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PUBLISHED ONLINE: 20 MARCH 2011 | DOI: 10.1038/NGEO1109

nature geoscience

# Impact of fjord dynamics and glacial runoff on the circulation near Helheim Glacier

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**Submarine melting is an important contributor to the mass balance of tidewater glaciers in Greenland, and has been suggested as a trigger for their widespread acceleration. Our understanding of this process is limited, however. It generally relies on the simplified model of subglacial discharge in a homogeneous ocean, where the melting circulation consists of an entraining, buoyant plume at the ice edge, inflow of ocean water at depth, and outflow of a mixture of glacial meltwater and ocean water at the surface. Here, we use oceanographic data collected in August 2009 and March 2010 at the margins of Helheim Glacier, Greenland to show that the melting circulation is affected by seasonal runoff from the glacier and by the fjord's externally forced currents and stratification. The presence of light Arctic and dense Atlantic waters in the fjord, in particular, causes meltwater to be exported at depth, and influences the vertical distribution of heat along the ice margin. Our results indicate that the melting circulation is more complex than hypothesized and influenced by multiple external parameters. We conclude that the shape and stability of Greenland's glaciers may be strongly influenced by the layering of the Arctic and Atlantic waters in the fjord, as well as their variability.**

The recent retreat and acceleration of outlet glaciers[1] accounts for 50% of Greenland's net mass loss since 2000 (ref. 2). These dynamic changes were initiated at the frontal margins of glaciers grounded hundreds of metres below sea level in deep, narrow fjords[3], and coincided with a warming of waters around Greenland[4–6], leading to speculation that an increase in submarine melting was the trigger[7,8]. Furthermore, submarine melting of Greenland's glaciers is recognized as an important term in their mass balance[9,10]. Thus, quantifying ocean-driven melting and identifying its controls on outlet glacier dynamics is critical to improving predictions of ice sheet variability and sea level rise.

Submarine melt rates for several Greenland glaciers have been estimated as a residual from mass balance calculations using ice flow and ice thickness data[8,9]. This indirect approach, however, does not provide information on the circulation responsible for the melting, making it difficult to establish how it might vary in response to ocean changes. From ocean data, the submarine melt rate can, in principle, be estimated from the net oceanic heat transport to the glacier. Yet, obtaining appropriate temperature and velocity measurements to infer the heat transport to the margins of Greenland's glaciers is logistically challenging. An alternative is to assume that the heat-transporting circulation is driven by the discharge of meltwater and runoff from the glacier itself, and consists of a rising plume of meltwater, runoff and entrained ambient waters at the ice edge, that draws ambient water towards the glacier at depth and results in the outflow of an ambient/glacier mixture at the surface (the 'estuarine circulation'). This widespread paradigm[8,10,11] is based on observations from one tidewater glacier in Alaska and theories developed for glaciers terminating in an unstratified fjord[12], as is the case for fjords with shallow sills that allow the entry of a single ambient water mass. In Greenland, it has been used to estimate submarine melt rates[10] and to conclude that variations in the melt rate are mainly controlled by the temperature of the deep waters[7,8].

An increasing number of surveys of Greenland's fjords have revealed, however, that they are filled with cold, fresh Arctic waters (polar waters, PW) overlying warm, salty subtropical waters (STW) from the North Atlantic[7,13,14]. This raises the possibility that melting is driven by more than one water type and that the circulation at the ice margin is influenced by their density contrast, as predicted by laboratory and theoretical studies of ice melting in stratified waters[15,16]. Furthermore, the vigorous and variable circulation observed recently in several glacial fjords[14,17] indicates that externally forced circulations may also contribute in transporting heat to the glacier.

