Using **ECCO** to identify an ocean role in the thickening and advance of **Jakobshavn Isbrae**, central west Greenland

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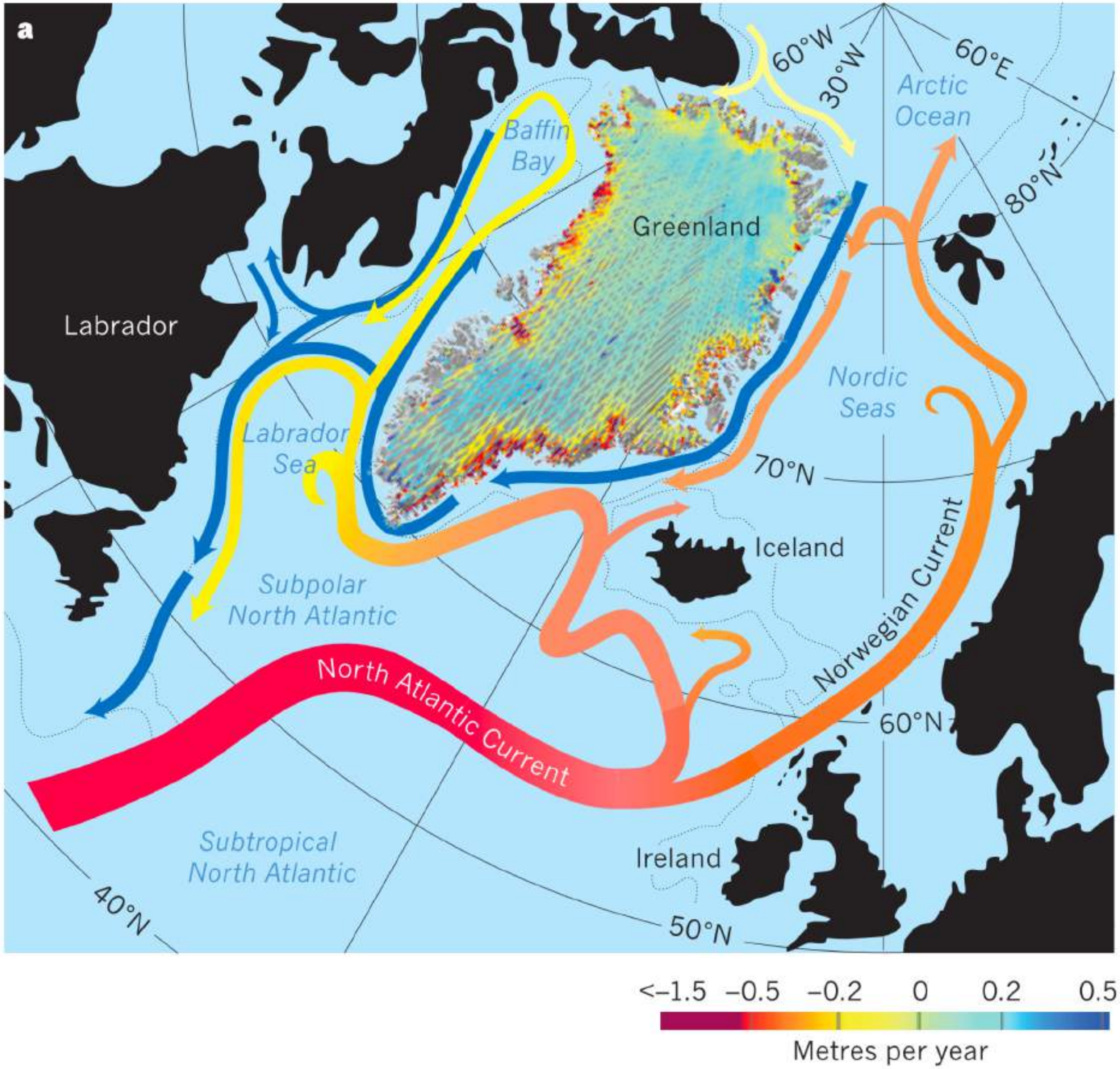
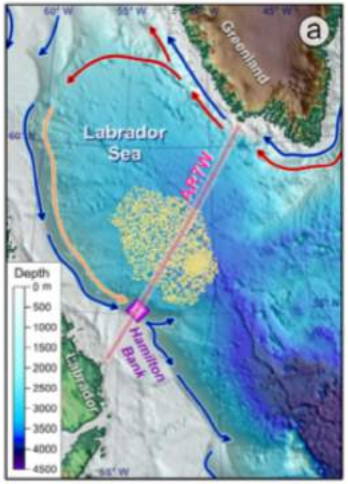


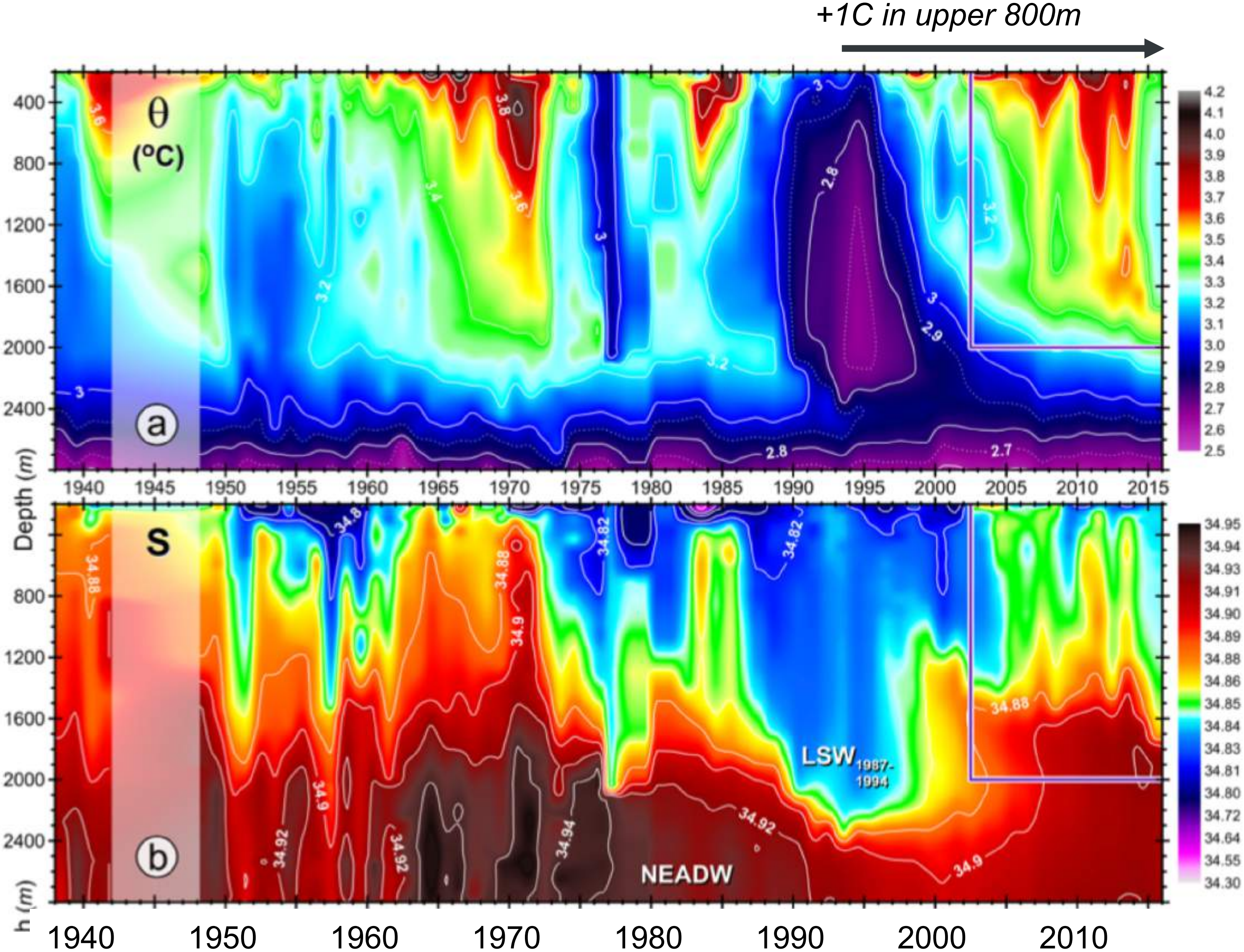
From the late 1990s-2000s the subtropical-origin waters in the North Atlantic subpolar gyre warmed by

Over the same period, remote sensing assets (*e.g.*, ICESat-1, GRACE, Landsat, Radarsat-1/2, Cryosat-2), recorded accelerating *glacier mass loss, surface lowering, and frontal retreat* mainly in the *southeast and northwest sectors* – sectors with marine-terminating glaciers.

Straneo, F., & Heimbach, P. (2013).

Labrador Sea T and S: 1940-2015





Yashayaev, I., & Loder, J. W. (2016)

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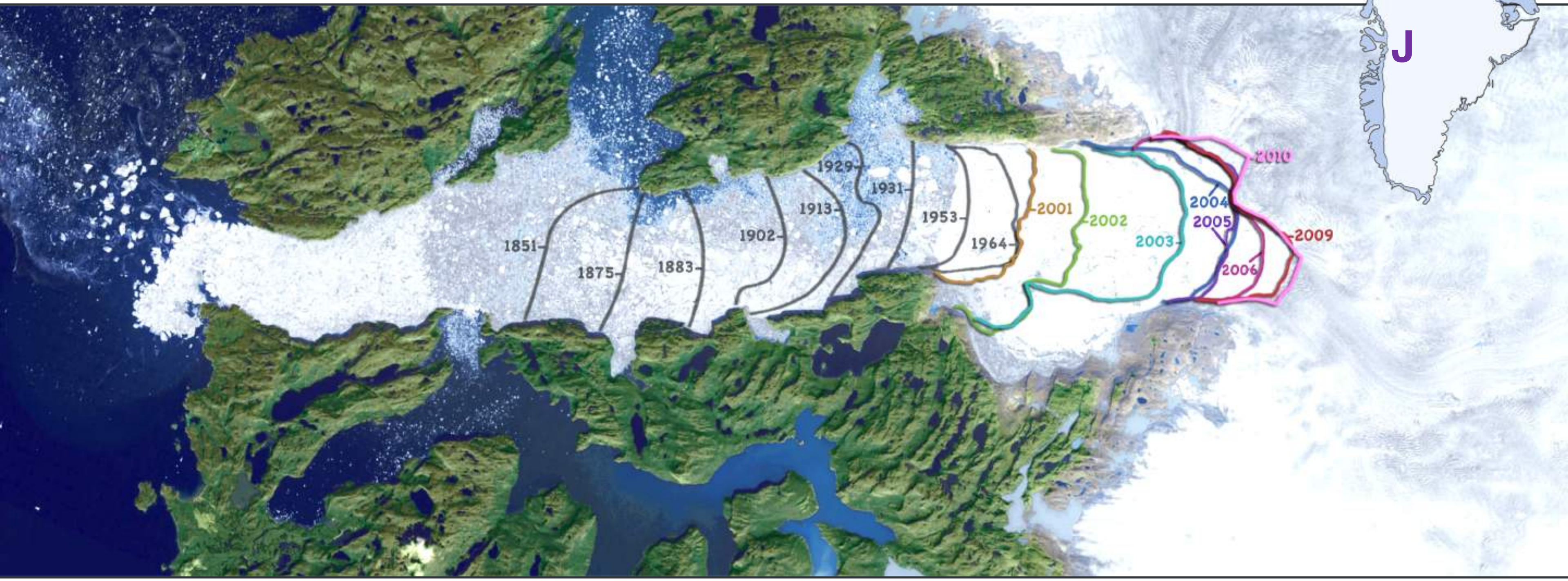
Jakboshavn Isbrae Front Location: 1851-2010

