

1. Introduction

The Greenland Ice Sheet's (GIS) contribution to sea level rise more than doubled in the last seven years, mostly because of the acceleration of outlet glaciers in the southeastern and western sectors of the ice sheet¹. Roughly at the same time, ocean temperatures around Greenland's western and southeastern coast also started to increase. This oceanic warming, which has affected the entire subpolar North Atlantic², has been attributed to inflows of anomalously warm water from the subtropical region³ driven by the North Atlantic Oscillation (NAO). The NAO, which is the dominant mode of atmospheric variability for this region, abruptly shifted in 1996 from a pronounced positive phase and has been in a neutral phase since then⁴.

The concurrent changes of the GIS and the adjacent ocean raise the possibility that the sudden acceleration of Greenland's outlet glaciers is due to the 'warm ocean trigger'. Warm ocean waters lead to increased rates of submarine melting at the tidewater margins of outlet glaciers. This melting, in turn, leads to a thinning, ungrounding, and subsequent reduction in frontal buttressing to glacier flow and hence to an increase in glacier speed. Thus, according to this scenario, the recent acceleration of the GIS's outlet glaciers is a result of fluctuations in the NAO⁵.

2. The Problem

Evidence supporting the warm ocean trigger is scarce and mechanisms underlying the proposed chain of events remain unclear.

1) What drives the warm, subtropical waters into glacial fjords?

