LETTERS
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Rapid circulation of warm subtropical waters in a major glacial fjord in East Greenland

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The recent rapid increase in mass loss from the Greenland ice sheet[1 2] is primarily attributed to an acceleration of outlet glaciers[3–5]. One possible cause of this acceleration is increased melting at the ice–ocean interface[6 7] driven by the synchronous warming[8–10] of subtropical waters offshore of Greenland. However because of the lack of observations from Greenland's glacial fjords and our limited understanding of their dynamics this hypothesis is largely untested. Here we present oceanographic data collected in Sermilik Fjord East Greenland by ship in summer 2008 and from moorings. Our data reveal the presence of subtropical waters throughout the fjord. These waters are continuously replenished through a wind-driven exchange with the shelf where they are present all year. The temperature and renewal of these waters indicate that they currently cause enhanced submarine melting at the glacier terminus. Key controls on the melting rate are the volume and properties of the subtropical waters on the shelf and the patterns of along-shore winds suggesting that the glaciers' acceleration has been triggered by a combination of atmospheric and oceanic changes. Our measurements provide evidence for a rapid advective pathway for the transmission of oceanic variability to the ice-sheet margins.

The Greenland ice sheet's contribution to sea-level rise more than doubled in the past decade[1,2], predominantly owing to the acceleration of outlet glaciers flowing into deep fjords in western and southeastern Greenland[3–5]. The glacier speed-up occurred at approximately the same time as a warming trend began in the subpolar North Atlantic Ocean, adjacent to Greenland's southeastern and western sectors[8–10], giving rise to the hypothesis that glacier acceleration was triggered by ocean warming[11–13]. The proposed mechanism involves enhanced melting at the front of the glacier, driven by increased ocean heat transport, which leads to ice thinning, ungrounding of the terminus and ice-flow acceleration[6,7].

A lack of measurements from Greenland's glacial fjords, however, makes it difficult to test this hypothesis. First, the warming waters belong to the Irminger Current (IC), a topographically steered branch of the North Atlantic Current (NAC), which carries warm, subtropical water (STW) into the subpolar basin (Fig. 1a). This water is trapped offshore over the continental slope, whereas cold, fresh polar water (PW), transported by the East and West Greenland Currents (EGC and WGC; Fig. 1a) dominates the shelf adjacent to the fjords[14]. Evidence that STW reaches Greenland's fjords is limited to a few summer profiles from Jakobshavn[12] and Kangerdlugssuaq[15] Fjords, and there is no direct evidence that it comes into contact with glaciers. The lack of adequate fjord measurements from the period before the glaciers' acceleration, in particular, means that we need to rely on our understanding of the processes that control the properties and circulation within the fjords (and hence the heat transport to the glaciers' termini) to infer past conditions and assess the ocean's role in triggering the acceleration of Greenland's glaciers. At present, the mechanisms governing the circulation of STW on the shelf and inside Greenland's glacial fjords are unknown.

The 100-km-long Sermilik Fjord (66° N, 38° W) connects Helheim Glacier with the Irminger Sea (Fig. 1b). In 2003, Helheim Glacier retreated several kilometres and almost doubled its flow speed[3,4]. Warm STW has recently been observed outside the fjord on the shelf[16] but there are no records of ocean properties within the fjord itself. We collected 38 temperature and salinity profiles, together with bathymetric and current data, in and just offshore of Sermilik Fjord during two surveys in July and September, 2008 (Fig. 1b). Additional data were collected by several moored instruments (Fig. 1b; see Methods summary).

Sermilik is a U-shaped glacial trough, which is deeper (900 m at the mouth) than most of the adjacent shelf (300–400 m). No sill was found in our surveys. Instead, we identified a 700-m-deep channel extending from the mouth (Fig. 1b) towards a deep trough that stretches across the entire shelf (Fig. 1a). In September, this 20-km-wide channel was mostly filled with warm (4.2 °C) STW, which, assuming geostrophy and no flow at the bottom, was flowing towards the fjord. Slightly cooler STW (3.5–4 °C) was present in large volumes inside the fjord from a depth of 200–300 m to the bottom at all surveyed locations (Fig. 2a–c). A 10–20-m-thick layer of glacial meltwater (GM) and a 100–150-m-thick layer of PW were found above STW throughout the fjord (Fig. 2a–c). Property changes within the fjord were mostly in the along-fjord direction, with limited across-fjord variation (consistent with a narrow fjord not strongly influenced by rotation).

