Observations and modelling of water masses and heat transport at a retreating tidewater outlet glacier (NE Greenland, 81 °N)

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Wandel Sea & tidewater outlet glaciers

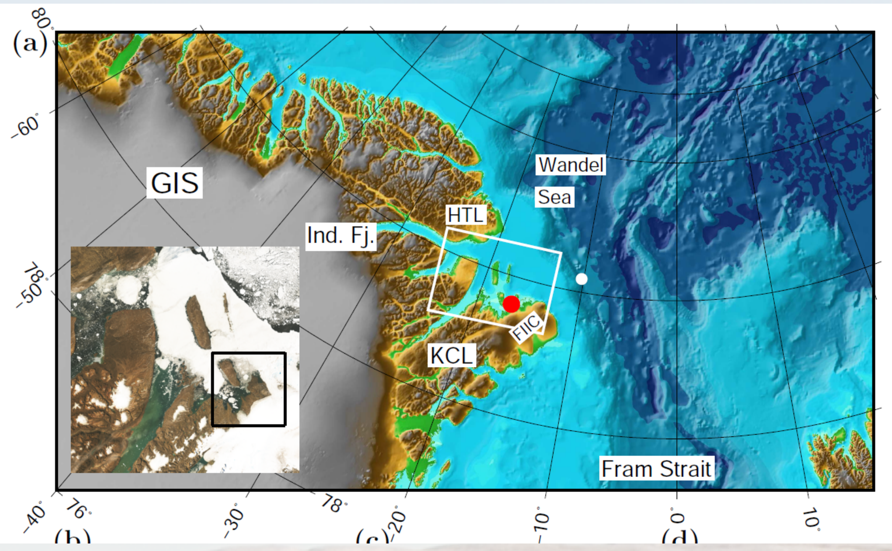

Figure 1 Observational study area around Villum Research Station (red bullet), located between the complex fjord system (e.g. Independence fjord) and the Wandel Sea. Flade Isblink Ice Cap (FIIC) is the largest peripheral ice cap in Greenland with several tidewater outlet glaciers (bathymetry from IBCAO).

Introduction

Accelerated mass loss from the Greenland Ice Sheet (GIS) and reduced sea ice cover change salinity and temperature in coastal water masses around Greenland. Ice-ocean interaction has been shown to be a major component in the heat balance in front of tidewater outlet glaciers (e.g. Mortensen et al., 2013; Bendtsen et al., 2015). Feedbacks between changing water masses and the melting of tidewater outlet glaciers from GIS, therefore, have to be better understood before the ongoing changes can be explained. However, few studies of coastal water masses near outlet glaciers have been made from the northern coast towards the Arctic Ocean that has remained nearly permanently ice covered.
Here we present results from an observational study near a tidewater outlet glacier from Flade Isblink Ice Cap - the largest peripheral Ice Cap in Greenland, and the impact of reduced ice cover on surface temperature is analyzed in a model study of the shelf area along the northern coast. The observational study is described in detail in Bendtsen et al. (2017).

Warm surface water and super-cooling/freeze below

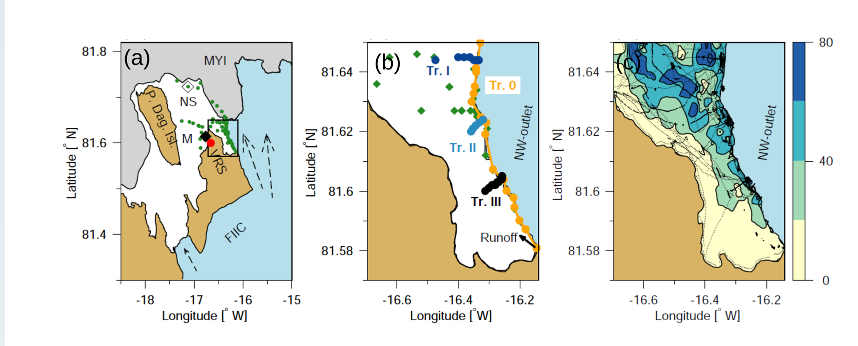

Figure 2 a) Digitized Landsat 8 satellite image from 12 August 2015 showing Flade Isblink Ice Cap (FIIC) and the extent of multi-year ice (MYI) around Villum Research Station (VRS). CTD-stations from August 2015 are shown with green bullets. **b)** Station map along the terminus of the NW-tidewater outlet glacier from FIIC (black rectangle in **(a)**) and stations along transects 0-III and **c)** bathymetry (m) near the terminus.