## Atlantic and Arctic waters near Helheim Glacier

Helheim Glacier is a major outlet of the ice sheet in southeast Greenland. Between 2001 and 2005, its terminus retreated ~8 km and its flow speed almost doubled[18,19]. The glacier terminates in Sermilik Fjord, which is approximately 100 km long, 8 km wide and 600–900 m deep[14] (Fig. 1). Surveys conducted in July and September 2008 found that the waters in the fjord were characterized by a 150 m thick layer of PW overlaying a 500 m thick layer of STW. Ice conditions prevented the 2008 surveys from reaching within 50 km of the glacier terminus, however, limiting direct information on the melting circulation. In August 2009, an icebreaker and a helicopter were used to conduct a more comprehensive survey of Sermilik Fjord and enabled measurements to be made within 10 km of the glacier terminus (see Methods section). A second survey using a small boat and a helicopter (see the Methods section) was conducted in March 2010, when ice cover in the fjord was incomplete, and reached within 6 km of the terminus (Fig. 1). These data are collectively used here to provide evidence

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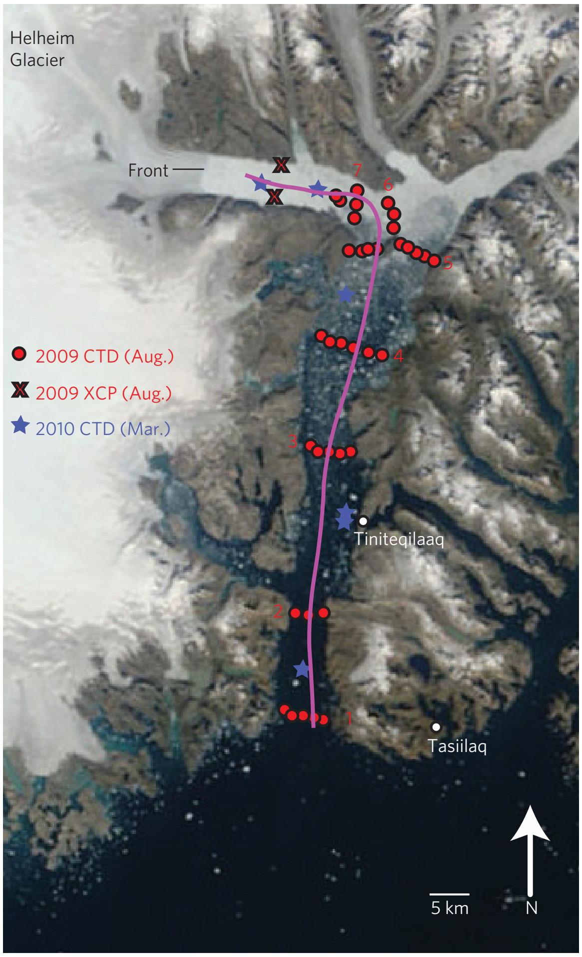


**Figure 1 | Summer 2009 and winter 2010 surveys of Sermilik Fjord.** MODIS image of Sermilik Fjord showing the 2009 and 2010 station position, including the position of Helheim's front. The magenta line indicates the along-fjord axis used in Fig. 3.

that the circulation at the ice edge is strongly influenced by the density contrast between PW and STW, the seasonal runoff from the glacier and the vigorous circulation of the fjord.

In summer (winter), the STW in Sermilik Fjord were 0.7 (1) kg m$^{-3}$ denser than the PW, resulting in a strongly stratified interface, between the depths of 150 and 250 m (Fig. 2). This interface is a stratification maximum in winter, when the PW are mostly unstratified, and is the base of an increasingly stratified layer in summer, when the surface layer is a mixture of PW and fresher waters (Fig. 2c). The temperatures of the waters differed in summer and winter, suggesting that melting is driven by both water masses in summer but only by STW in winter, when PW are at freezing temperatures (Fig. 2a). Our surveys, furthermore, revealed that STW were almost 1 °C warmer in winter (Fig. 2a, consistent with the seasonal cycle on the shelf[14]), raising the possibility that winter melt rates might be larger than those in summer.