The same three water masses were present in the fjord during both surveys but with different characteristics in the upper 300–400 m (Fig. 2). In particular, the PW layer was noticeably thinner and warmer in September, which increased the mean temperature of the upper 400 m from 0.5 to 2 °C. This warming is too large to be driven by local heating (it requires a surface heat flux of $470\,\mathrm{W\,m^{-2}}$ for July and August, which is three times larger than that estimated for the same period from the National Center for Environmental Prediction Renalysis[17] for the region outside the fjord, shown in Fig. 3c), and also surface fluxes would not penetrate

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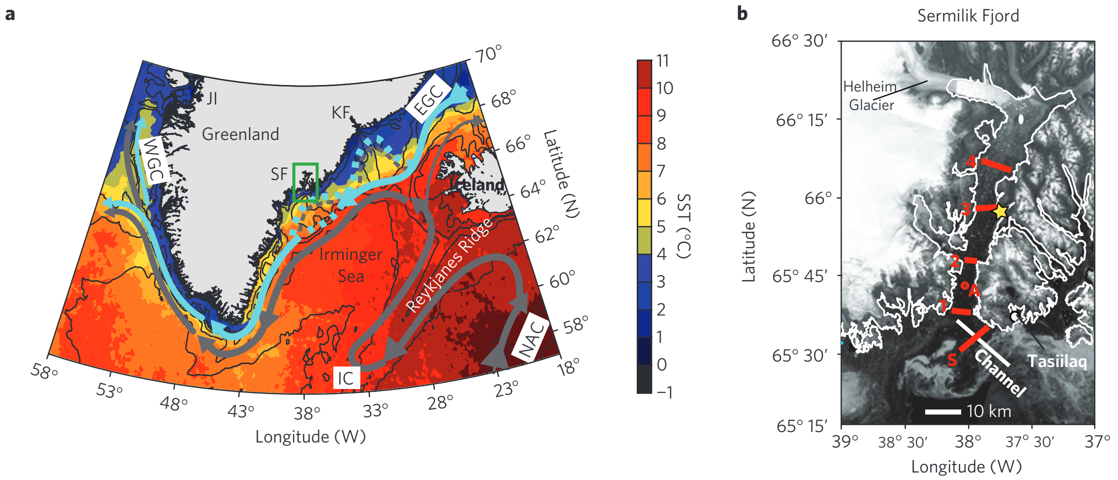

Figure 1 Circulation around southeast Greenland and Sermilik Fjord. a, Currents around Greenland overlaid on the 2003 mean sea-surface temperature from the Advanced Very High Resolution Radiometer (filled contours). Bathymetric contours (100, 500, 1,000, 2,000, 3,000 m) are overlaid in black. PW transported by the EGC and WGC is in blue (dashed paths indicate multiple branches) and STW transported by the NAC and IC in grey. Sermilik Fjord (SF, green box), Kangerdlugssuaq Fjord (KF) and Jakobshavn Isbrae (JI) are indicated. **b**, Landsat mosaic of Sermilik Fjord. Sections (1–4, S) plus station A occupied in the 2008 surveys are indicated in red, moorings' locations by the yellow star.

deep in this highly stratified environment. Thus, the change must result from the advection of warmer waters into the fjord, as confirmed by the presence of different water masses in the upper layers in July and in September (Fig. 2a–c). To investigate whether changes in the fjord are consistent with those occurring outside the fjord, we reconstructed the seasonal variation of temperature on the shelf using data collected by 19 hooded seals (*Cystophora cristata*) tagged with satellite-linked temperature–depth recorders[18] (5,269 dives from 2004 to 2008; ref. 19) (Fig. 3). These data reveal that STW (subsurface waters warmer than 3.5 °C) is present on the shelf year round and, also, that the shelf waters warm from July to December. Both the trend and the magnitude of the warming (the shelf's upper 400 m also warms, by ∼1.5 °C from July to September) support the conclusion that changes in the fjord are a result of advection from the shelf. (The shelf temperatures are warmer than those in the fjord because they represent a spatial average across the shelf, including regions close to undiluted STW on the slope.)