*The bathymetric steep slope near the terminus **(c)** was likely due to previous wider extension of the ice cap in the bay.*

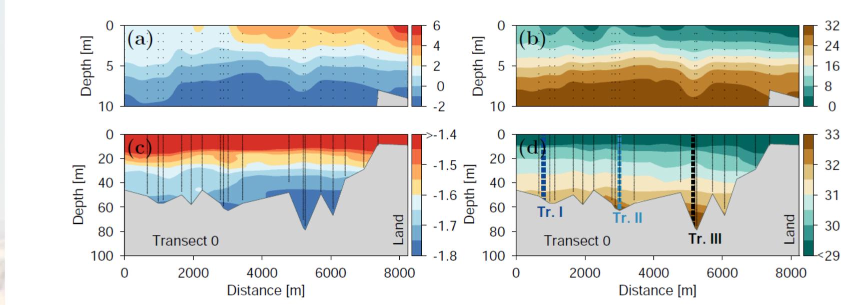

Figure 3 Transect 0 along the terminus (Fig. 2b) collected in the period 10 - 25 August. **(a)** Temperature in the upper 10 m, **(c)** in the whole water column and **(b)** salinity in the upper 10 m and **(d)** in the whole water column. Note the varying color scales.

Relatively warm (>1 °C) and low-saline surface water was observed along the terminus. Cold and saline bottom water present at the innermost deepest part (nearest land) indicated that the terminus was a floating ice shelf.

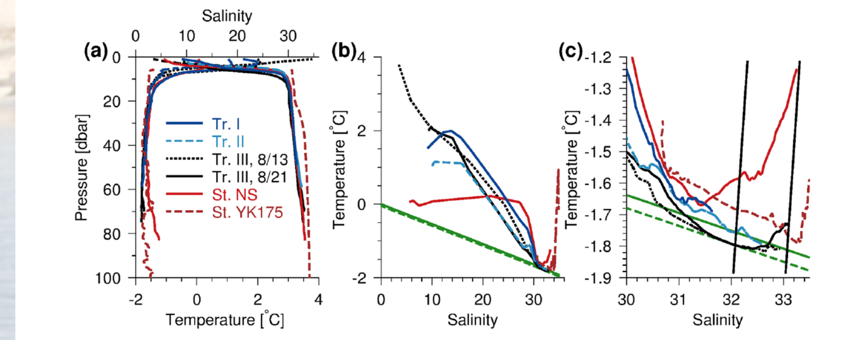

Figure 4 TS-diagrams. **(a)** Temperature and salinity profiles near terminus at transect I (blue), transect II (dashed lightblue), transect III (black dashed (13 Aug.) and solid (21 Aug.) lines), station NS (red line) and on the shelf (YK175, brown dashed line). **(b)** TS-diagram and **(c)** for S > 30. Meltlines (black near-vertical lines) and lines of freezing temperature are shown for P = 0 dbar (green) and P = 55 dbar (dashed green), respectively.

Sub-surface and bottom water was super-cooled or very near the freezing point and was a strong indication of net-freezing at the ice-ocean interface below the upper surface layer.