## Complex circulation near the ice edge

Submarine melting results from a transport of heat to the ice edge associated with an inflow of 'warm', ambient water and an outflow of a 'cold' mixture of ambient water, meltwater and runoff (glacially modified water, GMW). In the idealized estuarine tidewater glacier system, this transport is driven by entrainment in the subglacial discharge plume—that is by the glacier itself. In Sermilik Fjord, however, the net heat transport is probably due to a more complex circulation driven by external forcing (such as wind, tides and exchanges with the shelf) as well as by the glacier. Evidence of such a circulation was found in 2008 (ref. 14), in the lower half of the fjord, and in 2009, when we measured velocities within 20 km of Helheim Glacier. These data show that the instantaneous circulation is dominated by fast currents which reverse with depth and in time, probably wind-driven transients[14] and internal seiches[20] (see Supplementary Information). These externally forced flows probably contribute to the heat transport but, also, cause it to vary greatly over hours and days—suggesting that instantaneous velocity measurements cannot be used to infer the mean heat transport (see Supplementary Information). The alternative approach used here is to qualitatively reconstruct the mean, heat-transporting circulation by identifying the pathways of GMW outflow and ambient water inflow. To do this, we make several assumptions. First, we assume that the distribution of properties reflects the weekly to monthly averaged circulation—as opposed to the high frequency flows observed. This is legitimate for the observed flow speeds and periods shorter than a day (which includes tides, barotropic and internal seiches) as they will mostly transport properties back and forth over tens of kilometres or less. Second, we assume that the circulation is mostly two-dimensional in the along-fjord direction. This assumption is supported by the limited across-fjord variability observed both in 2008 and 2009 and is consistent with the fact that Sermilik is a narrow fjord, not strongly influenced by rotation. Third, we assume that the properties within the fjord are primarily controlled by the exchange with the shelf, at the mouth, and the interaction with Helheim Glacier at the head, whereas surface fluxes have limited impact. This is justified both in summer, when the surface fluxes are small and confined to a thin surface layer, and in winter, when the fjord is mostly insulated by sea ice. At the mouth, rapid fjord/shelf exchange[14] will tend to restore the fjord's properties to those of the ambient waters on the shelf, which, because of their large volume, are unaffected by the glacier. At the ice/ocean boundary, freshening and cooling of the fjord's waters will result from melting of ice and from glacial runoff[21,22]. Finally, except for a narrow boundary layer at the ice edge, where vertical motions are expected to dominate, we assume the circulation in the fjord to be horizontal, consistent with mostly flat isopycnals (except near the glacier) and the large stratification we observe.

As vertical gradients dominate the along-fjord sections of temperature and salinity (Fig. 3a–d) we use along-fjord anomalies—defined as the change at a constant depth (or, for much of the fjord, along an isopycnal) from conditions 37 km into the fjord (~ section 3, characteristic of the 'mouth' without the mouth's large temporal variability)—to infer the circulation at the ice edge (Fig. 3e–h). In these maps GMW are identified as anomalies that decay away from the ice, whereas ambient waters are associated with zero anomalies. (The tidewater estuarine circulation[10,12] would be associated with zero anomalies everywhere, except in a surface layer possessing negative temperature and salinity anomalies. If one also included vertical mixing throughout the fjord, then one would expect progressive warming of the surface outflowing layer and cooling beneath it.) We start with winter when glacial runoff is limited and melting is driven by STW only. Two distinct GMW layers are visible: (1) at the surface (sGMW), characterized by weak cold, fresh anomalies and (2) at 200 m at the PW/STW interface (iGMW), characterized by waters which are colder and fresher than STW but warmer and saltier than PW (Fig. 3f and h). The same two GMW layers are observed in summer, although the sGMW layer is considerably thicker and fresher and the iGMW is fresher than PW (Fig. 3e and g). Because of entrainment these outflowing GMW layers must be compensated by inflow of ambient waters towards the glacier. Several zero anomaly layers in the anomaly maps suggest that this inflow occurs both within the PW and the STW layers (Fig. 3e–h). Finally, a weaker cooling and freshening of the entire