The rapid flushing of the upper waters of the fjord indicates a vigorous circulation. We investigate its nature by first considering an estuarine-type circulation, driven by a large melt-water input at the head, consisting of a fresh outflow at the surface balanced by a saltier, subsurface inflow (see Supplementary Fig. S1a). The magnitude of the estuarine circulation and the related flushing time are estimated from the observed vertical property distribution and by applying conservation of mass and salt. Assuming that the circulation is limited to the upper 300 m, the 'fastest' estimated flushing time is ∼2 yr (see Supplementary Methods), indicating that the observed summertime changes cannot be attributed to this type of circulation alone.

A second type of circulation common in narrow, deep fjords[20] is an 'intermediary circulation'[21] driven by pressure gradients that arise between the fjord and the coastal region. It is associated with strongly sheared flows and an exchange of properties that persists until the fjord (the smaller volume) has equilibrated to the coastal region. Several pieces of evidence indicate that such a circulation may dominate in Sermilik Fjord. First, we observed large, strongly sheared currents in the upper 100–200 m during both surveys (Fig. 2e,g). These currents are more vigorous than the expected 10–15 cm s^{-1} tidal currents, which would arise from a barotropic tide in an 800-m-deep channel and a tidal range of 1.5 m (the maximum range measured by a tide-gauge deployed in the fjord from July to September 2008). Second, the observed currents must, by continuity, have compensating outgoing currents at depth, otherwise they would raise sea-level in the fjord by several metres within one hour, which is inconsistent with the tide-gauge data.

Intermediary circulations can be driven by any forcing that results in fjord/shelf gradients[20], but our observations indicate along-shore winds as the dominant driver in Sermilik Fjord. Northeasterly wind events, for example, will initially 'pile up' water and depress the halocline at the mouth of the fjord, driving an inflow in the upper layer and an outflow at depth, which, in turn, raises sea-level and depresses the halocline in the fjord. Once the winds subside, and the shelf relaxes back to the pre-event state, the fjord responds with the reverse circulation pattern (see Supplementary Fig. S1).

Several along-shore wind events, which occurred during our surveys and mooring occupations, enable us to test the wind-driven intermediary-circulation hypothesis. Both surveys were conducted during or immediately after strong northeasterly (see Fig. 3c for direction) wind events (Fig. 4a) and the observed velocities and shear are consistent with the expected response. Clear evidence for depression of the halocline at the mouth of the fjord (Fig. 2d) was found in the first survey, which took place during a wind event. Assuming that the observed velocities were sustained, the upper 300 m of the fjord would be renewed within four days. Also, data collected by two summer moorings (see Fig. 1b for location, and Methods summary for a description) show qualitatively that northeasterly wind events are associated with a temporary downward displacement (by 50–100 m) of the isotherms (Fig. 4b) and a temporary freshening at 25 m and 180–200 m (Fig. 4c), consistent with the response described above. Although the summer-mooring records are too short to establish statistical significance, an eight month record of pressure, temperature and salinity from a third mooring reveals that anomalies in all three fields are significantly correlated with along-shore wind events, and of the sign expected for a wind-forced intermediary circulation (see Supplementary Fig. S2). We conclude that along-shore wind events, which are intense and frequent along Greenland's eastern coast[22], control the renewal rate of waters in Sermilik Fjord and cause the fjord to track subseasonal changes on the shelf.