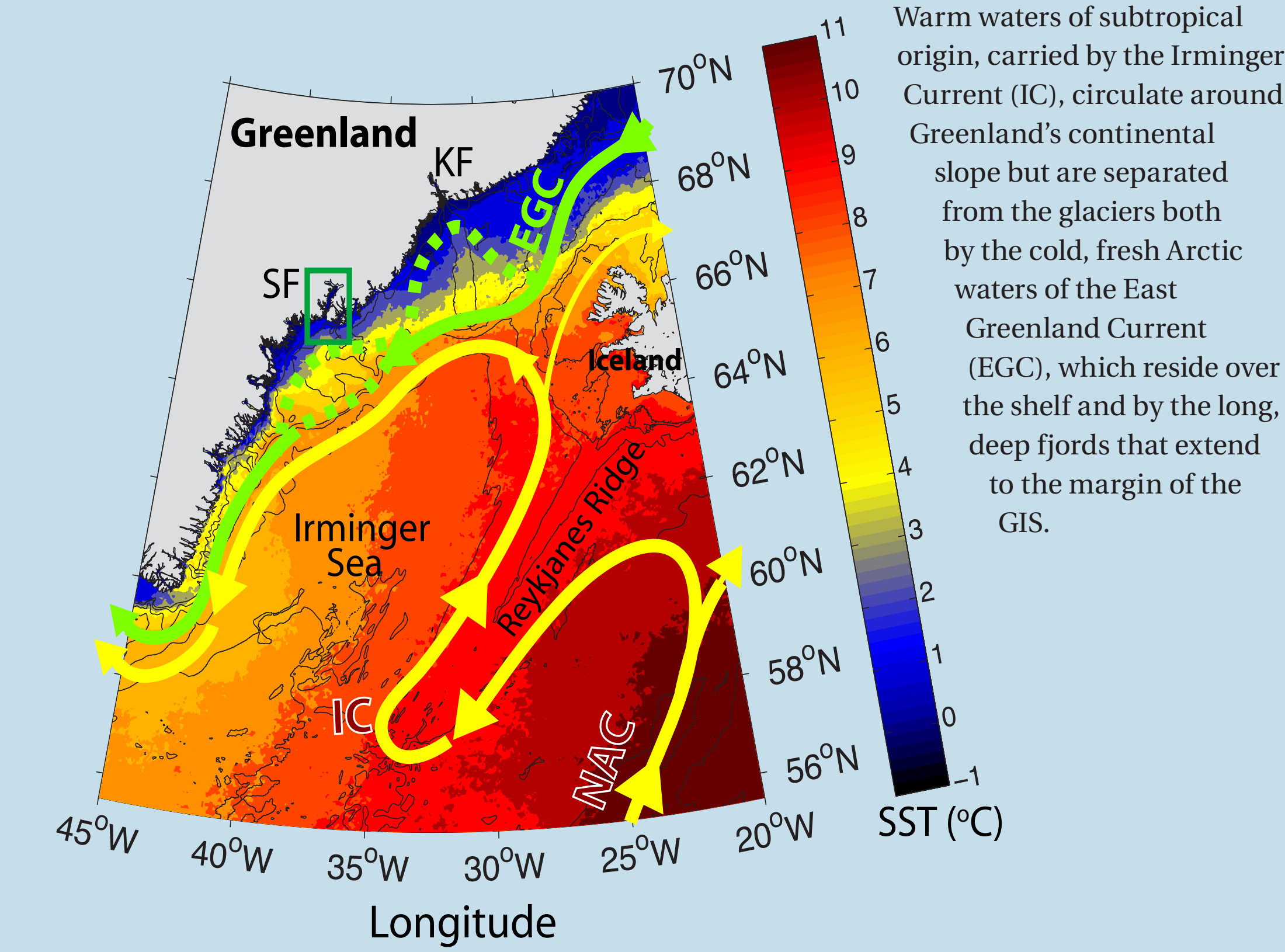


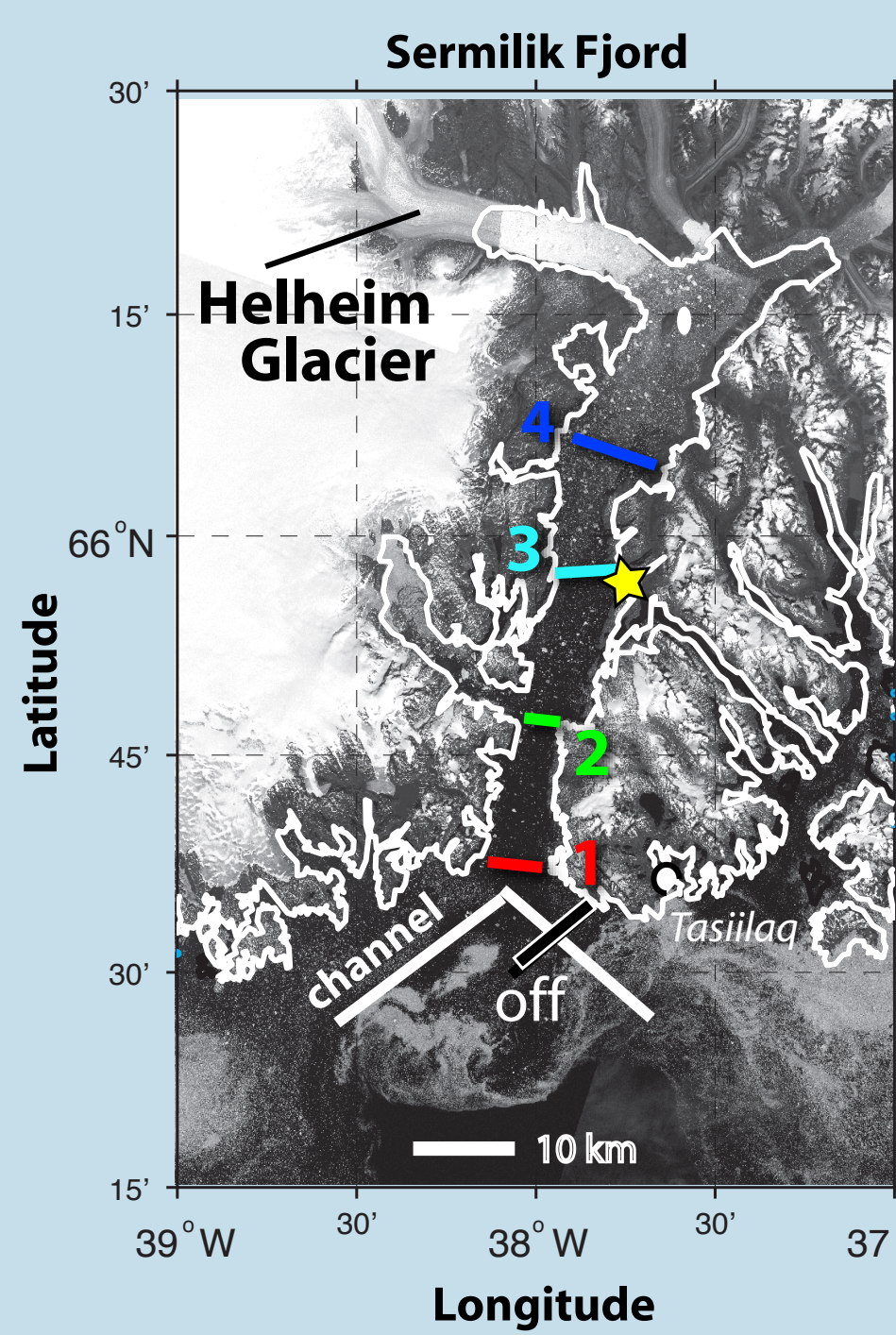
Figure 1: Sea surface temperature map (annual average for 1997-2007 from AVHRR data) of the Irminger Sea region.