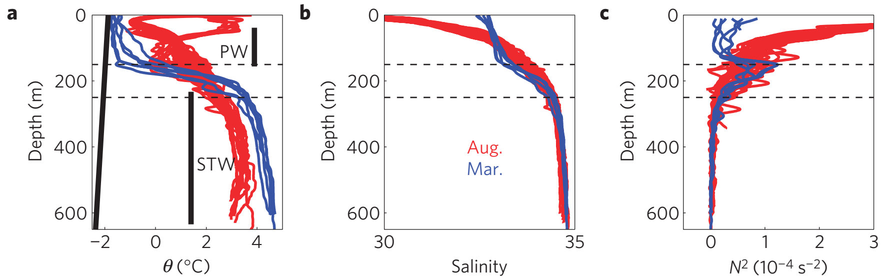


**Figure 2 | Atlantic and Arctic waters in Sermilik Fjord. a**, Potential temperature profiles from August 2009 (red) and winter 2010 (blue) from all the collected profiles. Overlaid in black is the freezing temperature profile with depth for a salinity of 34, representative of the fjord. The thickness and vertical position of the STW and PW are also shown. Note that the warm anomaly at the surface in summer was observed near the mouth only. **b**, same as **a** for salinity **c**, same as **a** for stratification (square of the Brunt–Väisälä frequency). The interface between the PW and STW is shown as dashed lines.