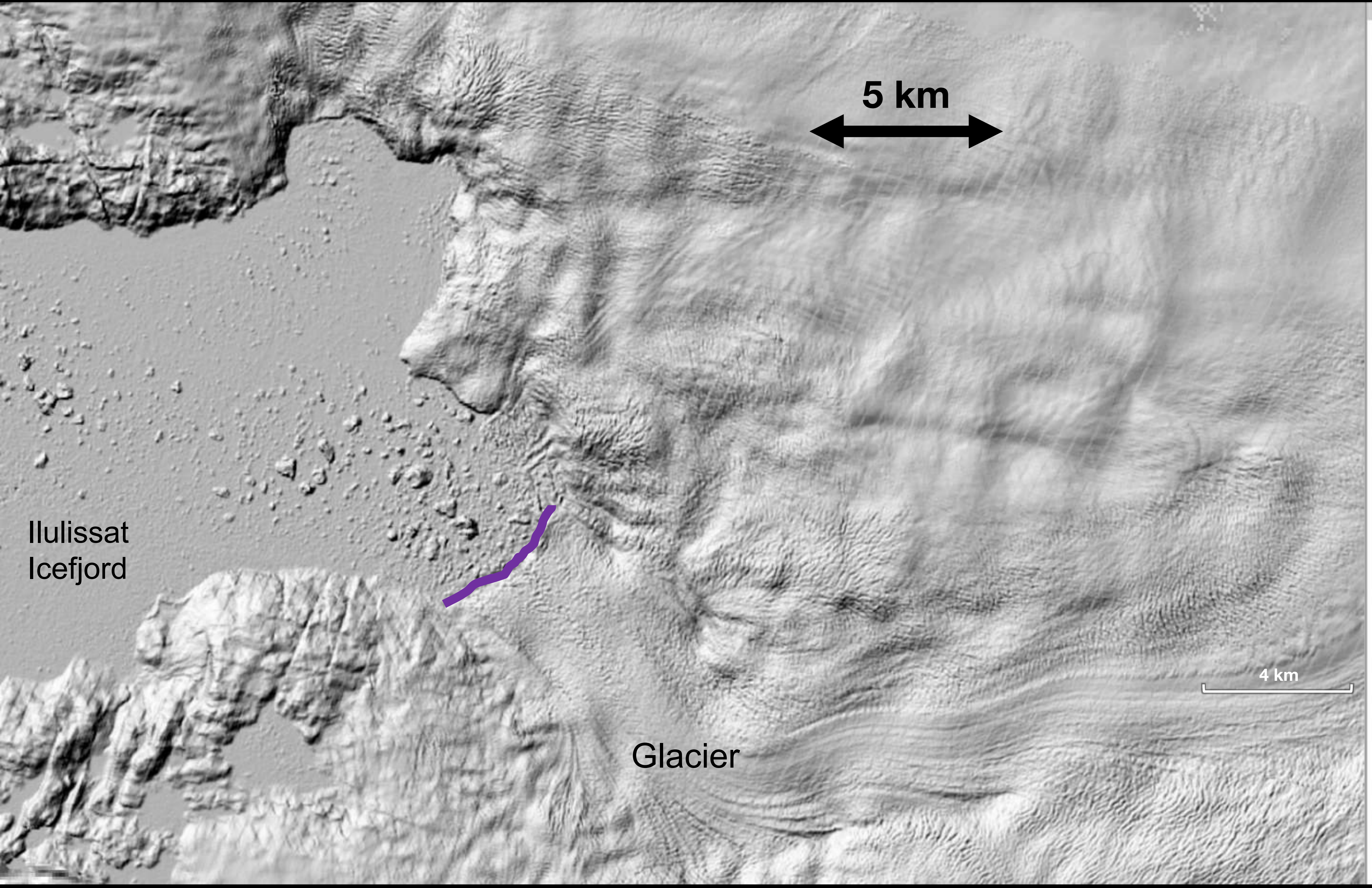


For two decades Jakobshavn Isbrae has shown a persistent pattern of frontal retreat, flow acceleration and thinning.

Between 2003 and 2016, for example, the surface of the lower reaches of the glacier dropped by ~160 m

Jakobshavn Surface Elevation from OMG GLISTIN-A radar

2016



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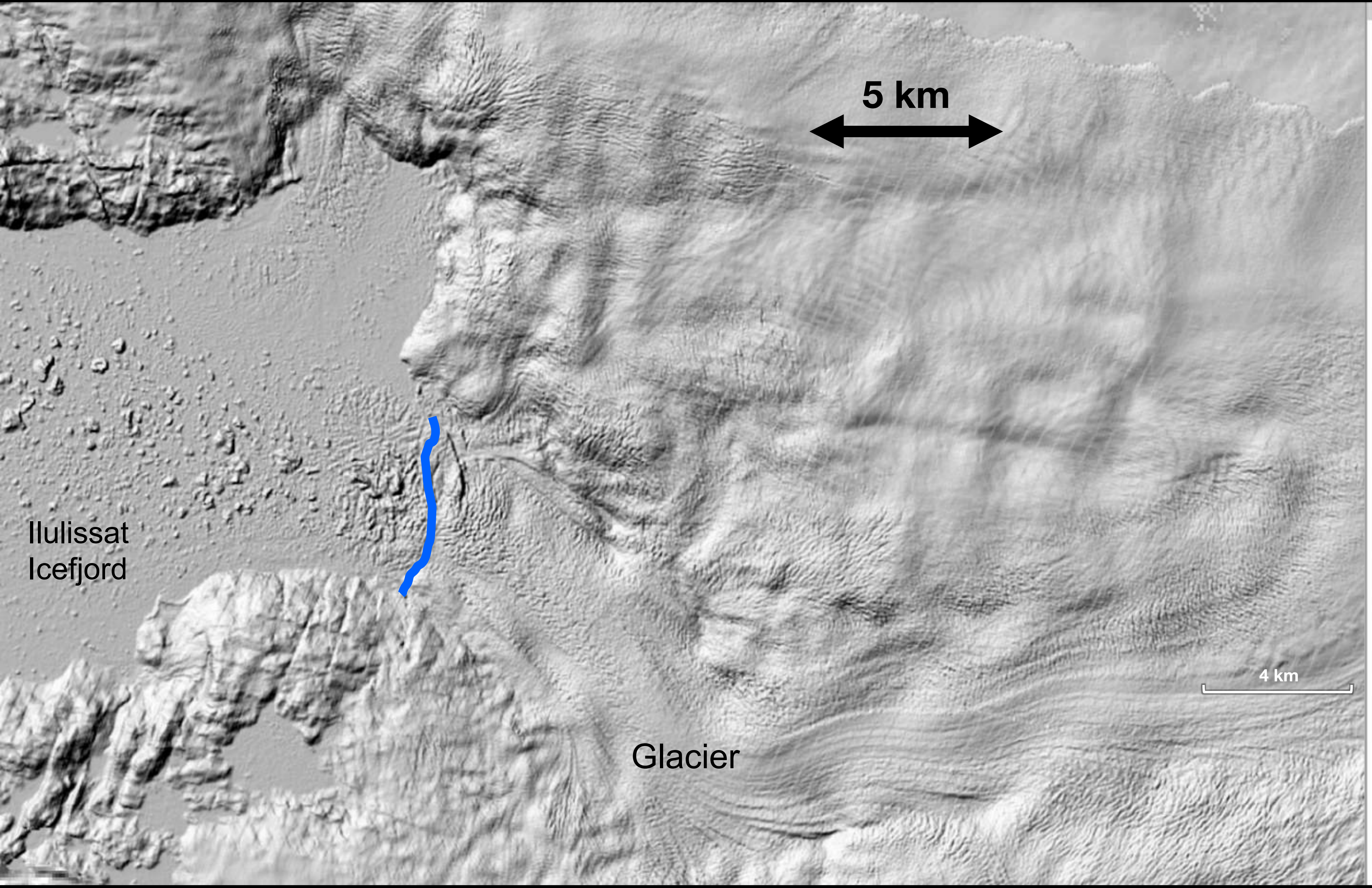
Jakobshavn Surface Elevation from OMG GLISTIN-A radar