2) If glacier acceleration is tied to the NAO – why was there no widespread acceleration during the 1960s, for example, when the NAO was in a similarly neutral/negative phase?

To address these questions, we:

- investigate the mechanisms for warm water inflow into a large glacier/fjord system in East Greenland.
- use an extensive ocean database to investigate the origin of the warming of the subtropical waters and its relation to the NAO.

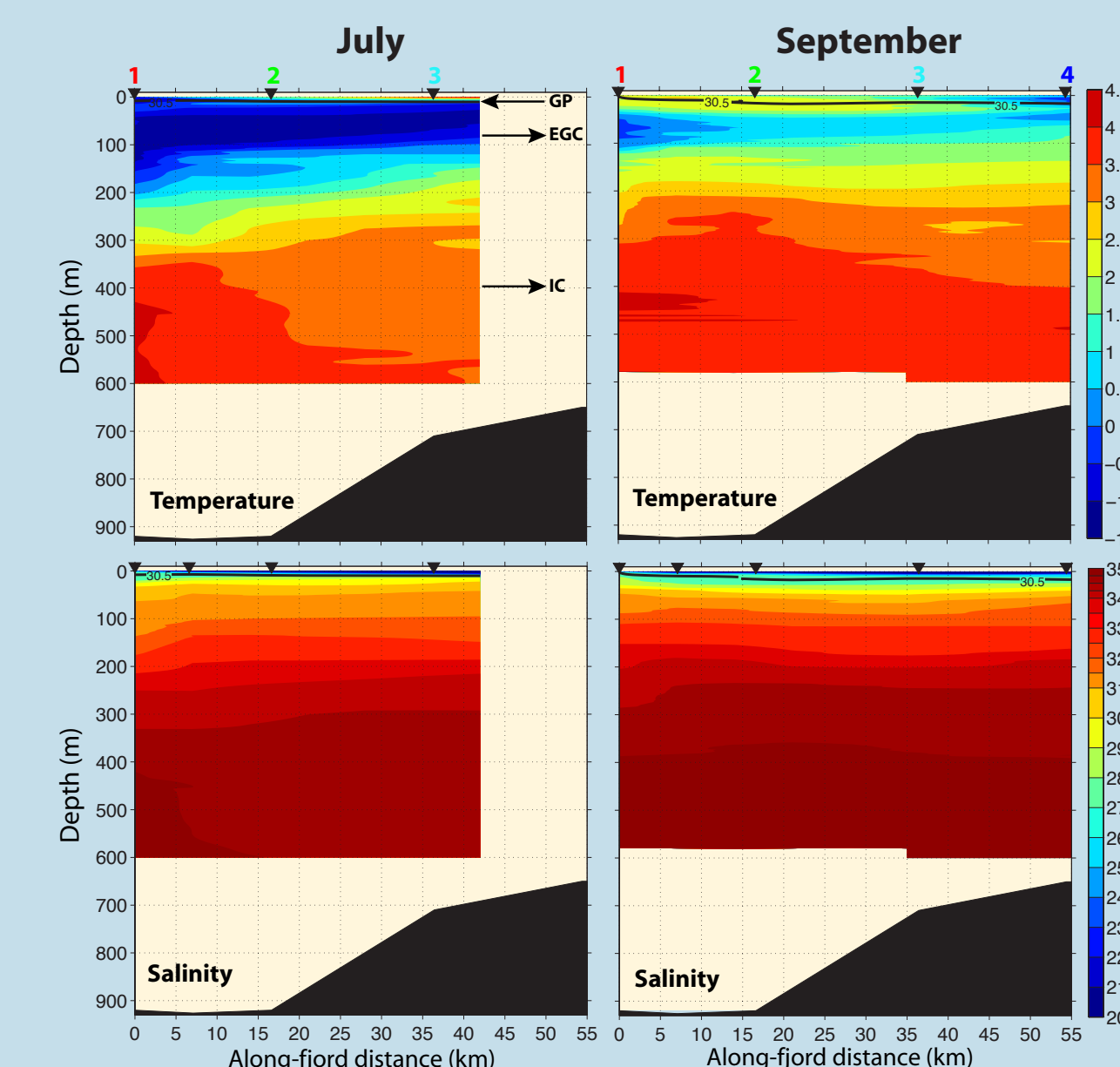
3. Circulation and Water Masses in Sermilik Fjord