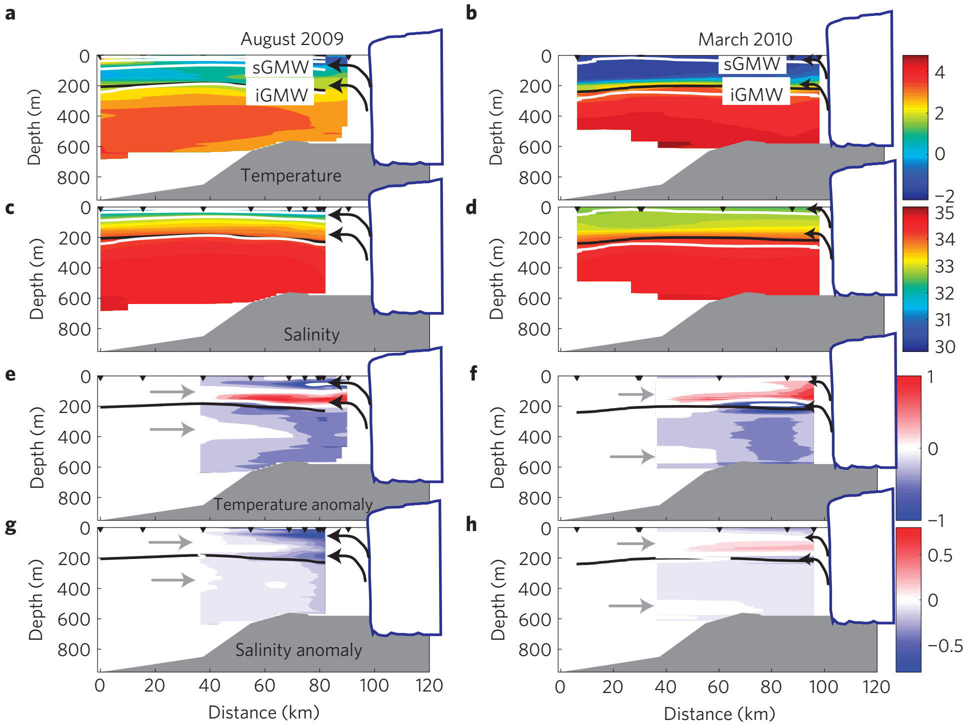


**Figure 3 | Layered circulation at the edge of Helheim Glacier. a**, **b**, Along-fjord potential temperature (°C) section for August 2009 and March 2010, respectively. See Fig. 1 for along-fjord axis location; **c** and **d**, same as **a** and **b** for salinity. **e** and **f**, same as **a** and **b** for the potential temperature anomaly (°C), with respect to section 3, distance = 37 km, see text. **g**, **h**, same as **c** and **d** but for the salinity anomaly. For 2009, the along-fjord profiles are obtained by averaging profiles across each section. Black arrows indicate export pathways for the glacially modified waters (sGMW, iGMW, labelled in **a** and **b** only), grey arrows are for the ambient water inflow pathways. Overlaid are the 34.2 salinity contour (black), separating STW and PW, and the 24.6, 25.6 and 27.6 $\sigma_\theta$ isopycnals (white) in **a** to **d**. Bathymetry shown uses the maximum depth observed for each section. An idealized Helheim Glacier is shown on all plots. Triangles at the top indicate section (summer) or station (winter) location.

STW layer near the glacier suggests that some meltwater is also exported at depth, both in summer and winter.

## Outflow of meltwater and runoff at depth

Next we use the potential temperature/salinity ($\theta$/S) characteristics of the fjord's waters and their particulate content to support the circulation scheme inferred from the anomalies shown in Fig. 3 and, also, to show that the GMW layers identified above contain meltwater and runoff. To do this, we rely on the fact that interaction with the glacier changes the $\theta$/S properties of the ambient waters in characteristic ways. First, melting of ice in seawater causes cooling and freshening of the ambient waters along a characteristic meltwater line[21,22] in $\theta$/S space. In Sermilik Fjord, the predicted slope of this line, 2.8 °C psu$^{-1}$, is close to that of the ambient waters (3 °C psu$^{-1}$ in summer, and 3.3 °C psu$^{-1}$ in winter, see Supplementary Information) meaning that the two lines practically overlap. Second, addition of glacial runoff modifies the $\theta$/S properties along a mixing line which joins the ambient properties with those of waters with zero salinity and temperature (see Supplementary Information). Finally, we expect meltwater and runoff discharged at depth, and especially at the base of the glacier, to be characterized by a large particulate content which can be traced as a turbid layer.

A pronounced change in $\theta$/S characteristics is observed in summer over the upper 300 m, approaching Helheim Glacier (Fig. 4a–e). These waters are colder and fresher near the glacier and their $\theta$/S characteristics fall within the melting and runoff lines, indicating that these waters have been transformed both by melting of ice and by the addition of runoff (Fig. 4a–e; see Supplementary Information). These modified waters include not only the sGMW