2017



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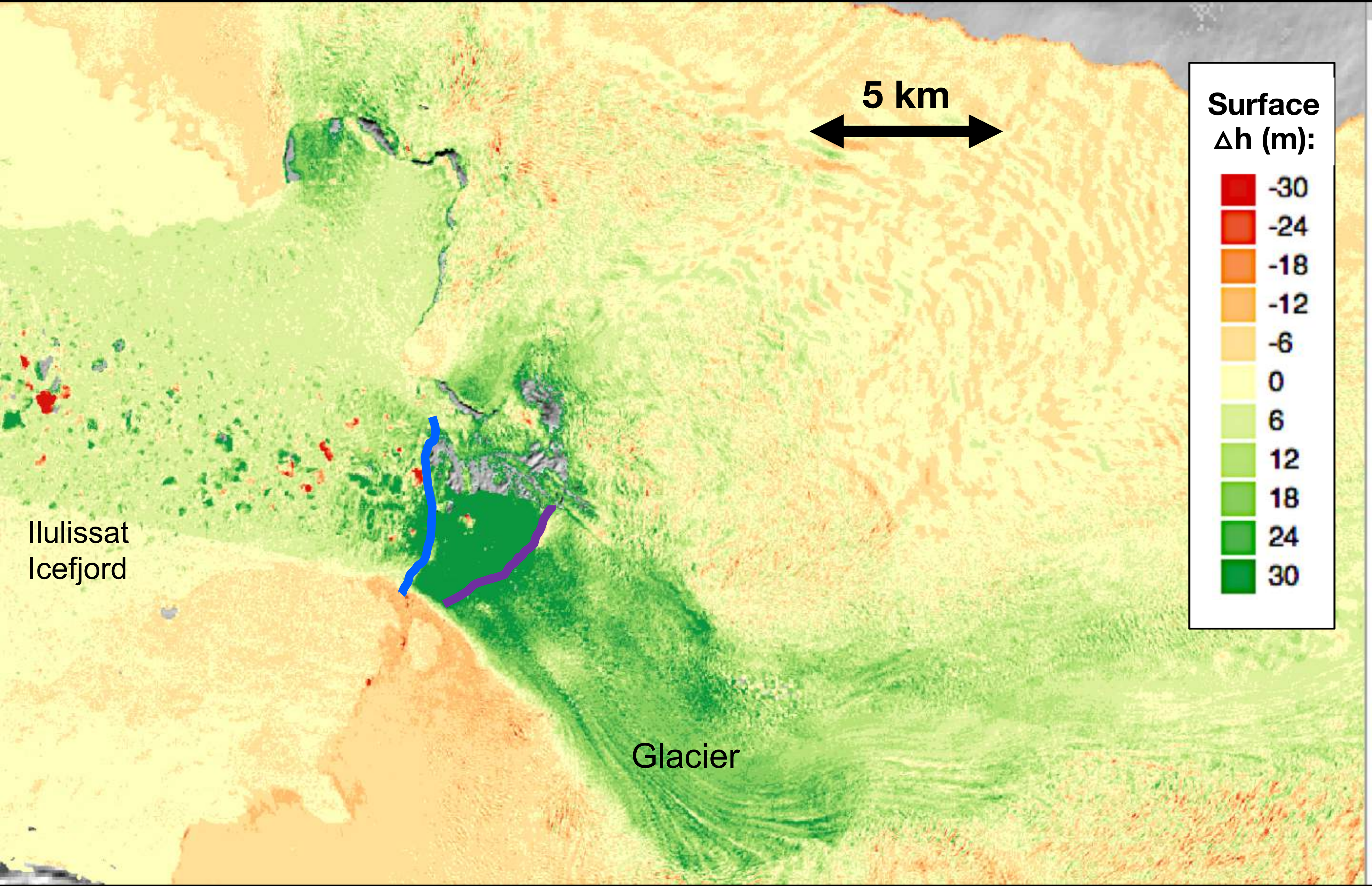
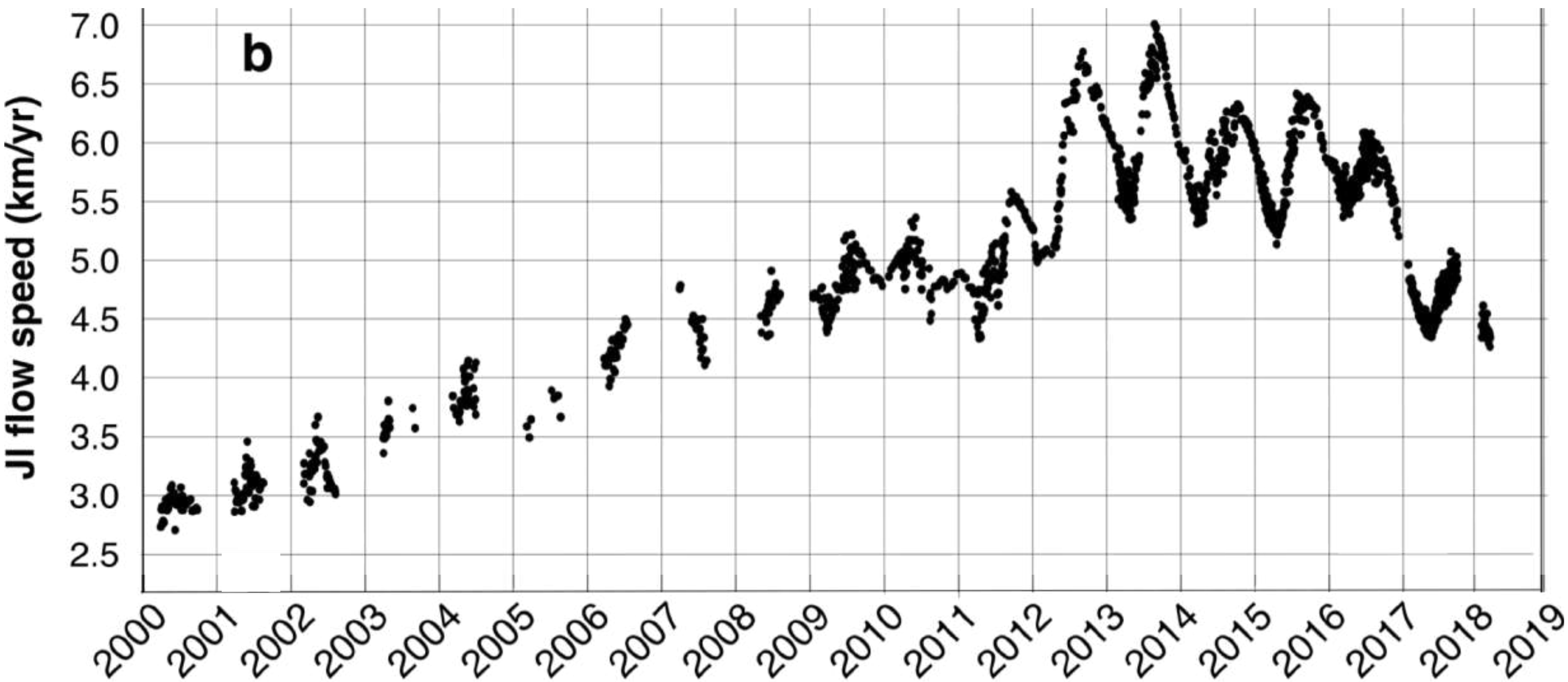
Jakobshavn Surface Elevation Delta from OMG GLISTIN-A radar

2017-2016



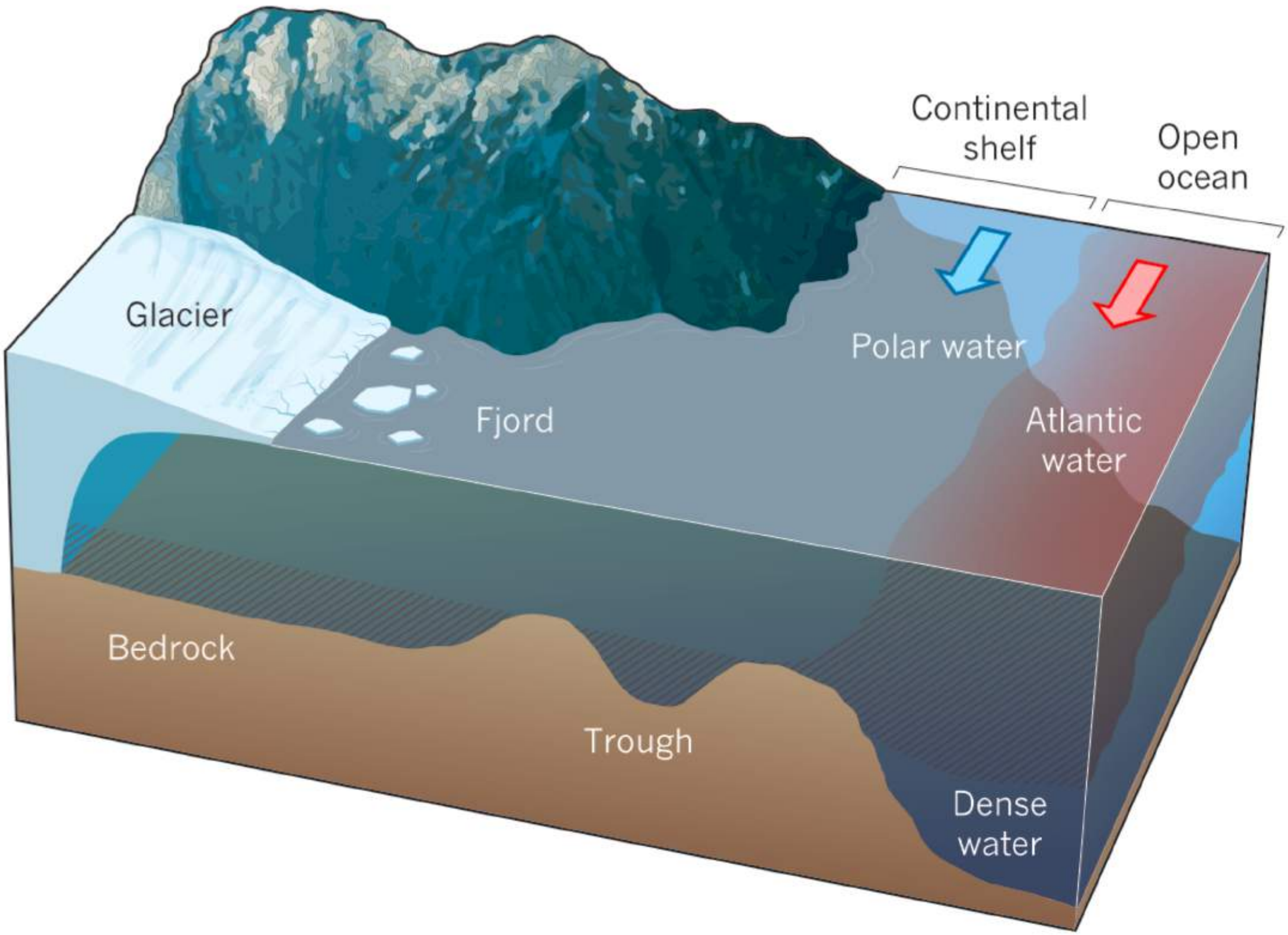
Jakboshavn Flow Speed: 2000-2018



Loss of floating ice shelf

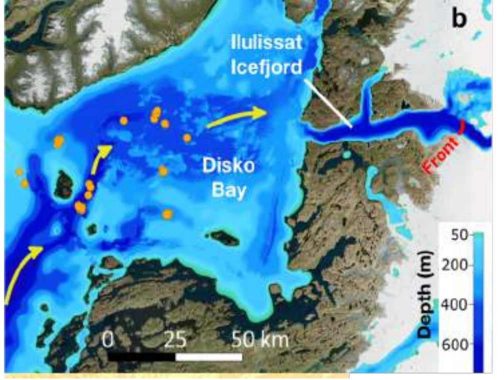
Highest recorded speed

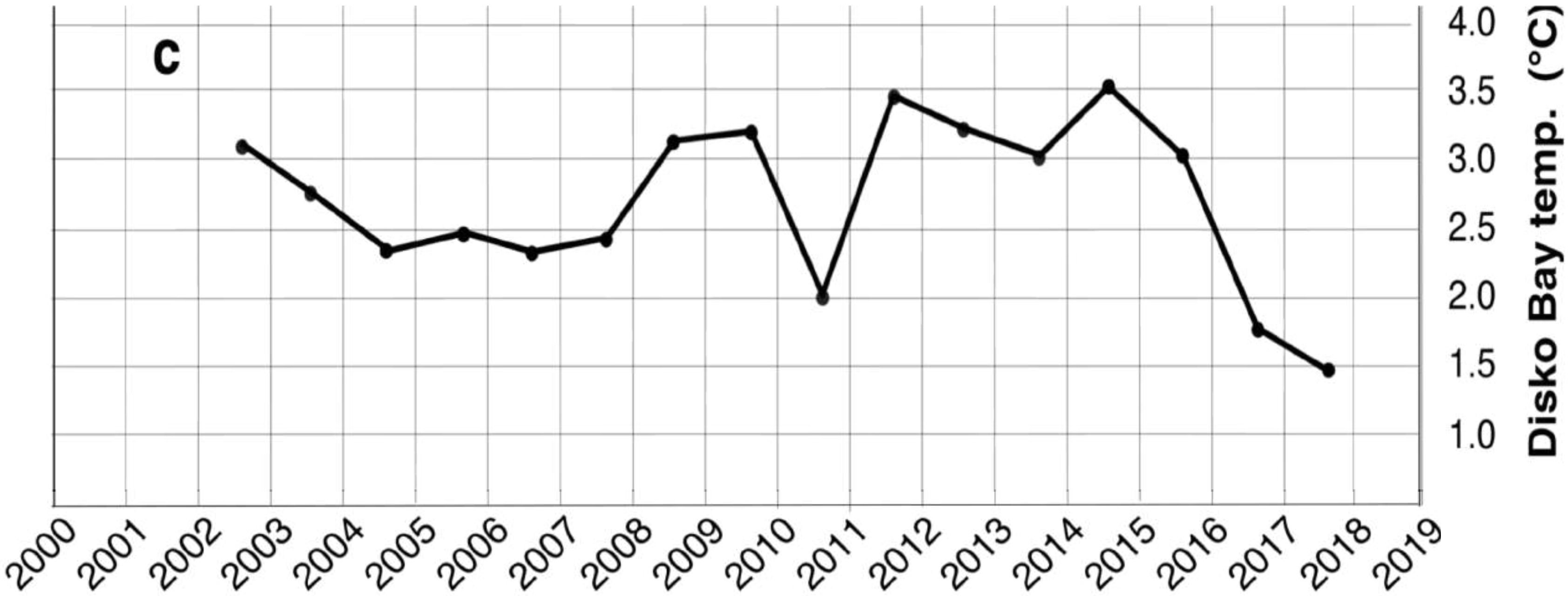
Recent slowdown



Straneo, F., & Heimbach, P. (2013).