Sermilik Fjord (SF) is a 100 km long, U-shaped glacial fjord fed by Helheim Glacier, one of Greenland's largest outlet glaciers (it discharges about 11% of the annual mass input to the GIS). Since 2003, Helheim has retreated ~6 km, thinned by 200 m, and almost doubled its flow speed, accounting for a significant portion of the sea-level rise attributed to changes in the GIS⁶.

Oceanographic and bathymetric surveys were conducted in SF in July and September of 2008.

Figure 2: Sermilik Fjord from a Landsat mosaic. Oceanographic data was collected across the sections indicated: July (sections 1, 2, 3); September (sections off, 1, 2, 3, 4). Two moorings were deployed in July and recovered in September (yellow star).



Properties of the Waters in Sermilik Fjord

Three water masses are present in Sermilik Fjord:

- Glacial Meltwater Plume (GP), very fresh 0-10m
- Cold, fresh EGC water - 10-200m
- Warm (3.5-4 °C), salty IC waters of subtropical origin (200m to the bottom)

Circulation in the fjord:

- EGC and IC flowing into the fjord, GP flowing out
- Different properties of the EGC and IC waters in the fjord between the surveys => rapid flushing of the fjord (inconsistent with estuarine circulation).
- Strong vertical mixing between the EGC and IC layers as they move towards Helheim

Figure 3: July and September 2008 Surveys of Sermilik Fjord. Top: Across-fjord averaged temperature and salinity profiles as a function of distance from the mouth. The 30.5 isohaline marks the glacial meltwater plume (GP). Bottom: Temperature Profiles and Temperature/Salinity diagram for the surveys. Lines are color coded by section as shown in Figure 2 (black offshore, red –mouth, green, cyan and blue towards the head).

4. What drives the inflow of warm waters across the shelf and into glacial fjords?

Warm waters across the shelf

SF is a deep fjord with no sill, instead two deep channels connect it to the inner shelf/slope region. A thick layer of warm, IC water was flowing towards the fjord in one of the channels (section off) suggesting that these channels steer the IC onto the shelf. Such channels are typical of Greenland's glacial fjords since they are geomorphic feature resulting from glacial erosion by expanded Ice Age ice sheets.⁷ Indeed, warm intrusions onto the shelf appear to occur in correspondence of several glacial fjords (Figure 1 – SF, KF).

Warm waters inside the fjord

Data collected by two moored CTD (conductivity, temperature and depth recorders), deployed mid-fjord at 25 and 180m depths (Figure 2 for location) during the period between the two surveys shows a large degree of variability on timescales of several days. In particular, sea-surface height variations observed were found to be associated with changes in density at the deeper instrument and with the magnitude and direction of the along-shore winds outside the fjord (Figure 4).