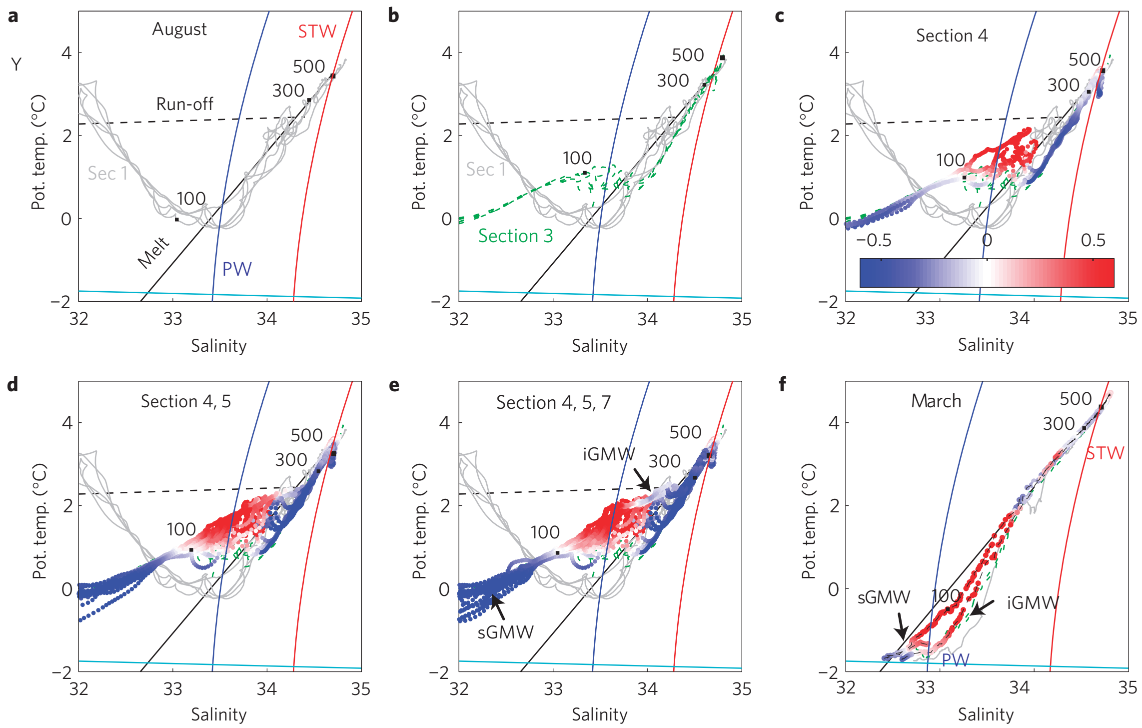


**Figure 4 | Impact of glacial runoff and melt on the fjord's waters. a–e**, potential temperature/salinity profiles from August 2009. **a**, Mouth (section 1, grey), **b**, section 3 (green) **c** to **e** progressive addition of profiles from sections 4, 5 and 7 (see Fig. 1) colour coded with the potential temperature anomaly shown in Fig. 3e. Overlaid are the meltwater line (black solid; uses the densest STW as an end point), the runoff mixing line (black dashed; uses properties at 300 m as an end point, see Supplementary Information). The blue (red) lines are constant density lines characteristics of PW (STW) density observed in August 2009. **f**, $\theta$/S profiles from March 2010, grey is the mouth, green is close to section 3 and the colour-coded profiles are those closer to Helheim Glacier. Colour indicates the potential density anomaly shown in Fig. 3f. The meltwater line shown uses the winter STW properties as one end point (see Supplementary Information). The blue (red) lines are constant density lines characteristics of PW (STW) density observed in March. The line showing the freezing point temperature at the surface is overlaid on all profiles (cyan). The sGMW and iGMW for summer and winter are shown in **e** and **f** respectively. Depths of 100, 300 and 500 m are shown for reference.

layer, the presence of which is not surprising as we expect very fresh waters to rise to the surface, but also the iGMW (Fig. 4a–e). The latter contains 'new' waters that are warmer, saltier and denser than PW but colder, fresher and lighter than STW—indicating that a fraction of the plume upwelling at the ice edge spreads out at the PW/STW interface (see Supplementary Information). Below 300 m, we see no conspicuous difference in the $\theta$/S profiles near Helheim Glacier (Fig. 4a–e). In principle, this could indicate that these are unmodified waters, but two pieces of evidence lead us to the opposite conclusion. First, as shown above, they are colder and fresher than waters near the mouth (Figs 3e–h and 4c–e)—a change which is consistent with interaction with Helheim Glacier. Second, their particulate content (turbidity) is higher than that of any other water in the fjord (Fig. 5), suggesting that they contain basal meltwater. (The iGMW and, to a lesser extent, the sGMW, are also associated with relative turbidity maxima—supporting the conclusion that they contain GMW).

The changes in the $\theta$/S characteristics near the glacier in winter are consistent with what we expect from melting alone, that is a progressive veering towards the meltwater mixing line (Fig. 4f), consistent with the notion that glacial runoff is mostly suppressed in winter. As in summer, the iGMW is associated with waters that are colder (warmer) than STW (PW) and mostly denser than PW (Fig. 4f), indicating the same export of meltwater at the PW/STW interface.

## Impact of stratification and runoff

Our collective measurements indicate that the two main pathways for GMW export are at the surface and at the PW/STW interface.