Surface melt & retreat of Flade Isblink outlet glacier

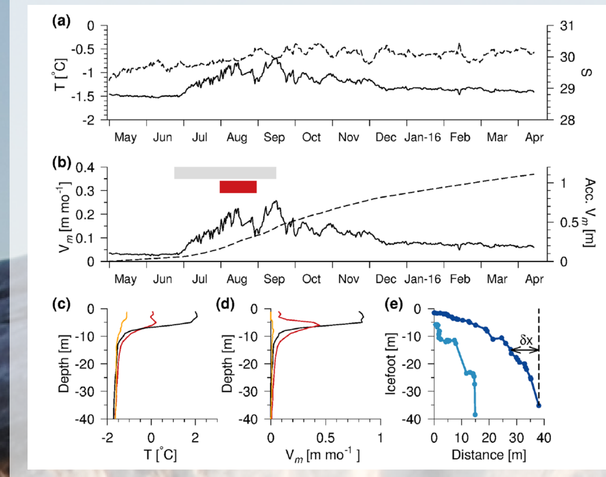

Figure 5 Melt rates and Icefoot. **(a)** Temperature (solid line) and salinity (dashed, triangle) from mooring (13 m depth) at station M off Villum Research Station. **(b)** Calculated melt rate from surface water and accumulated melt during the periods where duration of ice breakup (gray bar) and open water in front of the terminus (red bar) are indicated. **(c)** Temperature near the terminus (transect III, black), station NS near the MYI and a profile from April 2015 (orange), **(d)** the corresponding calculated melt rates and **(e)** observed ice foot (transect I, light blue; transect III, blue) and glacier melt (δx).

*Ice foot morphology **(e)** show that surface heating is a significant source for ice melt. Calculated melt rates **(b)** show increased melt during open water periods.*

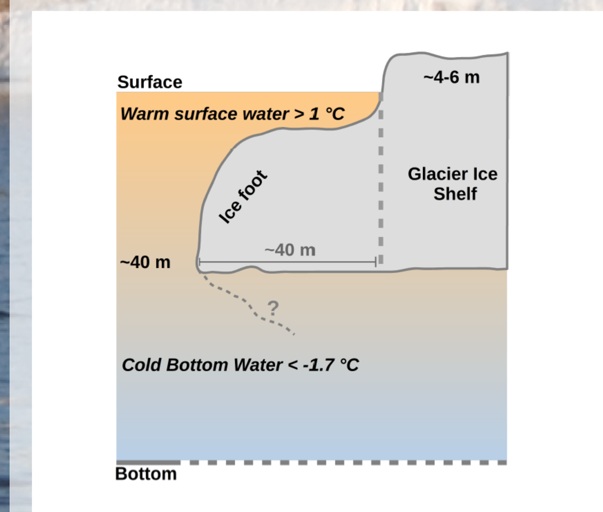

Figure 6 Ice foot at the terminus. Conceptual illustration of the terminus at the NW-outlet ice shelf from Flade Isblink ice cap showing an ice foot of about 40 m deep and a height of 4-6 m above sea level (observed ice foot shapes are shown in Fig. 5e). The vertical dashed line show the terminus after calving of the ice foot. The question mark below the ice foot indicate the unknown shape (dashed line) below the glacier.

Water mass analysis near the terminus and satellite observations supported that the NW-outlet was a floating ice shelf. Warm surface water gradually melts the upper part of the glacier and it, thereby, obtain the observed sub-surface shape.

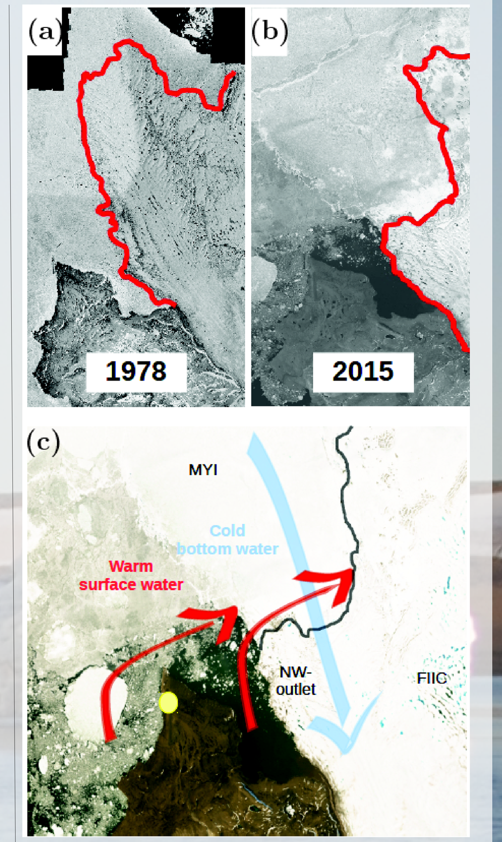

Figure 7 Melt due to open water **(a)** FIIC in 1978 and **(b)** 2015. **(c)** conceptual figure of water transports.