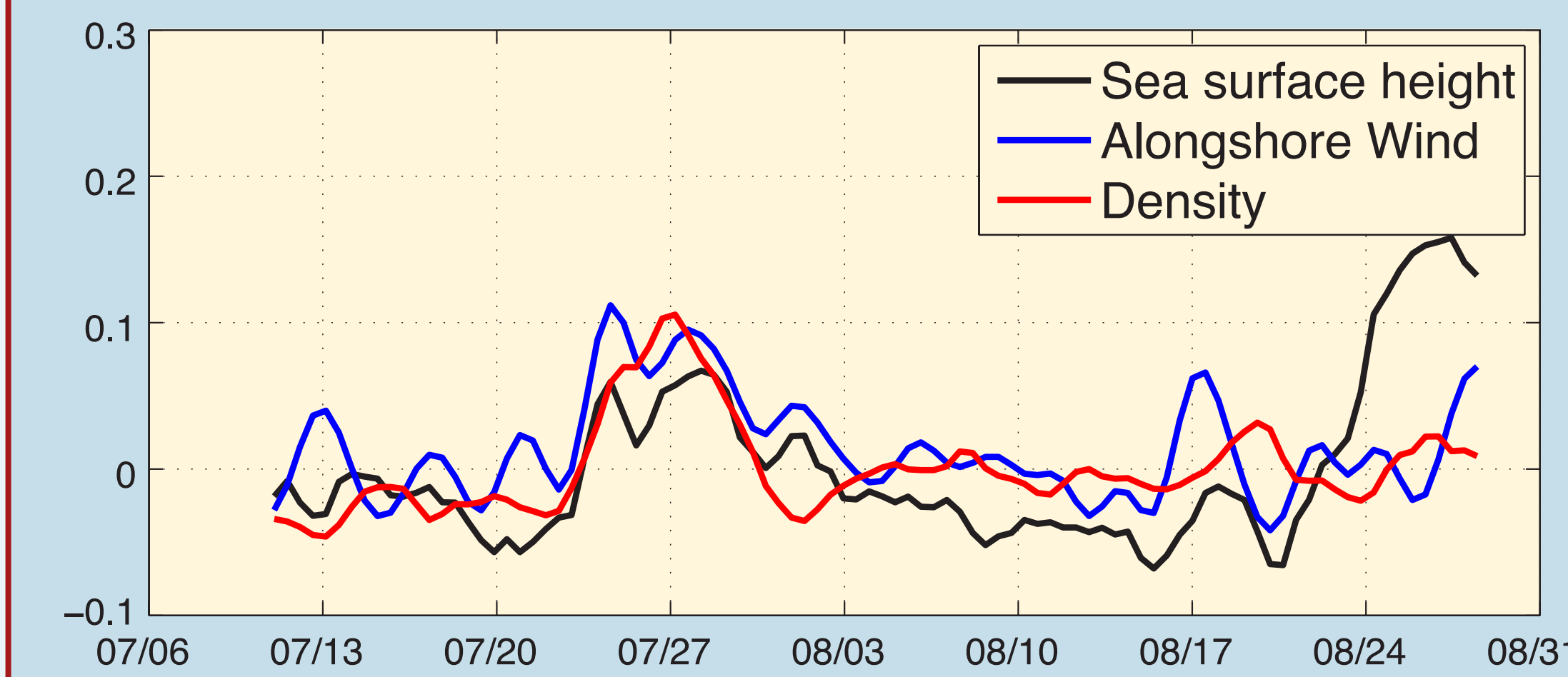


Figure 4: Mooring data from Sermilik Fjord showing synchronous variations in the alongshore winds, density at 180m and sea-surface height. Graphs shown are for the detided sea-surface height (m), along-shore wind speed/10 (m/s; positive is downwelling favourable) and density*(1/3) (kg/m³).