Disko Bay 250m Temperatures: 2000-2018





- Similar recent cooling pattern between 200-500m
- -2C from the peak in summer 2014
- Experiments with a plume model showed ocean cooling to be the most important factor modulating subglacial melt rates

1.5C cooling 2015-2016

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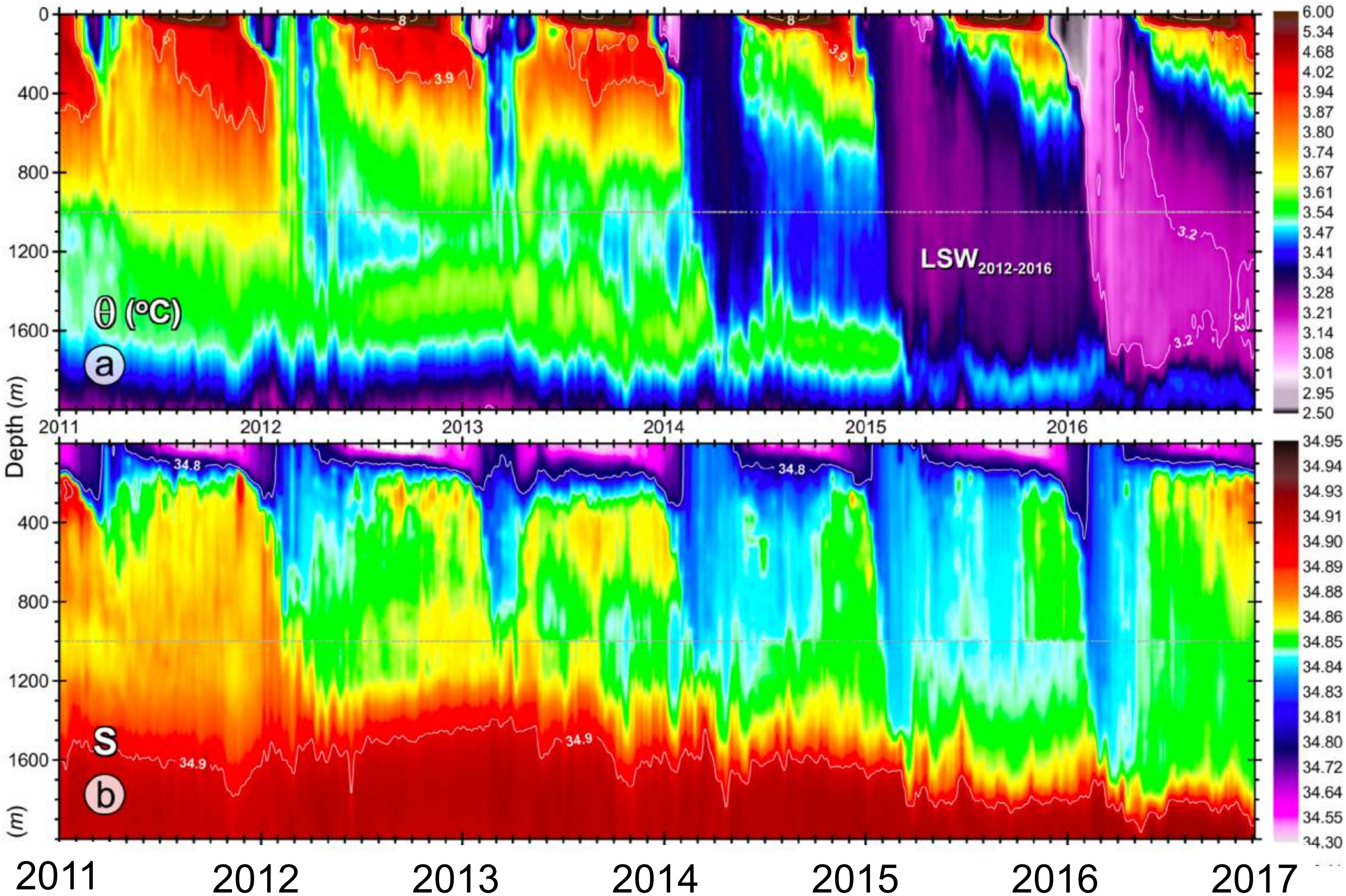
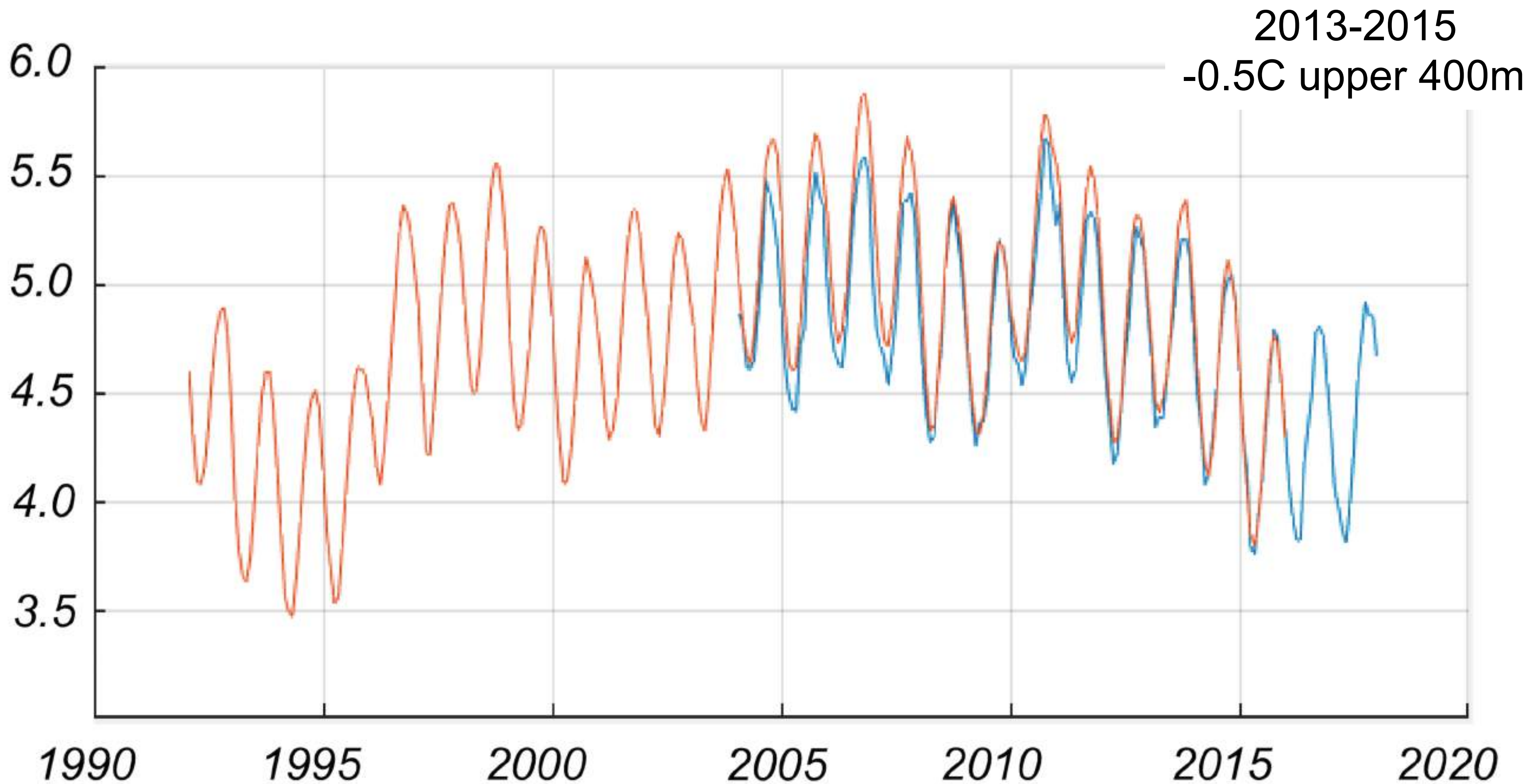
Labrador Sea T and S: 2011-2017

2013-2015
-0.5C upper 400m



Yashayaev, I., & Loder, J. W. (2017).

Labrador Sea T:
ECCO v4 (red), Roemmich-Gilson Argo Hydrography (blue)



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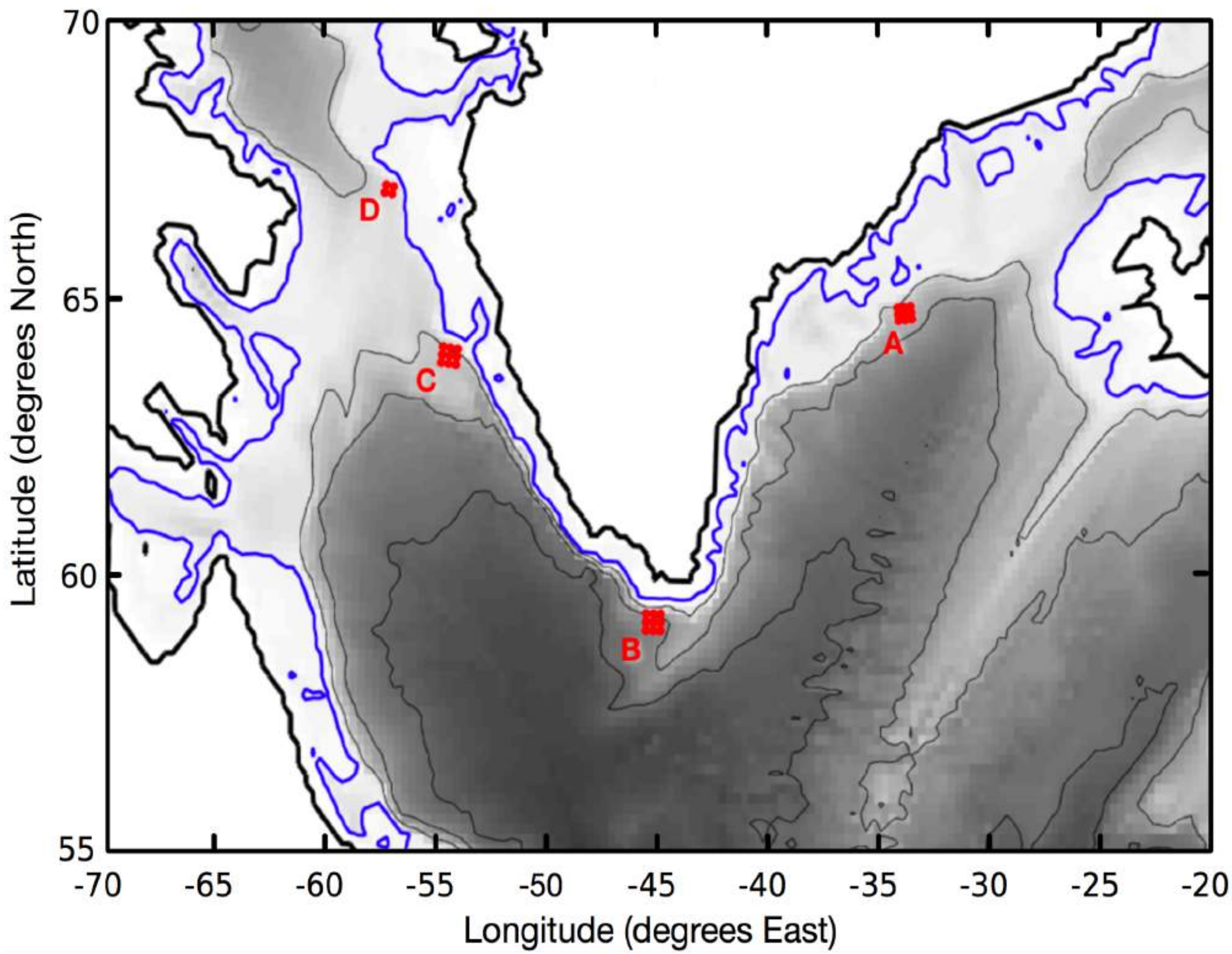
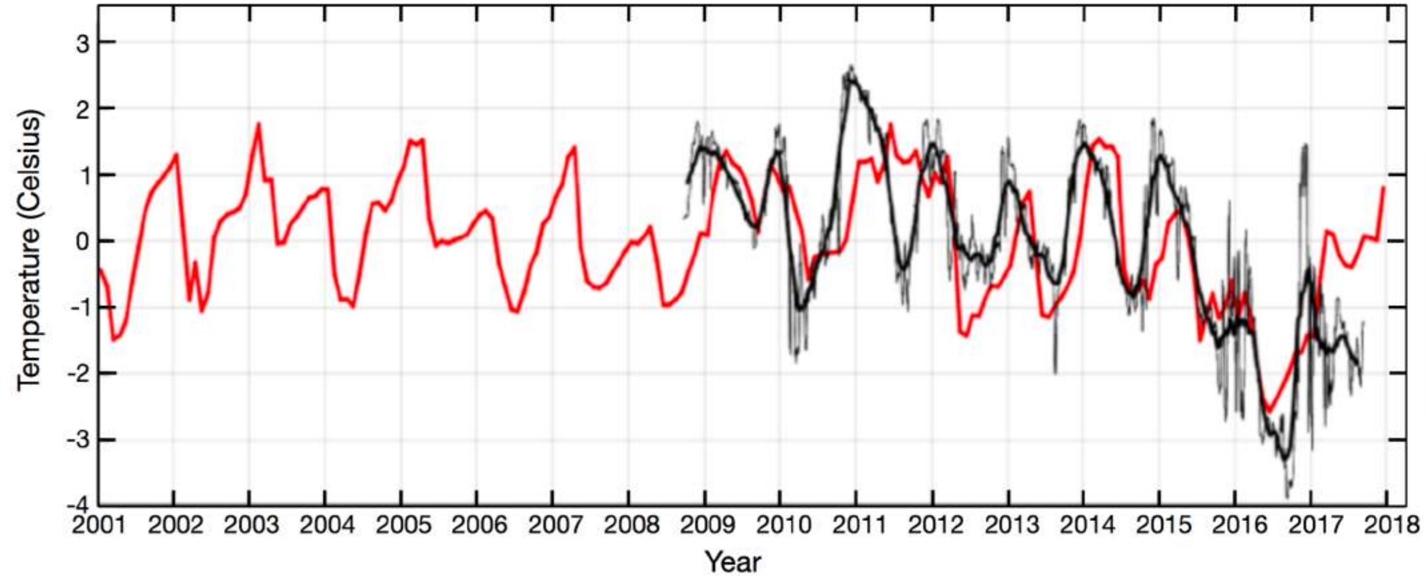
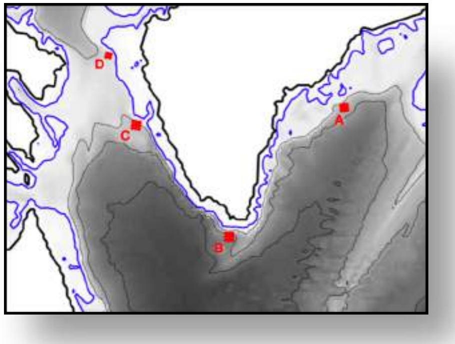