The presence of large volumes of STW in Sermilik Fjord during the summer, their renewal rate and observations that these waters are found on the shelf year-round suggest that STWs are also present in the fjord year-round. Their temperature, circulation and

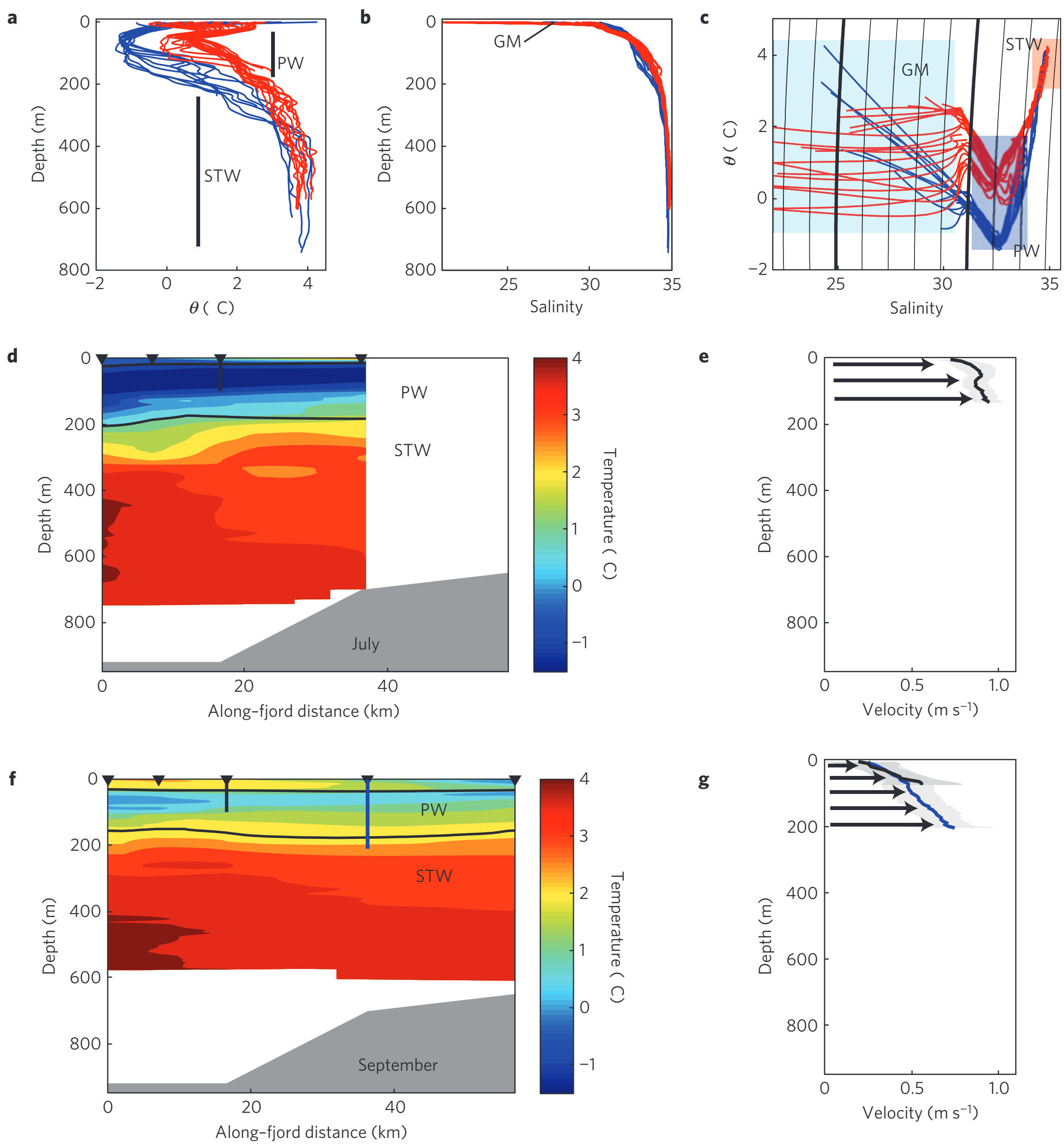

Figure 2 Measurements in Sermilik Fjord in summer 2008 and the three water masses GM PW and STW. a, Potential temperature in July (blue) and September (red). **b**, Salinity (colours as **a**). **c**, Potential temperature versus salinity (colours as **a**). Potential-density contours are overlaid in black (thick lines are σ = 20 and 25 kg m 3). **d**,**f**, Potential-temperature distribution in the along-fjord direction (= 0 is the mouth) from across-section averages, in July and September, respectively. The 31.5 and 34 isohalines are overlaid to separate the three layers. Top triangles indicate section location and vertical bars the velocity sections. Bathymetry is shaded in grey. **e**,**g**, Along-fjord velocity averaged across fjord at the sections indicated in **d** and **f**, respectively; positive is towards the head of the fjord. Shading indicates the standard deviation across the section; arrows indicate the direction of flow.