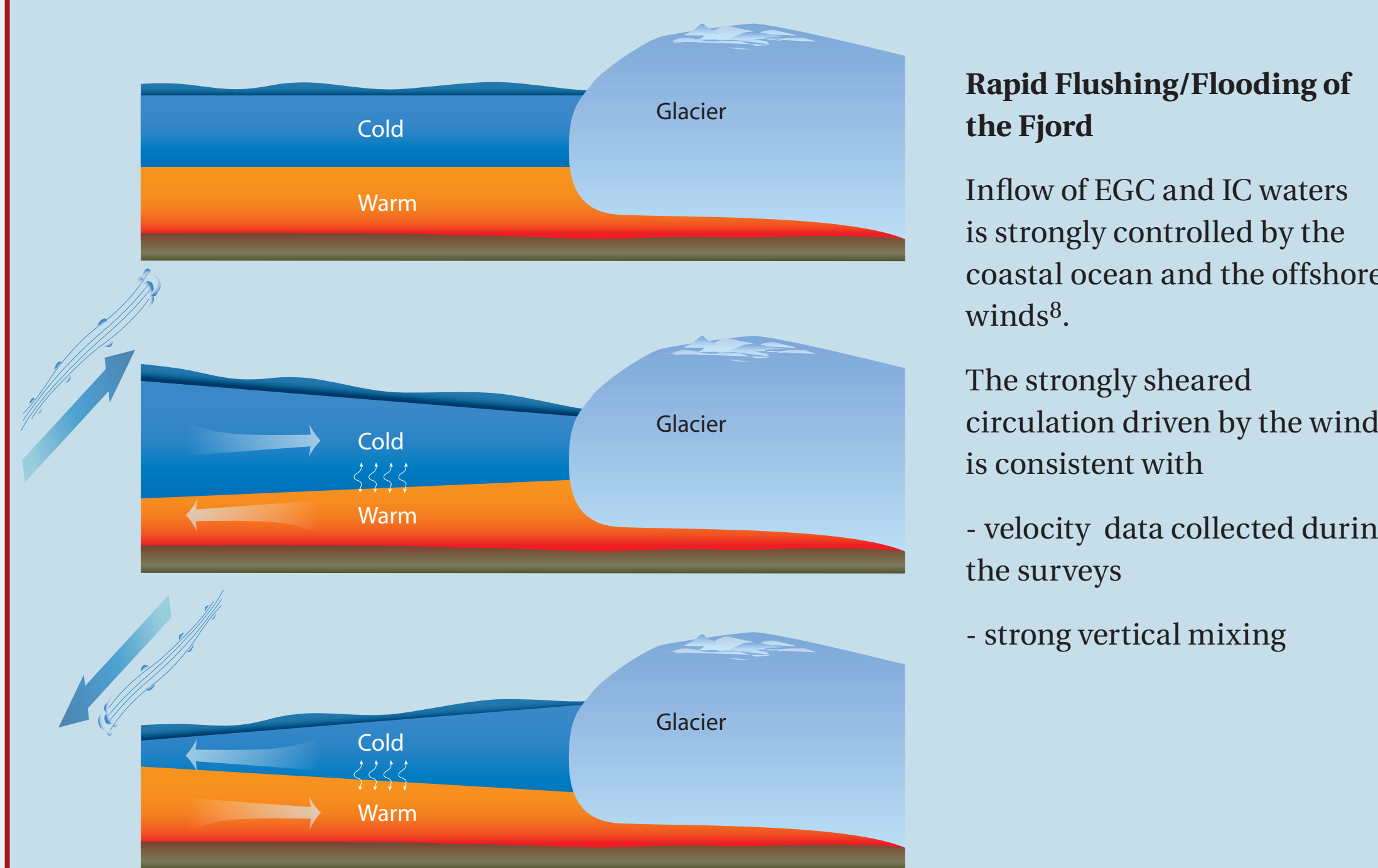


Figure 5: Along-shore winds drive downwelling (upwelling) at the fjord's mouth which drives flooding (flushing) of the fjord.