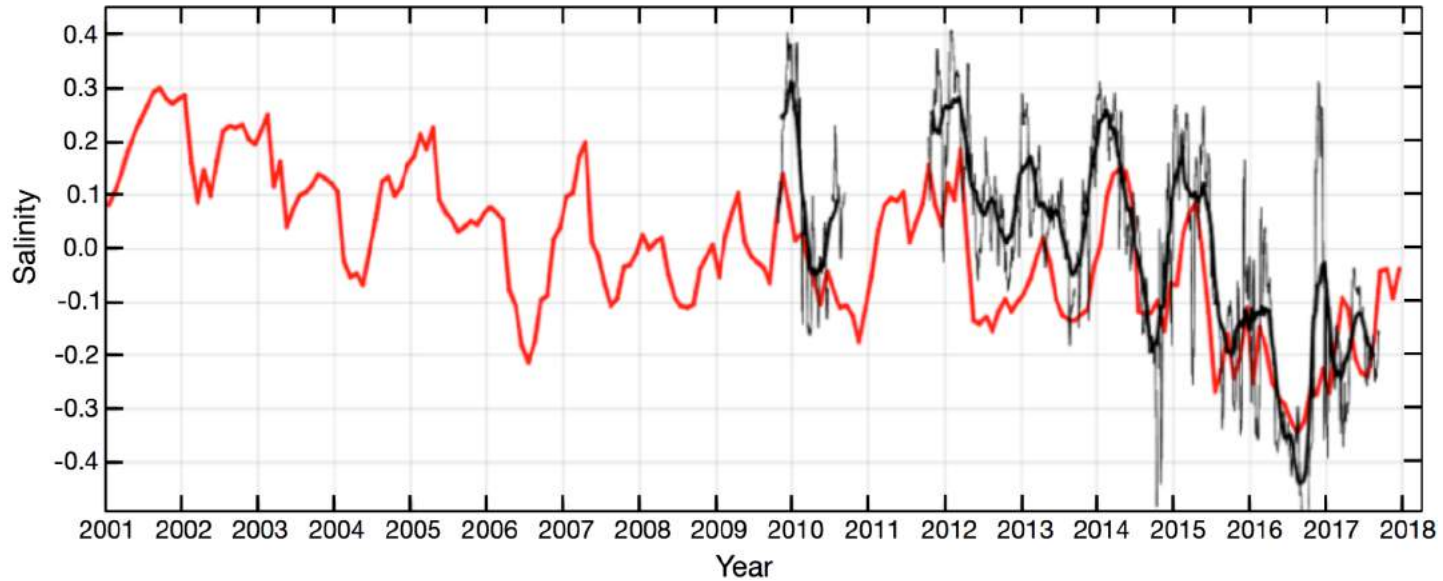
A is is where the warmest Atlantic Water enters the E. Greenland Current
B is southern tip of Greenland, Cape Desolation
C is near bifurcation of the 1000 m isobath
D is near E. Davis Strait Mooring, before deep trough to Disko Bay

All points are within the E and W Greenland Current in the model.

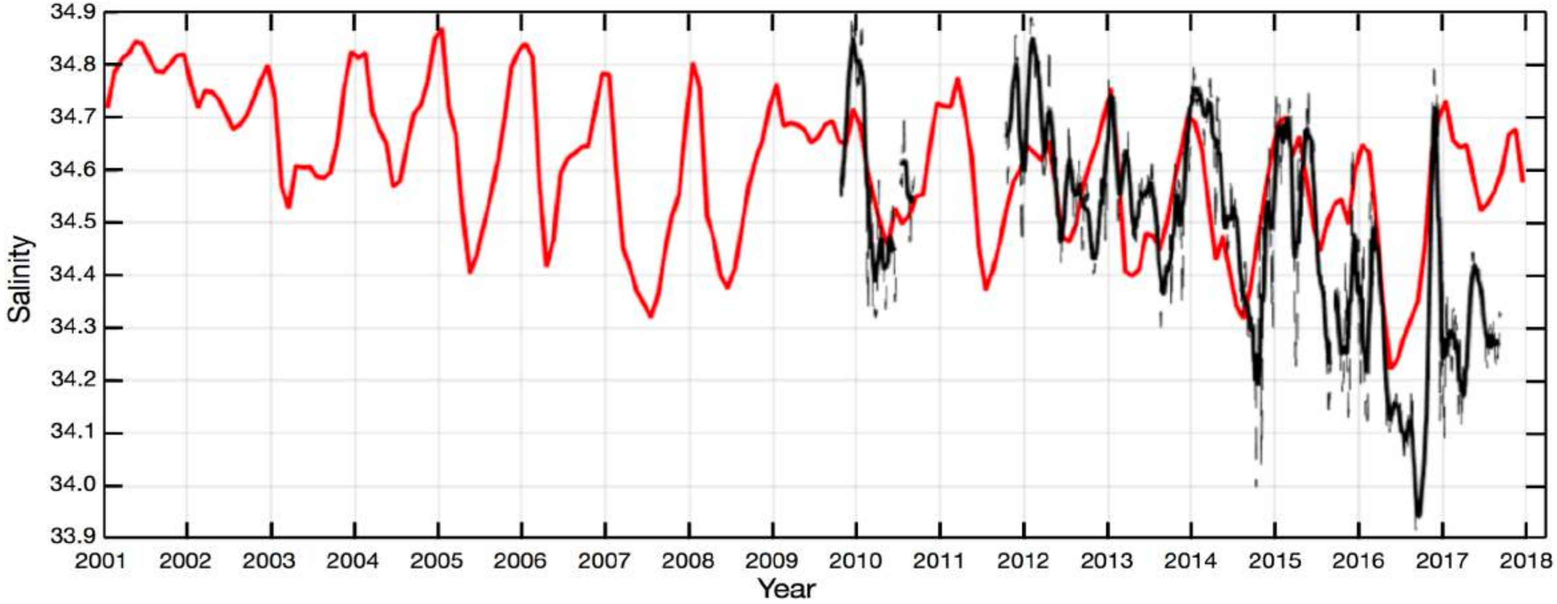
ECCO v5 (red) vs. Mooring (black)
T and S ***anomaly*** at 250m point **D**