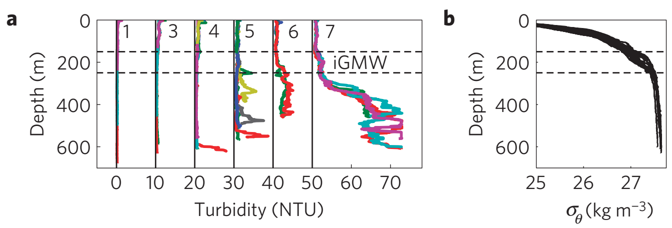


**Figure 5 | Particulate discharge at depth from Helheim Glacier in summer 2009. a**, Turbidity profiles from sections 1 to 7, shifted by 10 NTU each (the vertical line indicates zero for each section). Each station is shown as a different colour. The iGMW layer is indicated for section 7 only. **b**, Potential density profiles from all 2009 CTD stations. Horizontal dashed lines bracket the PW/STW interface.

As vertical motions are confined to the ice edge, this means that some of the rising mixture reaches the surface (as expected) but, also, that some reaches its level of neutral buoyancy at the PW/STW interface, where it spreads horizontally. This assertion is supported by a simple theoretical consideration. The fraction of meltwater contained in an ambient/meltwater mixture is limited by the amount of heat available to melt the ice[22]. If we consider, for example, the winter STW properties ($\theta \sim 4.5\,°C$, $S \sim 34.75$) we expect such a mixture to have a density that is only slightly lighter than that of PW. Given that melting presumably occurs hundreds of metres beneath the PW/STW interface and that turbulent entrainment will cause the mixture's density to become greater than that of PW within tens of metres (see Supplementary Information), we expect that plumes originating at depth will become denser than PW long before they reach the interface. Multiple GMW layers are predicted by theory and observed in laboratory experiments of ice melting in a stratified fluid[15,16].

Summer/winter differences in the GMW layers and in the properties near Helheim Glacier can be qualitatively explained in terms of changes in runoff and the ambient water properties. Increased summer runoff, some of which is discharged at depths greater than 300 m, probably explains the thicker sGMW and the freshening of the entire upper layer of the fjord, including both the iGMW and sGMW layers. Melting by warmer summer PW, also, will contribute to a larger sGMW export. In winter, on the other hand, even though STW are warmer (Fig. 2a), the sGMW layer is almost absent—suggesting that the bulk of the melting occurs beneath the PW/STW interface and meltwater export mainly occurs in the iGMW. This is consistent with the observation that the large temperature contrast between PW and STW is mostly preserved near Helheim Glacier (although a slight warming of PW near the glacier in winter indicates that some exchange does occur, Fig. 3f). Thus the PW/STW density contrast acts as a vertical barrier to the transport of heat contained in STW. This conclusion is further supported by noting that iGMW temperatures are well above freezing both in summer and in winter (Fig. 4), indicating that not all of the heat available to melt the ice was extracted. Finally, the cooling, freshening and high particulate content of the deep waters in the vicinity of Helheim Glacier suggests that some of the meltwater is also exported at depth, something that could be explained from the horizontal mixing driven by the oscillatory flows observed.

These measurements have shown that the circulation and heat transport at edge of Helheim Glacier is more complex than previously thought and influenced by a variety of glacial and oceanic processes. These include the fjord's stratification, externally forced flows and seasonal change properties as well as seasonal glacial runoff. The observations presented here are confined to one glacial fjord system in southeast Greenland. However, the fact that the characteristics of Sermilik Fjord, including the size, depth and presence of Arctic and Atlantic waters, and those of Helheim Glacier, including dimensions and seasonality of the runoff, are common to other major glacier/fjord systems in East and West Greenland, including Jakobshavn[7], Kangerdlugssuaq[13], Nioghalvfjerdsfjorden[23] and Petermann[24], suggests that these results are generally applicable to Greenland's glacial fjords.