along-fjord retention of heat indicate that significant submarine melting is occurring at Helheim Glacier, which has an estimated terminus depth of 700 m (ref. 23). Key controls to the rate of melting are the volume and properties of STW on the shelf as well as the along-shore winds. As the characteristics of Sermilik Fjord and of the nearby shelf/slope region, including the along-shore winds[22] and deep channels[24] stretching across the shelf, are common to glacial fjords in southeastern and western Greenland, it is likely that these results can be generalized to other glacial fjords in this region—which contains the majority of the accelerating glaciers[1].

The data presented here are limited to the period that followed Greenland's glacier accelerations and, thus, cannot provide direct evidence on the ocean's role in triggering the acceleration. Nonetheless, our results offer several new insights to this issue. First, the presence and renewal of STW in Sermilik Fjord provides evidence of a fast and direct pathway connecting the subpolar North Atlantic Ocean to glacial fjords along Greenland's southeast and west coasts. This supports the proposed hypothesis that changes in the North Atlantic might have impacted Greenland's glaciers within one year[12]. Second, our findings indicate that either changes in the volume and properties of STW on the shelf and/or changes in the intensity and number of transiting storms[25] would affect melting at the tidewater margins of outlet glaciers. Both mechanisms are plausible (and probably connected), given the pronounced changes in the North Atlantic's ocean and atmosphere that began in the mid-1990s (refs 26, 27). Thus, our findings support increased submarine melting as a trigger for the glacier acceleration, but indicate a combination of atmospheric and oceanic changes as the likely driver.

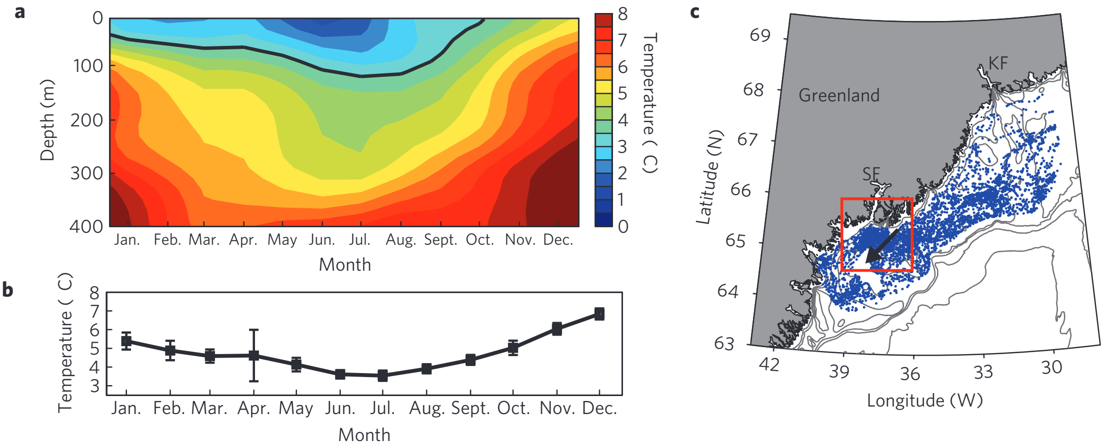

Figure 3 Seasonal temperature variation on the East Greenland Shelf from tagged hooded seals. a, Monthly and spatially averaged temperature profiles versus depth (the solid line is 3.5 °C and approximately separates the PW from the STW). **b**, Mean monthly temperature averaged over the upper 400 m (vertical bars indicate standard error). **c**, Locations of the 5,269 seal dives. Both the winds and the heat fluxes referred to in the text were averaged over the red box shown. The direction of the northeasterly winds (oriented at 54°) is shown by the black arrow.