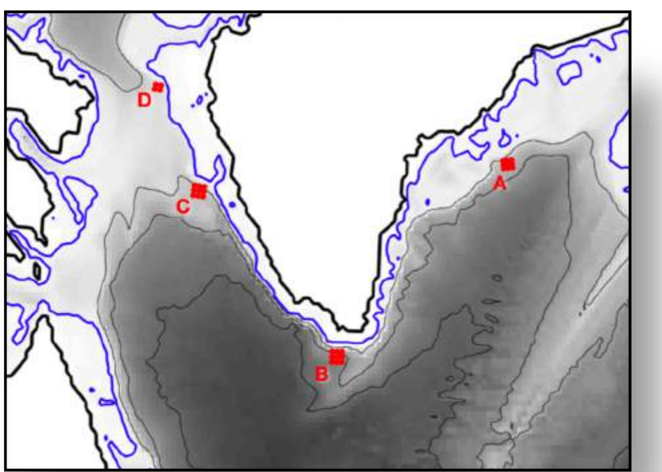






ECCO v5 (point C, red) vs. Mooring (point D, black)
S absolute at 250m





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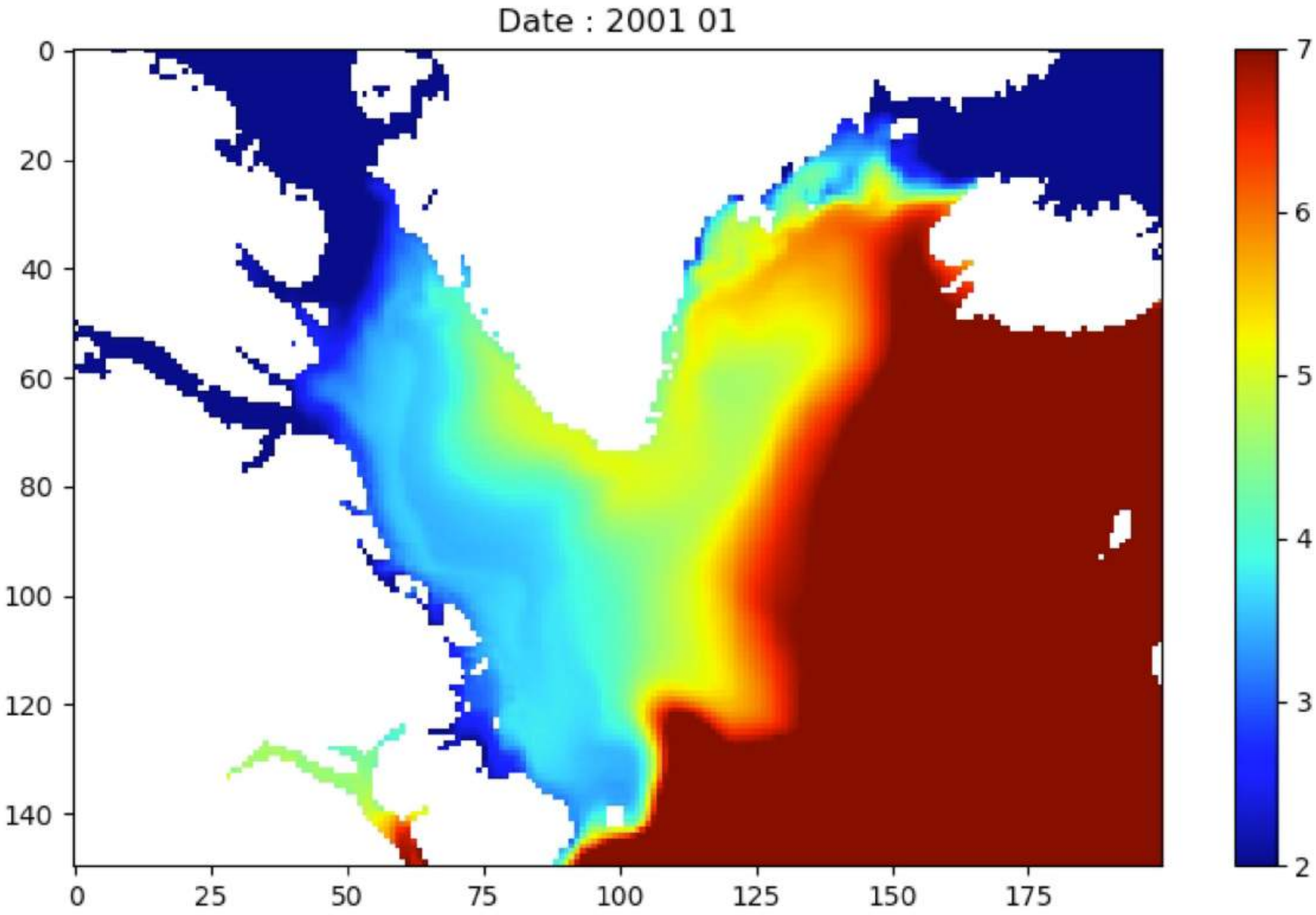
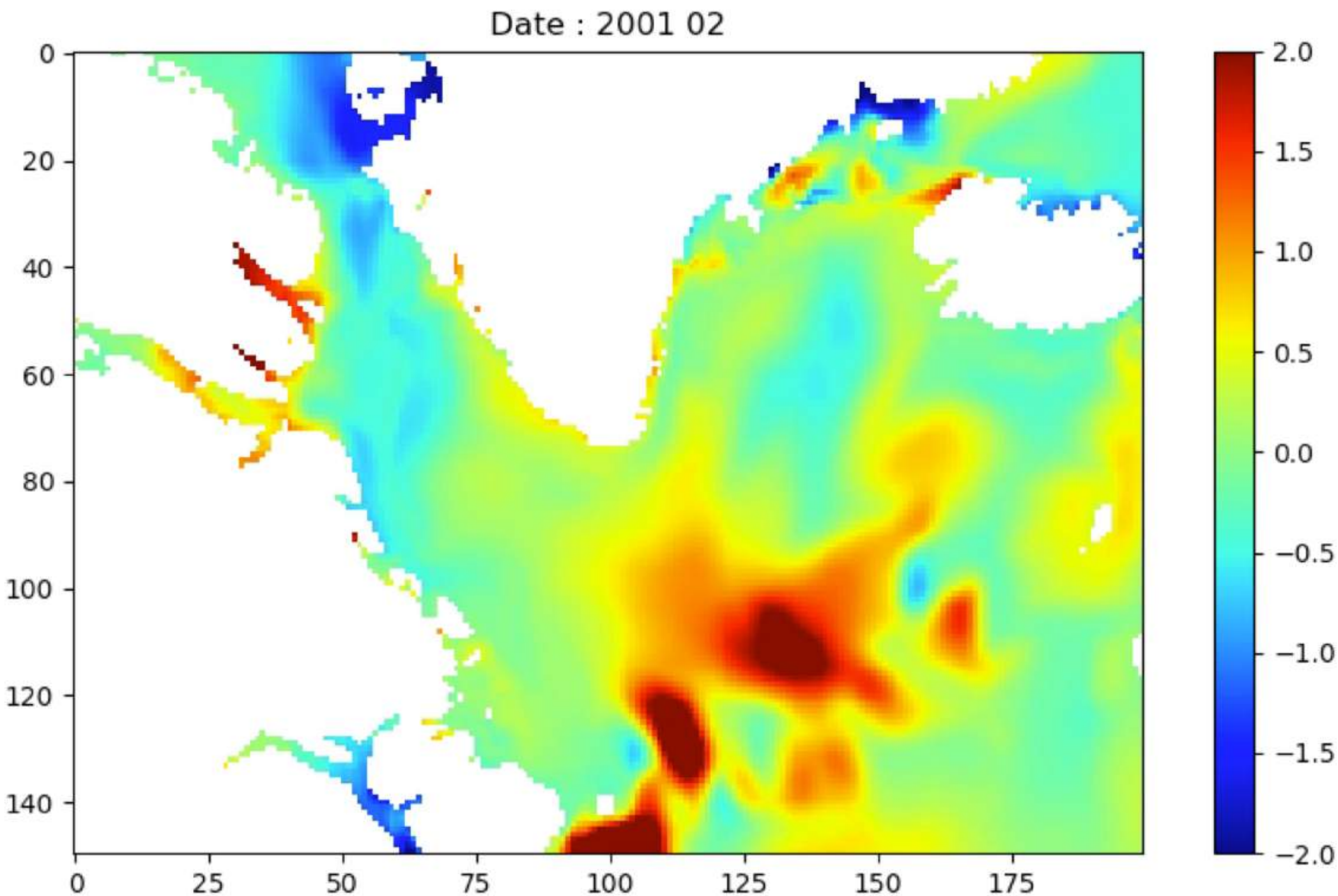
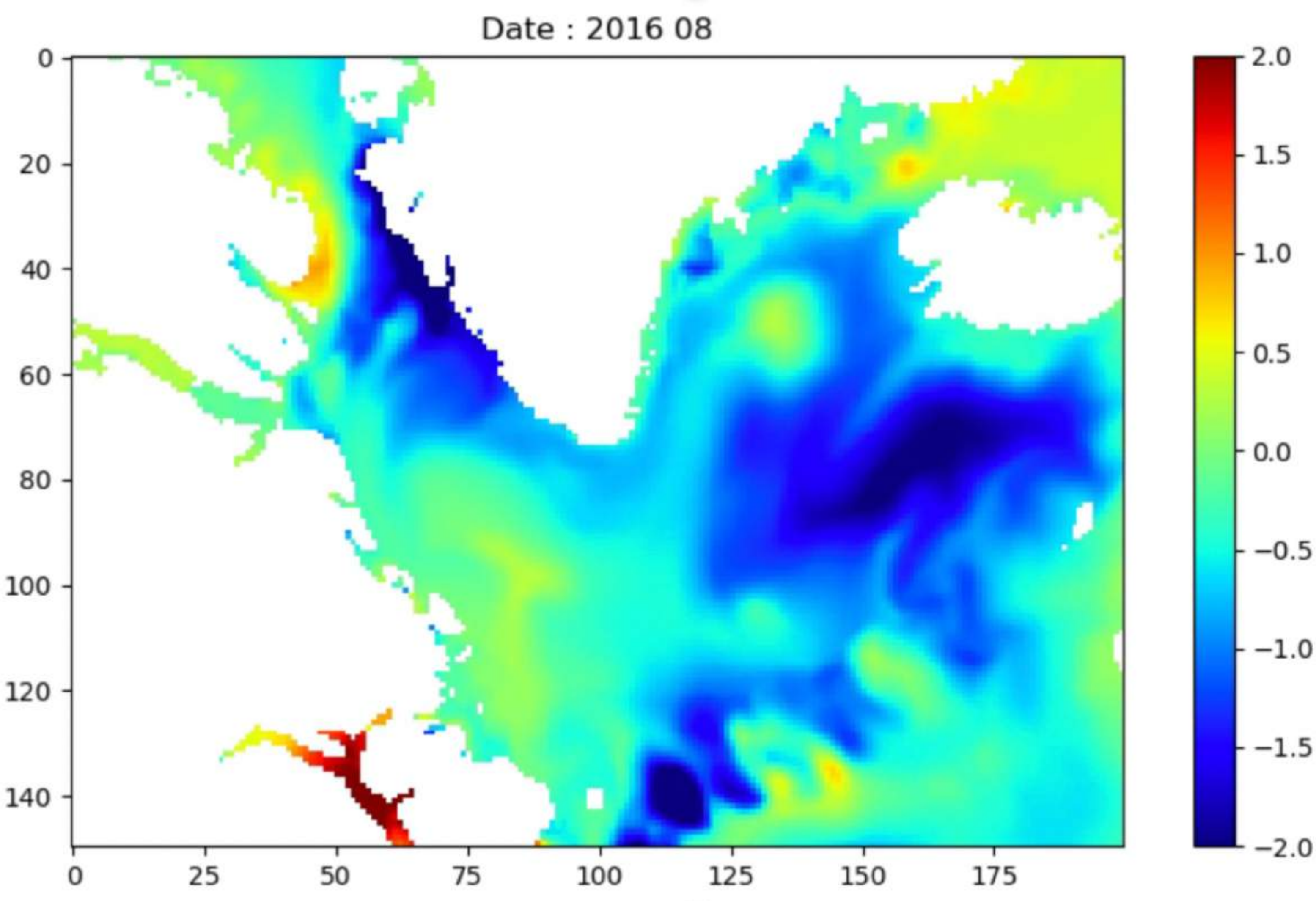
ECCO v5 250 T: 2001-2017