These results have several important implications for efforts to quantify submarine melt rates and the processes controlling their variability. First, they question the significance of heat transport (and the related melt rate) estimates based on synoptic (or instantaneous) velocity and temperature measurements[10,24] and the applicability of the estuarine paradigm[10,12] to Greenland's glacial fjords. Instead, these results indicate that meaningful heat transport estimates will require flow and property measurements over longer periods of time that include the annual cycle. Second, any idealized formulation of submarine melting must take into account the fjords' stratification and properties, the different fjords' circulations, subglacial discharge and their variability. Third, these results clearly indicate that the Atlantic water temperature variability alone is a poor indicator of the ocean's impact on submarine melting. Indeed it is unclear from the existing data whether the submarine melt rates are larger in winter, when the Atlantic waters are warmer, or in summer, when the injection of runoff at depth seems to enhance upwelling at the glacier edge. Thus, more sophisticated coupled ocean/glacier models need be developed in conjunction with process-oriented field and laboratory experiments to be able to resolve the relevant dynamics and, eventually, provide parameterizations which can be implemented in predictive climate/ice sheet/ocean models.

One important implication of these findings is that the Atlantic/Arctic water layering may significantly influence the structure of floating sections of glaciers in Greenland, and hence glacier stability, by impacting the vertical distribution of heat and melting. On the ocean side, these findings indicate that a substantial fraction of meltwater and runoff enters the ocean at depth—questioning the widespread notion that Greenland's mass loss can be equated to an increased freshwater discharge at the surface. Given the sensitivity of the downstream convective regions to changes in stratification, the vertical distribution of the freshening must be taken into consideration.

## Methods

Measurements in Sermilik Fjord in summer 2009 were conducted from the M/V Arctic Sunrise, a class II icebreaker, from 19 to 24 August. Conductivity, temperature and depth (CTD) and turbidity profiles were collected at 42 stations using a 6 Hz RBR XR-620 sensor (Fig. 1). Water samples were collected at a range of depths and on multiple casts to calibrate the conductivity sensor. Pre- and post-deployment calibrations of the temperature and conductivity sensors were carried out. Bathymetric data were obtained using a 320 Knudsen 12 kHz Echosounder. Velocity profiles were collected over the entire water column at all CTD stations using a 300 kHz RDI lowered Acoustic Doppler Current Profiler (lADCP). Two additional temperature and velocity profiles were collected using eXpendable Current Profilers (XCPs) deployed from a helicopter in open water leads in the sea ice.

The winter survey consisted of two expendable CTDs (XCTD) deployed from a small vessel near section 3 on 15 March and three XCTDs and one eXpendable bathythermograph (XBT, recording temperature only) deployed from a helicopter on 16 March, Fig. 1. Except for the last XCTD deployed at the mouth, all profiles collected with the expendable probes were cross-calibrated against data collected over the upper 50 m using an RBR XR-620 CTD (deployed either from the boat or from the helicopter).

Received 22 August 2010; accepted 11 February 2011; published online 20 March 2011

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## Acknowledgements

We thank M. Duchin and I. Menn from Greenpeace, P. Willcox (captain), A. Sørensen (ice pilot) and the entire crew of the M/V Arctic Sunrise, and Greenpeace International for their support in making the summer measurements in Sermilik Fjord; J. Ryder, J. Kemp and his group for logistic planning of the fieldwork; D. Torres, A. Ramsey, and S. Worrilow for instrument preparation and support. F.S. acknowledges support from Woods Hole Oceanographic Institution's Ocean and Climate Change Institute's Arctic Research Initiative and from NSF OCE 0751554 and ARC 0909373, and G.S.H. and L.A.S. acknowledge support from NASA's Cryospheric Sciences Program.

## Author contributions

F.S., D.A.S., R.G.C. and G.S.H. conceived the study, F.S., D. A. S., R.G.C, K.V., L.A.S. and G.S.H. participated in the collection of oceanographic data in Sermilik Fjord, and F.S., D.A.S. and C.C. were responsible for the analysis and interpretation.

## Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to F.S