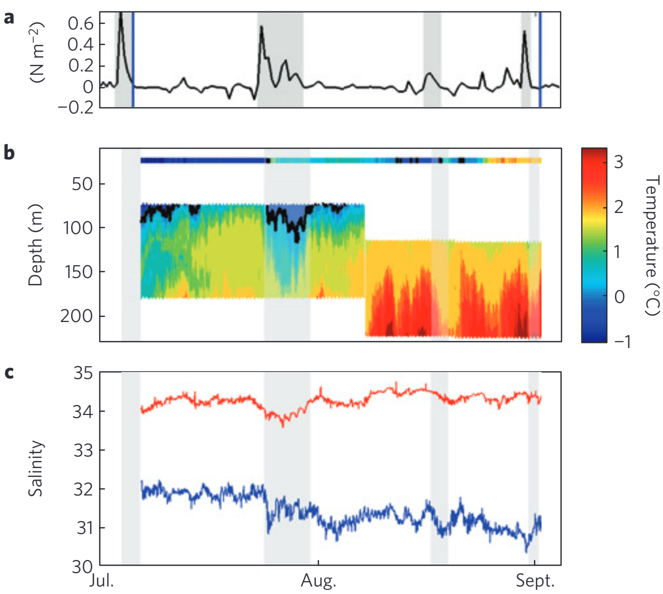

Figure 4 Along-shore winds in Sermilik Fjord. a, Northeasterly wind stress outside Sermilik Fjord from Quikscat. Wind events are shaded (see Supplementary Methods). Blue lines show when the velocity data were collected. **b**, Potential temperature from the two summer moorings. Data from the 11 temperature recorders were vertically interpolated. The deep mooring was hit by ice and relocated 40 m deeper in early August. Wind events are as in **a** but lagged by one day (see Supplementary Methods). **c**, Salinity from the two moorings at 25 m (blue) and at 180–200 m (red). Shaded regions are as in **b**.

Methods summary

Measurements in Sermilik Fjord were conducted from a locally chartered 24-foot vessel. Conductivity, temperature and depth profiles were collected using a 6 Hz XR-620 RBR sensor to 800 m in July and to 600 m in September. Four to six conductivity, temperature and depth profiles were collected across sections 1, 2 and 3 and one at station A between 4 and 6 July and again between 31 August and 3 September, when sections S and 4 (Fig. 1b) were added. Cross-instrument and pre- and postdeployment calibrations were carried out. Underway velocity data were collected using a vessel-mounted 300 kHz RDI Acoustic Doppler Current Profiler, combined with continuous vessel tracking by Global Positioning System, across section 2 in July and across sections 2 and 3 in September. Bathymetric data were obtained using a 320 Knudsen 12 kHz Echosounder.

Two moorings were deployed at depths of 25 and 180 m from July to September and a third mooring was deployed at 35 m from September 2008 to August 2009 (Fig. 1b). All three moorings carried a Seabird SBE 37-SM conductivity, temperature and depth recorder approximately 1 m above the bottom. In addition, the deeper mooring carried a thermistor string consisting of 10 Starmon Mini temperature recorders, spaced 10 m apart from the bottom to 100 m off the bottom. An RBR DR1050 depth recorder located above the uppermost recorder provided a measure of mooring tilt. The deep mooring was hit by ice three times and eventually displaced to a depth of 220 m. The 35 m mooring was also hit by ice and displaced several times until it settled at 65 m at the end of December (where it stayed until it was recovered). All three moorings were located within 300 m of one another and displacements were less than 100 m.

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Author contributions

F.S. and G.S.H. conceived the study, F.S., D.A.S., L.A.S. and G.S.H. participated in the collection of oceanographic data in Sermilik Fjord, and F.S. and D.A.S. were responsible for the analysis. M.O.H., G.B.S. and A.R.-A. were responsible for the capture of the seals and deployment of the transmitter and F.D. for processing the data from the seals.

Additional information

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