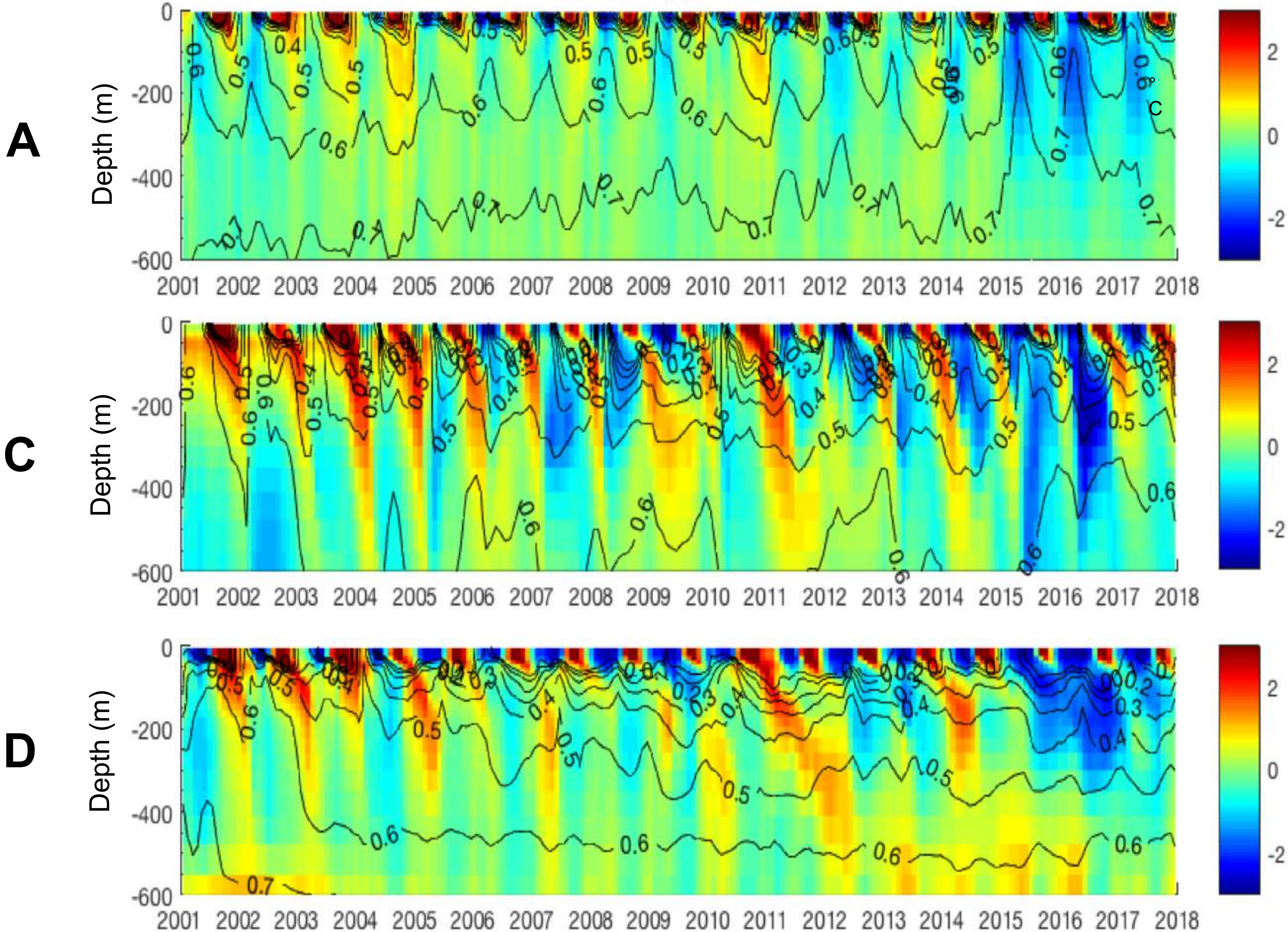
ECCO v5 250 T anomaly: 2001-2017



ECCO v5 250 T anomaly: Summer 2016



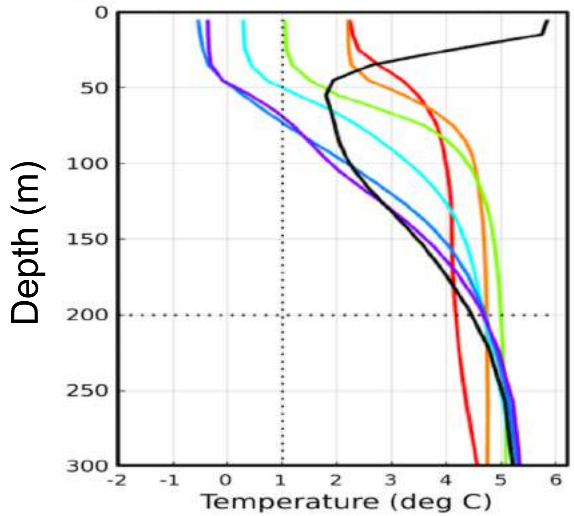
Upper 600 m temperature **anomaly** (A, C, D)



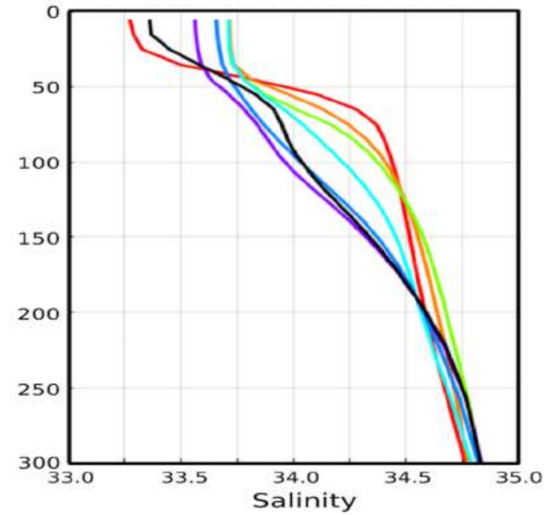
T and S profiles from ECCO at point “C”

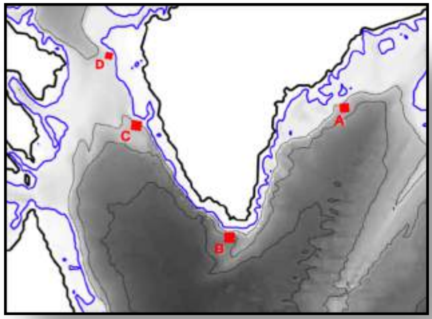
2008-2009

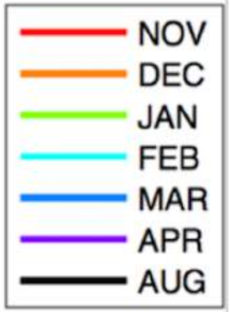
Temperature



Salinity

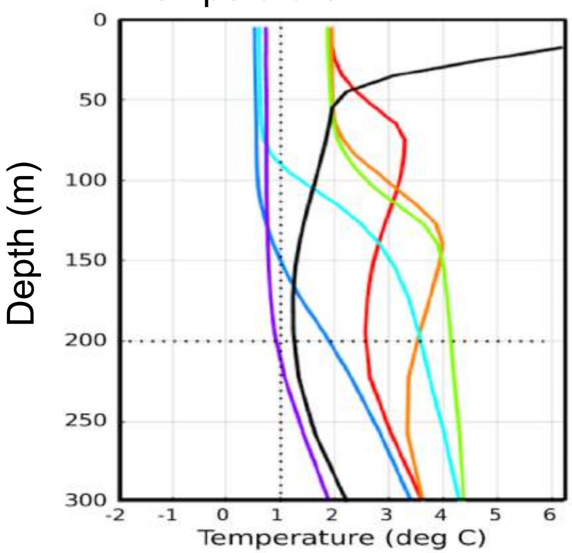




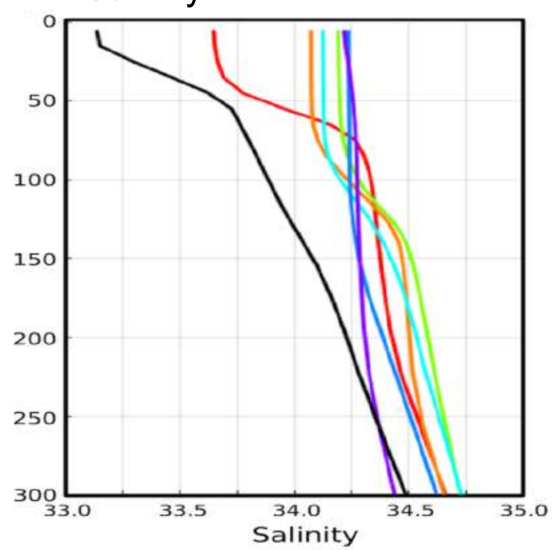


2015-2016

Temperature



Salinity



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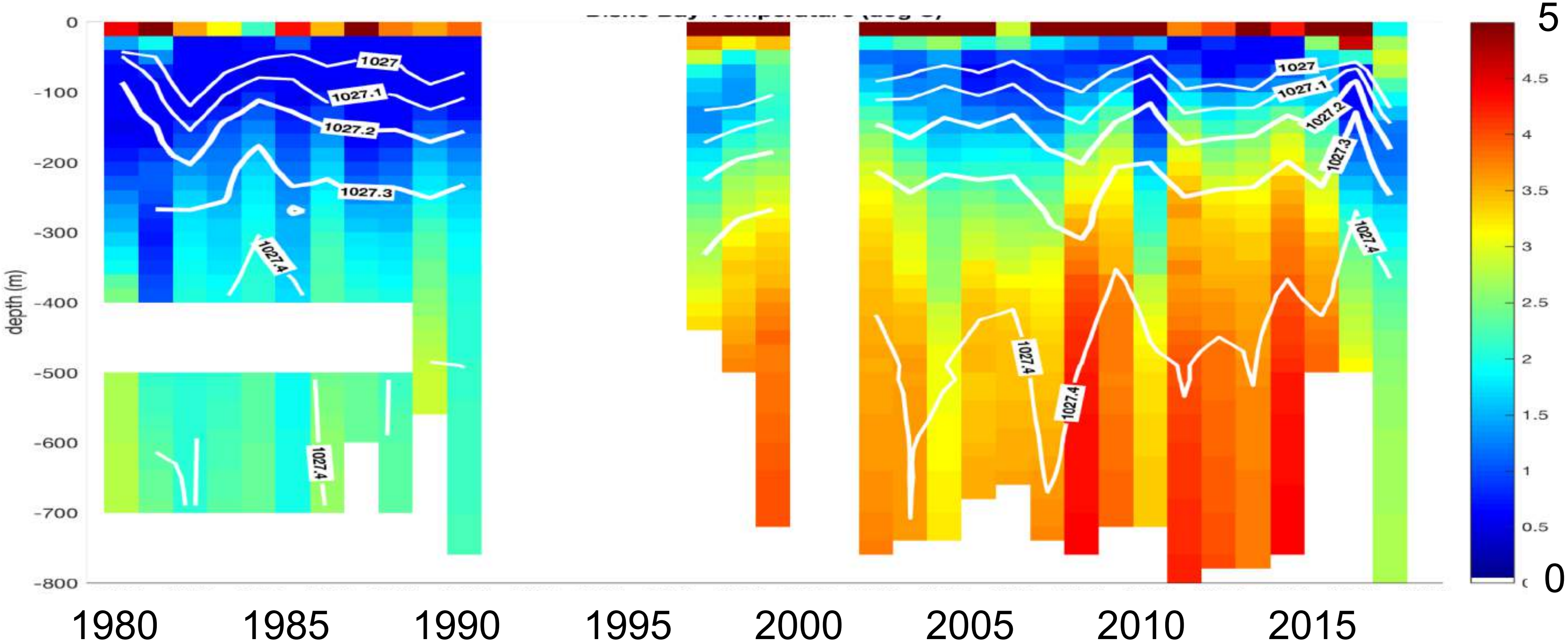
Summary

- We observed an advance, thickening, and slowdown of Jakobshavn Isbrae between 2016-2017, ending a nearly two decade trend of glacier thinning
  - Thickening continues in between 2017-2018
- A concurrent cooling in Disko Bay ocean temperature and fjord plume modelling suggests an ocean role in glacier response via subglacial melting
- ECCO v4 and v5 reproduce basin-scale large hydrographic variability in the subpolar gyre including the 2015/2016 anomalous winter cooling
- ECCO v5 matches the Davis Strait mooring temperature and salinity both at the mooring site (point D) and further upstream
- Analysis of ECCO proved instrumental in showing that the 2014/2015 cooling anomaly was so widespread that temperatures did not fully recover in 2015. Winter 2015/2016 was not anomalous but drove temps lower still, especially along the boundary current along W. Greenland which feeds JKS.