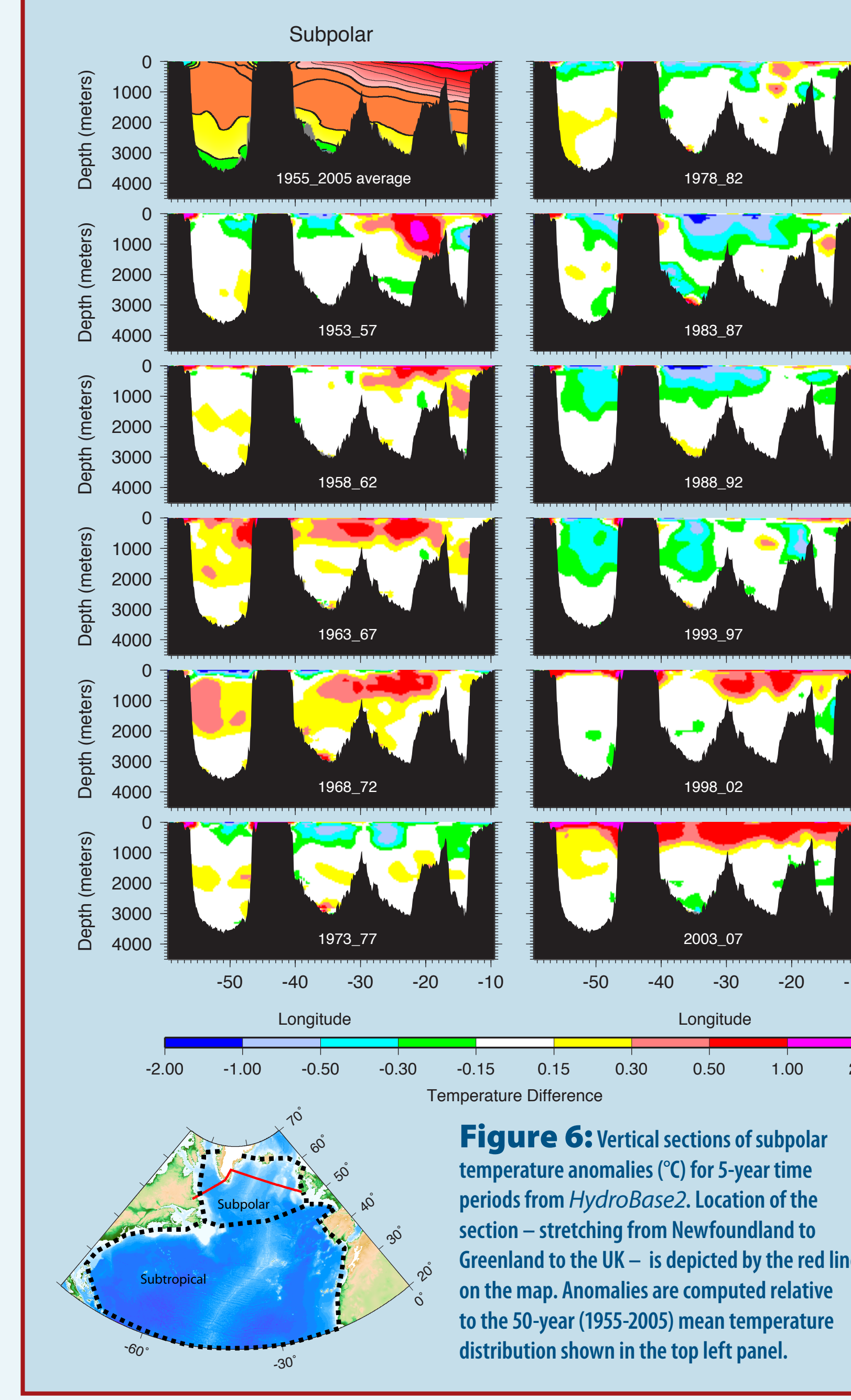


Figure 6: Vertical sections of subpolar temperature anomalies (°C) for 5-year time periods from HydroBase2. Location of the section – stretching from Newfoundland to Greenland to the UK – is depicted by the red line on the map. Anomalies are computed relative to the 50-year (1955-2005) mean temperature distribution shown in the top left panel.

5. What is behind the warming of the seas around Greenland?

The temperatures of the IC waters around western and southeast Greenland have exhibited large multi-decadal fluctuations over the last 50+ years that have pervaded the upper 1200m of the entire subpolar gyre. The 1960s were warm and the late 1980s to early 1990s were cold. At present the IC waters are warmer than any on record. (Figure 6)

