurred in 1997, with warm waters flooding Disko Bay, and subsequently the Jakobshavn ocean fjord.

Given an ocean-forced mechanism for Jakobshavn Isbræ, the question remains: what drives the change in the subsurface ocean? The warm, subsurface waters off the west Greenland coast are fed from the east by the subpolar gyre of the North Atlantic, via the Irminger current[13]. Since the mid-1990s, observations show a warming of the subpolar gyre[19,20] and the northern Irminger Basin[21]. A key source of variability in the forcing of the subpolar gyre is the North Atlantic Oscillation (NAO) (see Supplementary Information, Fig. S5). A major change in the behaviour of the NAO was observed during the winter of 1995–1996, when it switched from a prolonged positive phase with strong westerly winds to a negative phase with weaker winds[22]. The net effect of the change was to weaken the subpolar gyre[23] (see Supplementary Information, Fig. S6) with the consequence of moving the subpolar frontal system (the boundary between cold polar waters and warm subpolar waters) from an easterly position to a more westerly one[22,24]. Such a large-scale change in the subpolar gyre allowed warm subpolar waters to spread westward, beneath colder surface polar waters, and consequently on and over the west Greenland continental shelf (Fig. 4).

Predicting the contributions of the large ice sheets, Greenland and Antarctica, to future sea level remains challenging[25,26] partly because the mechanisms for change in the ice sheets remain uncertain. Here, we have explained one mechanism operating in nature to demonstrate that a change in wind patterns over the subpolar gyre of the North Atlantic in 1995–1996 precipitated a chain of events that ultimately led to a flooding of the Jakobshavn ocean fjord with warm, subsurface water which then forced a rapid change of Jakobshavn Isbræ after 1997. The future behaviour of Jakobshavn Isbræ is not at present predictable. It is possible that the ocean may continue to force the retreat of Jakobshavn Isbræ well inland, melting away the inland ice fjord as the inland bedrock is more than 1,000 m below sea level for a considerable distance (Fig. 1d). We currently lack theoretical models to predict such behaviour and the most basic observations on which to base such models. Future global sea-level contributions from Jakobshavn Isbræ, and more importantly from western Antarctica, where the bulk of the ice sheet is grounded below sea level, will consequently remain unknown until these issues are addressed.

METHODS

BATHYMETRY

To enter the Jakobshavn ocean fjord, subsurface waters of Disko Bay, whether warm or cold, must pass over a submarine sill, at depths between 250 and 350 m. Once over the sill, such dense waters could in principle have an unobstructed pathway to the grounding line some 50 km inland, provided there were no further bathymetric obstructions along the floor. As the bathymetry of the ocean fjord was unknown, we measured it during the summer of 2007 and found it to be of an almost uniform depth of 800 m (Fig. 1c). From a helicopter, we lowered a depth sounder into leads at ten distributed locations in the ocean fjord with position taken by a global positioning system. The soundings are archived at the National Geophysical Data Center.

Because of the great depth of the ocean fjord, dense waters at the sill can indeed reach the grounding line, unobstructed. Close to the grounding line, the bed is about 800 m below sea level. Farther inland, previous seismic and radar measurements show the bed dipping below 1,000 m, remaining deep over a distance of more than 100 km from the present grounding line[27,28] (Fig. 1d). Thus, continuing inland from the present calving front, there exists a long narrow ice fjord. Warm, subsurface waters from the shelf break off Disko Bay hold the potential for controlling the melt rate of this ice fjord because a submarine pathway exists between the source region for the warm waters off the continental shelf all the way inland to the end of the ice fjord.

MODERN CONDUCTIVITY–TEMPERATURE–DEPTH HYDROGRAPHY

The first recorded oceanographic measurement[29] in the Jakobshavn ocean fjord, during the first international polar year 1881–1884, showed that relatively warm (> 1 °C) and saline (> 34) waters of the North Atlantic Ocean penetrated at depth, into the fjord. Lack of any hydrographic measurements in the fjord since that time motivated our efforts during the summer of 2007. Because the ocean fjord is covered by icebergs and brash sea ice, and not easily accessible by ship, we used airborne expendable conductivity–temperature–depth (AXCTD) probes launched from a helicopter to obtain a temperature and salinity profile in the fjord (see Supplementary Information, Fig. S4a, blue curve).

On impact with the ocean surface (or in a lead in an ice-covered ocean surface), the sensor head of an AXCTD probe descends through the water column, reaching a maximum depth of 1,000 m. A frequency-modulation radio transmitter remains at the surface and a frequency-modulation radio receiver in the helicopter records the transmitted data. Our profile extends to a depth of 500 m and reveals that below the fresh near-surface waters, there is a large volume of warm (∼1.8 °C) and saline water (>34), the immediate origin of which is the warm, subsurface waters of Disko Bay.

At the mouth of the ocean fjord, we also made a series of measurements, using a SeaBird-19 CTD lowered from a boat, which showed warm and saline water at the sea floor but also at depths shallower than 350 m (see Supplementary Information, Fig. S4a, red curves), clearly indicating that warm waters are currently in Disko Bay close to the sill depth of the Jakobshavn ocean fjord (250–350 m). It is evident that a layer of warm, subsurface water at the mouth of the fjord (see Supplementary Information, Fig S3c) is the source water for the subsurface water in the fjord. Such subsurface water exchange in fjords is commonly observed in nature.

INFERRED EARLIER HYDROGRAPHY

To assess whether the recent behaviour of Jakobshavn Isbræ deviates from longer-term behaviour, glacier surface elevations and terminus positions for Jakobshavn Isbræ were assessed by others[6] using data from historical records so as to reconstruct the history of changes over the past century. They identified three periods of rapid thinning: 1902–13, 1930–59 and the recent event of 1997. During the 1920s and 1930s, there was a marked warming of the northern North Atlantic Ocean that included an enhanced Atlantic inflow in northern regions[30]. Evidence of this previous warmer period is seen in the century-long temperature time series (see Supplementary Information, Fig. S7) constructed from data at station 'Fylla2', located south of Jakobshavn Isbræ, on the west Greenland coast.

Ecosystem changes associated with the warm period included a general northward movement of fish. Boreal species of fish such as cod, expanded farther north and colder-water species such as polar cod retreated northward. The maximum recorded movement involved cod, which spread approximately 1,200 km northward along west Greenland. We suggest that the warm water event of the 1920s and 1930s as inferred by the cod fisheries data[30] shows further evidence of the previous arrival of a warm water pulse on the west Greenland continental shelf, and in particular one that arrived in Disko Bay in about 1930 (see Supplementary Information, Fig. S8). This earlier pulse probably kick-started the rapid thinning event of Jakobshavn Isbræ that was reported[6] for the 1930–1959 time period.

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