*The conceptual figure in **(c)** shows the hypothesized transport of warm surface water (red) and relatively cold bottom water (blue) below the ice shelf.*

Modelling coastal - shelf exhange

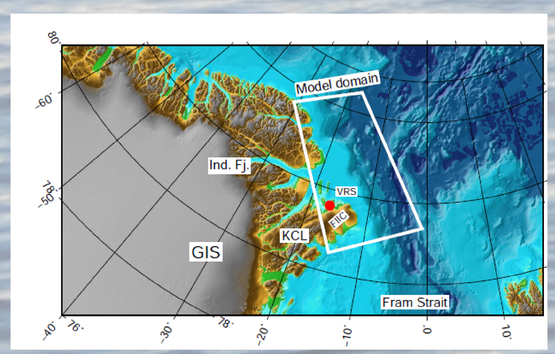

Figure 8 Model domain along the northern shelf, including the outer fjord regions from F. E. Hyde fjord, Independence fjord, Denmark fjord. Villum Research Station is shown with a red bullet.

Model domain along the northern coast towards the Arctic Ocean. The model is based on a 3D-primitive equation model (COHERENS, Luyten et al., 2014) and solves the momentum and transport equations for temperature and salinity on a Cartesian equidistant grid (2x2km) with 20 vertical stretched sigma levels. The model is forced with 8 tidal constituents along the open boundaries, meteorological forcing and the daily sea ice concentration at the surface, a prescribed barotropic transport along the shelf towards Fram Strait and a prescribed runoff from the fjords. Initial conditions are based on the relatively few observations on the shelf (<80 m) and from the open Wandel Sea (>1000m).

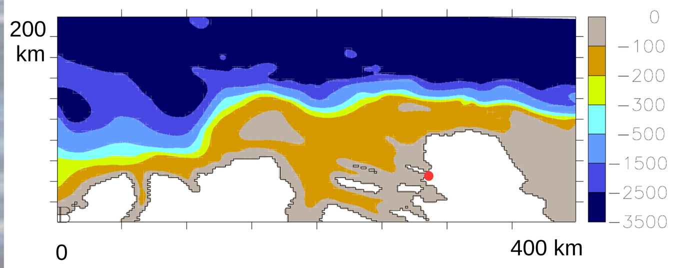

Figure 9 Model bathymetry (based on Gebco_2014) along the northern coast of Greenland. The domain is rotated (see Fig. 8) and configured with a Cartesian grid with a length of 400 km along the coast, 200 km off shore and with a grid spacing of 2 km. The red bullet shows the location of Villum Research Station (cf. Fig. 8).

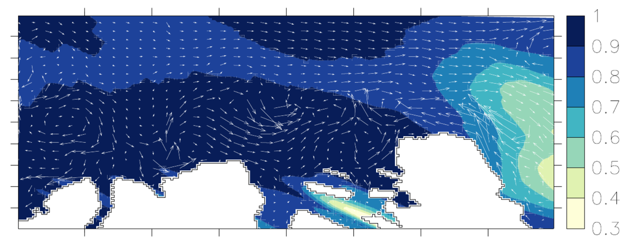

Figure 10 Model solution of instantaneous barotropic velocities (white arrows, maximum values ~0.8 m s^{-1}, example from 27 July 2015) and sea ice concentration (colors, values between 0 and 1).

Low sea ice concentration of ~50% is seen off Nordostrundingen whereas a relatively dense sea ice cover (>90%) characterizes most of the Wandel Sea.