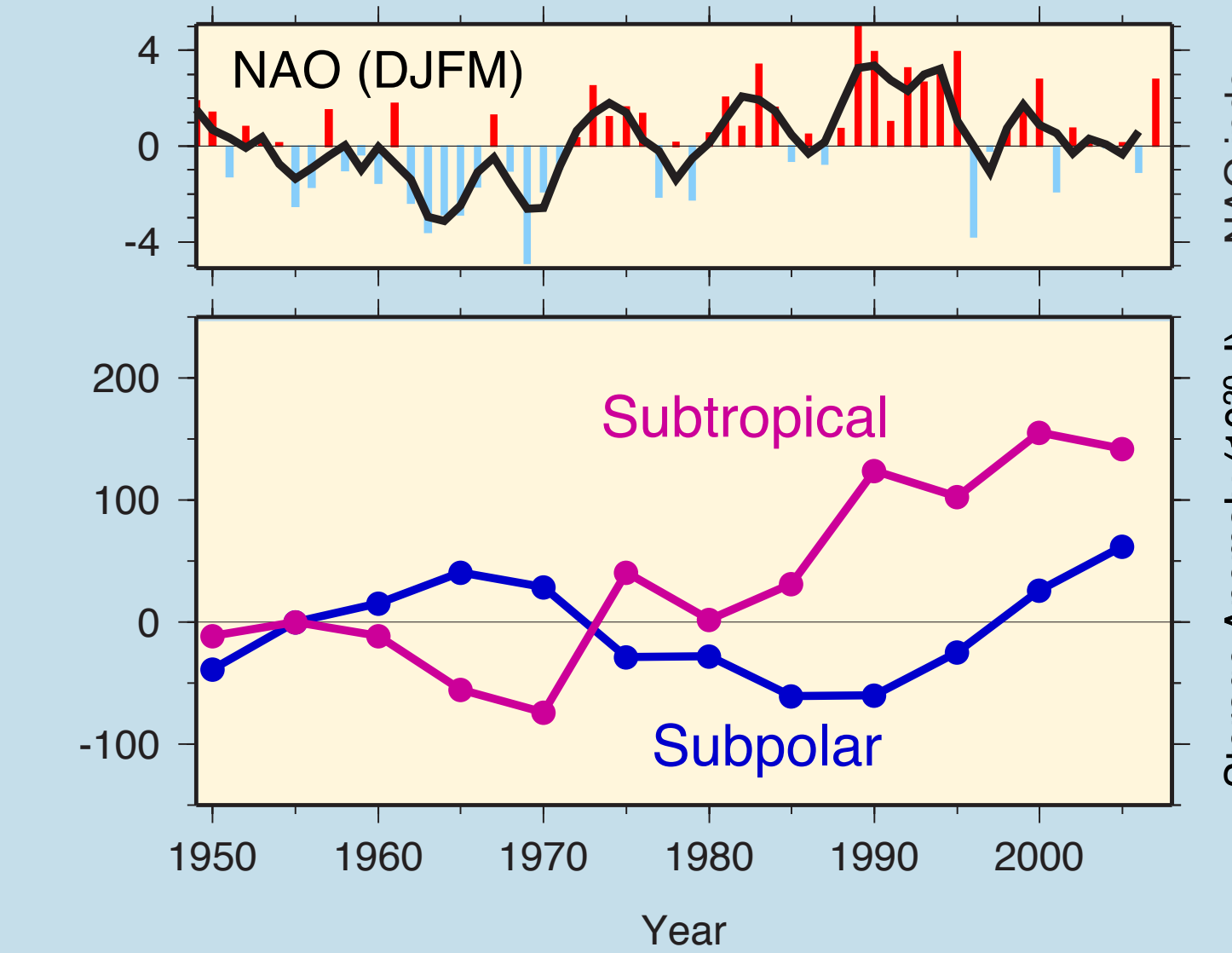


Figure 7: Timeseries of volumetric heat storage anomaly (1020 Joules) for the upper ocean layer 0-1200 meters in the subpolar North Atlantic (20°-50°N) and subpolar basins (50°N to Davis Strait and the G-I-S Ridge) (see map for Fig 6). Heat storage anomalies relative to 1955 were computed from 5-year averages of profile data (pressure, temperature, salinity) with the seasonal cycle removed. The data and analysis come from the HydroBase2 package: <http://www.whoi.edu/science/PO/hydrobase>. The winter NAO index (Dec – Mar) is shown as bars and a 3-year smoothed curve (source: <http://www.gd.ucar.edu/cas/hurrell/>)

The changes in heat content are broadly consistent with shifts in the NAO⁸ (Figure 7):

NAO- => warmer subpolar, cooler subtropics with enhanced flow from the subtropics to the subpolar

NAO+ => cooler subpolar, warmer subtropics and reduced flow from the subtropics to the subpolar

However, this direct correlation appears to break down in the mid-1990s. Since the shift in the NAO of 1996, both the subpolar and subtropical upper oceans have gained heat and are presently warmer than at any time in the modern instrumental record¹⁰ (Figure 7).

Although the internal (or "natural") variability of this region is quite large, the Atlantic upper ocean anomalies are beginning to rise above the background noise—especially in the lower latitudes where temperature and salinity changes cannot be explained by climate models without invoking anthropogenic forcing¹¹.

6. Summary

Measurements from Sermilik Fjord, East Greenland, support the notion that warm IC waters come in contact with the tidewater margin of Helheim Glacier.

Two deep channels steer the warm IC waters onto the shelf and towards the mouth of Sermilik. Similar conditions likely apply to other glacial fjords in Greenland since such channels are a typical geomorphic feature associated with the advance and retreat of the ice sheet.

Warm IC waters (as well as cold EGC waters) circulate vigorously through Sermilik Fjord due to the periodic flushing and flooding of the fjord driven by the along-shore winds. This circulation, much more rapid than an estuarine circulation, increases the renewal of warm waters inside the fjord and enhances the rate of submarine melting. Again, this mechanism is not unique to Sermilik and likely plays a role in the circulation within many of Greenland's fjords.

The waters around Greenland are presently (and since the time glaciers started accelerating) the warmest in the instrumental record. This rapid warming of the subpolar North Atlantic is due to the inflow of exceedingly warm subtropical waters, at the end of a prolonged NAO+ phase. The subtropical warming can no longer be attributed to the NAO alone but instead appears to be a prolonged trend which began in the 1980s. According to climate models, this trend cannot be attributed to natural variability alone but is tied to increases in anthropogenic greenhouse gas emissions. Our observations in Sermilik Fjord provide a basis on which to explain recent changes in Greenland glacier dynamics as a response to the global warming signature in the subpolar North Atlantic, and indicate the importance of including glacier-ocean interactions in future models of ice sheet response to climate change.

Acknowledgements

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