Interannual sea ice variability and surface heating

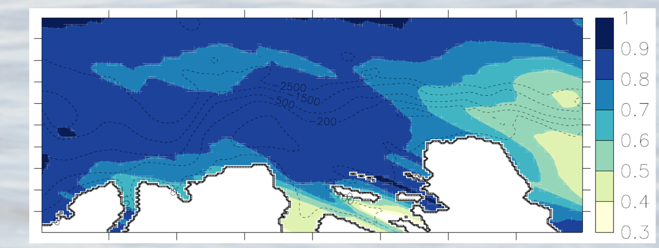

Figure 11 Sea ice concentrtion 5 August 2015. Low values below 50% are seen in the eastern part of the domain, i.e. off Nordostrundingen (Depth contours are shown).

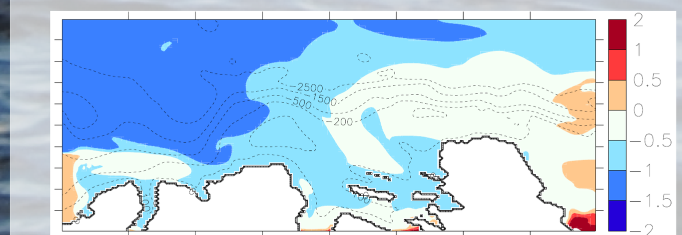

Figure 12 Sea surface temperature, 5 August 2015. Temperature below sea ice is ~-1 - -1.5 °C, whereas the partly open water areas in the eastern part of the domain has increased by more than 1 °C (warm temperatures at the western boundary near land are due to the prescribed boundary conditions).

Large areas of the Arctic Ocean is permanently covered by sea ice. However, the sea off Fladen Isblink glacier is located in the transition zone between the permanently ice covered Arctic Ocean and more open water areas towards Fram Strait. Thus, inter-annual variability of sea ice cover in late summer is relatively large, for example due to wind conditions.

The potential impact from surface heating of the partly open water area in the Wandel Sea was analyzed by simulating the period from end of June - August 2015, using realistic meteorological fields and satellite-derived daily sea ice concentrations. Energy fluxes at the ocean surface was proportional to the observed open water area and heat fluxes below sea ice was calculated from surface currents and below-ice exchange coefficients (Bendtsen et al., 2014).

Preliminary results of the SST distribution in August (Fig. 12) shows the impact from the low sea ice concentration in the area in August 2015. Heating of the open water area causes SST to increase by more than 1 °C in a large area around Fladen Isblink glacier. Thus, in addition to local heating due to sea ice break-up in front of tidewater outlet glaciers, as observed in front of the NW-outlet glacier (cf. Figs. 3 & 5), additional heating from the open sea is expected in periods with reduced sea ice cover.

Reduced sea ice cover on the shelf and slope area due to increased warming of the Arctic Ocean is, therefore, expected to cause additional heating of coastal water masses in contact with Fladen Isblink tidewater outlet glaciers.

Summary

Observations near the NW-tidewater outlet glacier from Fladen Isblink showed open water in in front of the terminus in August 2015. This caused a significant heating of the surface layer and relatively high surface temperatures above 1 °C was observed at the terminus.

Sections along the terminus were characterized by a relatively large ice foot of up to 40 m from the glacier above sea level. This ice foot morphology at the floating ice shelf could be explained by melt from the surface layer. Calculated melt rates, based on temperature recordings from a continuous CTD-mooring (2015-2016) accounted for the observed surface melt.

The NW-tidewater outlet glacier from Fladen Isblink was previously characterized by a long ice tongue. However, comparison of orthorectified aerial photographs from 1978 with present day conditions showed a significant decrease of the long and narrow ice-tongue from the NW-outlet by more than 10 km. This decrease may be explained from increased heating of the surface layer in the area surrounding Fladen Isblink.

A model simulation of conditions along the shelf at the northern coast of Greenland showed that varying sea ice cover in the eastern part of the Wandel Sea caused a significant SST increase in coastal water masses around Fladen Isblink.

Thus, increased surface temperatures in coastal water masses around Fladen Isblink can be explained from both local sea ice break-up in front of the terminus and variations in summer sea ice concentrations on the shelf and slope area further off-shore.

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