- **The correspondence between ocean-induced melting and Jakobshavn's evolution**
- As in the late 1990s, changes in the ocean emerge as the main influence on the recent slowing and thickening of Jakobshavn Isbrae. Synchronous changes in the other two large glaciers terminating in Ilulissat Icefjord further support the connection between oceanic conditions and glacier dynamics changes over the study period. We investigate those possible links by starting the analyses shortly after the disintegration of the ice shelf in 2003.
- Ocean temperature variability in the fjord is not sufficient alone to infer changes in melting rates [Straneo and Heimbach, 2013]. We therefore calculate ocean-induced melting at the front (Fig. 3a) with an approach that considers subglacial freshwater discharge (mainly runoff of glacier surface meltwater), the depth at which the subglacial discharge emerges at the grounding line, and ocean temperature and density stratification (Methods). These parameters have been shown to control submarine melting rates [Xu et al., 2012; Carroll et al., 2016]. The flux of buoyant, fresh meltwater emerging from beneath the glacier affects the dynamics of the turbulent plumes that modulate the mass and heat exchanges between the ocean and ice (Supplementary Fig. 17) [Jenkins, 2011]. Water properties in the fjord link submarine melting to oceanic forcing while subglacial discharge links submarine melting to atmospheric forcing.
- The variability of the modeled frontal melting rates corresponds well to changes in ice flow speed and thickness, the two main diagnostics of glacier dynamic evolution. Before 2010, average flow speed increased from year to year in a remarkably near-linear manner (Fig. 3b), and glacier thinning rates varied within a relatively narrow range (Fig. 3a). After that year, flow speed and changes in glacier thickness became highly variable, and both agree well with large changes in submarine melting rates. Those changes in submarine melting reflect the interplay between the variability in ocean properties and in subglacial discharge volumes. Especially salient, following a one-year dip in 2010, is the increase in ocean-induced melting in 2011 and 2012 (Fig. 3a) and the concurrent jumps in flow speeds and thinning rates, both the highest recorded for Jakobshavn during the study period (Figs. 3b, 3a, 2, Supplementary Fig. 2). Such high melting rates were the result of higher ocean temperatures (Fig. 3c, Supplementary Fig. 7, Supplementary Fig. 8) coinciding with increased subglacial discharge during those two years (Supplementary Fig. 17). Starting in 2013, volumes of subglacial discharge were lower, which contributed to lower melting rates in 2013 and 2015, corresponding to the slower thinning observed in 2014 and 2016 (Figs. 2; 3a). Most prominently, the sharp drop in ocean temperatures in 2016 and 2017 by 2°C relative to the peak temperature observed in 2014 corresponds to the observed slowing and dramatic thickening of the glacier in 2017 and 2018. The high melting rate in 2014 simulated in our plume model is not reflected in flow acceleration and thinning, which we are unable to explain. Despite this, the correlation coefficient between the time series of normalized surface elevation changes (Supplementary Table 1) and melting rates is 0.67, with a p-value of < 0.02 (Fig. 3a).
- Further compelling evidence of the origin of recent changes is the concurrent slowing and thickening of the other two large glaciers that terminate in Ilulissat Icefjord (Supplementary Fig. 1). The thickening of Jakobshavn Isbrae's Northern Branch in its lower reaches was a few meters between 2016 and 2017, but reached 20 to 25 m between 2017 and 2018 (Supplementary Fig. 4). Avannerleq Ilulissat Glacier, also on the fjord's northern side, thinned by 5 to 7 m between 2016 and 2017 in the areas located ~4 km and farther upstream from the front, where the glacier is less crevassed and surface elevation change is easier to detect. In contrast, between 2017 and 2018 surface elevation was slightly higher or unchanged within measurement uncertainty (Supplementary Fig. 18). Time series of the flow speeds of the three glaciers from 1985 to 2018 (Supplementary Fig. 6) show remarkable similarities. The flow speeds of the three glaciers were relatively stable during the first 15 years of the time series. After that, the flow speeds of all three glaciers started to increase significantly between 1998 and 2000, when warmer waters were observed to arrive in Disko Bay [Holland et al., 2008]. The glaciers started to slow down between 2014 and 2016. Such synchronicity of behavior strongly suggests that both oceanic and atmospheric forcings, which are common to the three glaciers, dominate their evolution over decadal timescales.

Disko Bay Temperatures: 1980-2017



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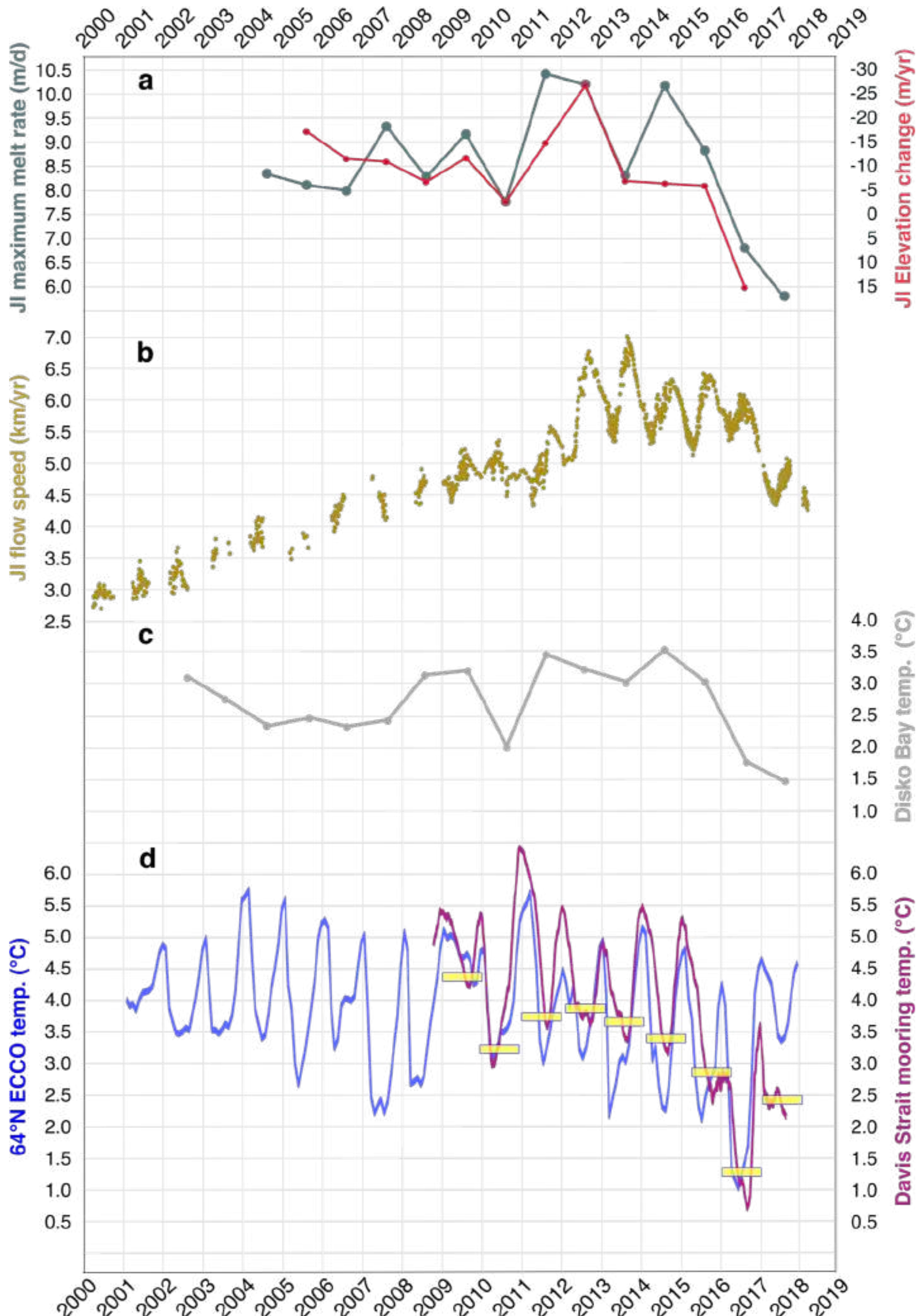
a
b
c
d
JI maximum melt rate (m/d)
JI Elevation change (m/yr)
JI flow speed (km/yr)
Disko Bay temp. (°C)
64°N ECCO temp. (°C)
Davis Strait mooring temp. (°C)
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
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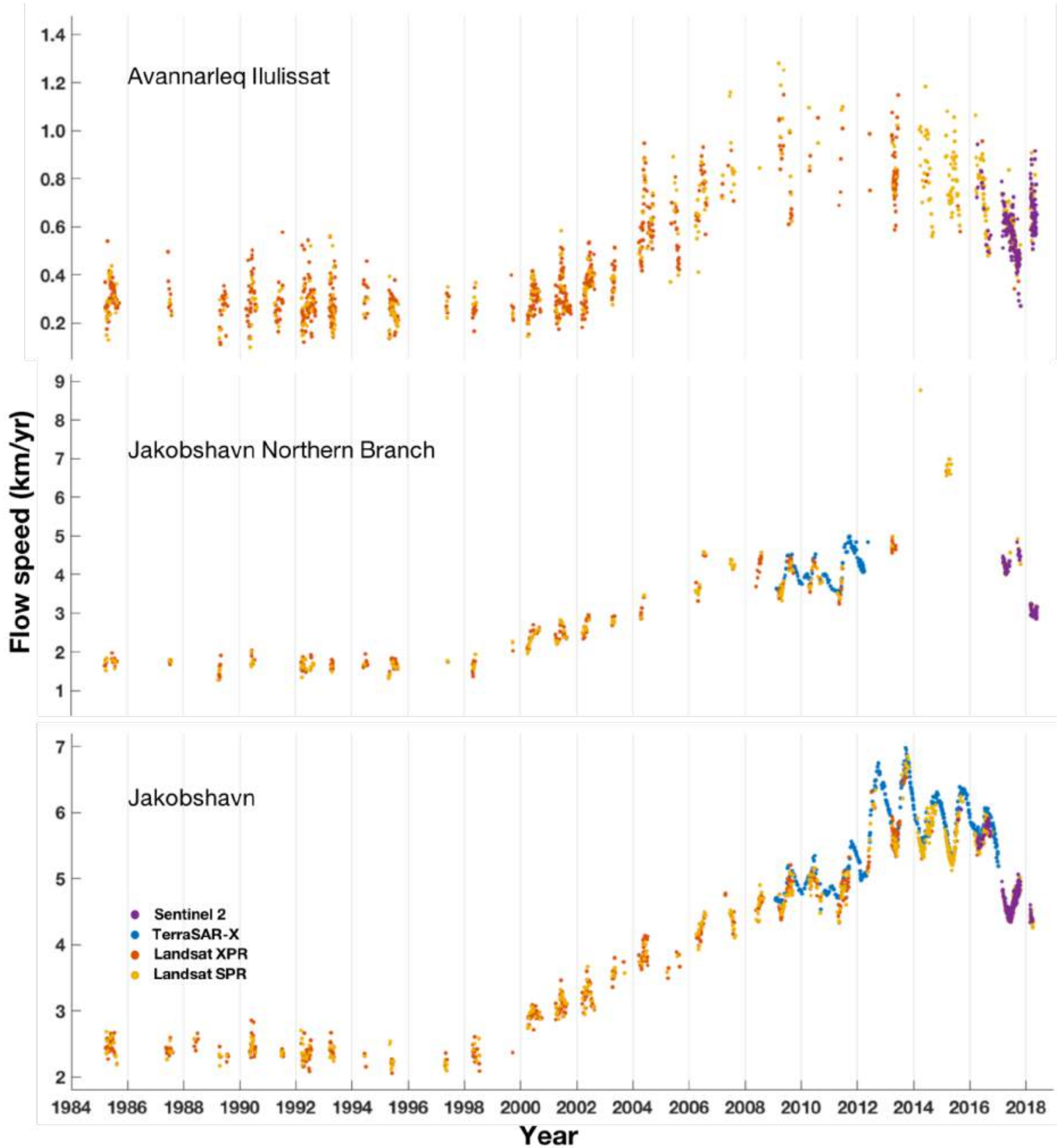
2011
2012
2013
2014
2015
2016
2017
2018
2019



Avannarleq Ilulissat
Jakobshavn Northern Branch
Jakobshavn
Flow speed (km/yr)
Year
Sentinel 2
TerraSAR-X
Landsat XPR
Landsat SPR
1.4
1.2
1.0
0.8
0.6
0.4
0.2
9
8
7
6
5
4
3
2
1
7
6
5
4
3
2
1984
1986
1988
1990
1992
1994
1996
1998
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2002
2004
2006
2008
2010
2012
2014
2016
2018

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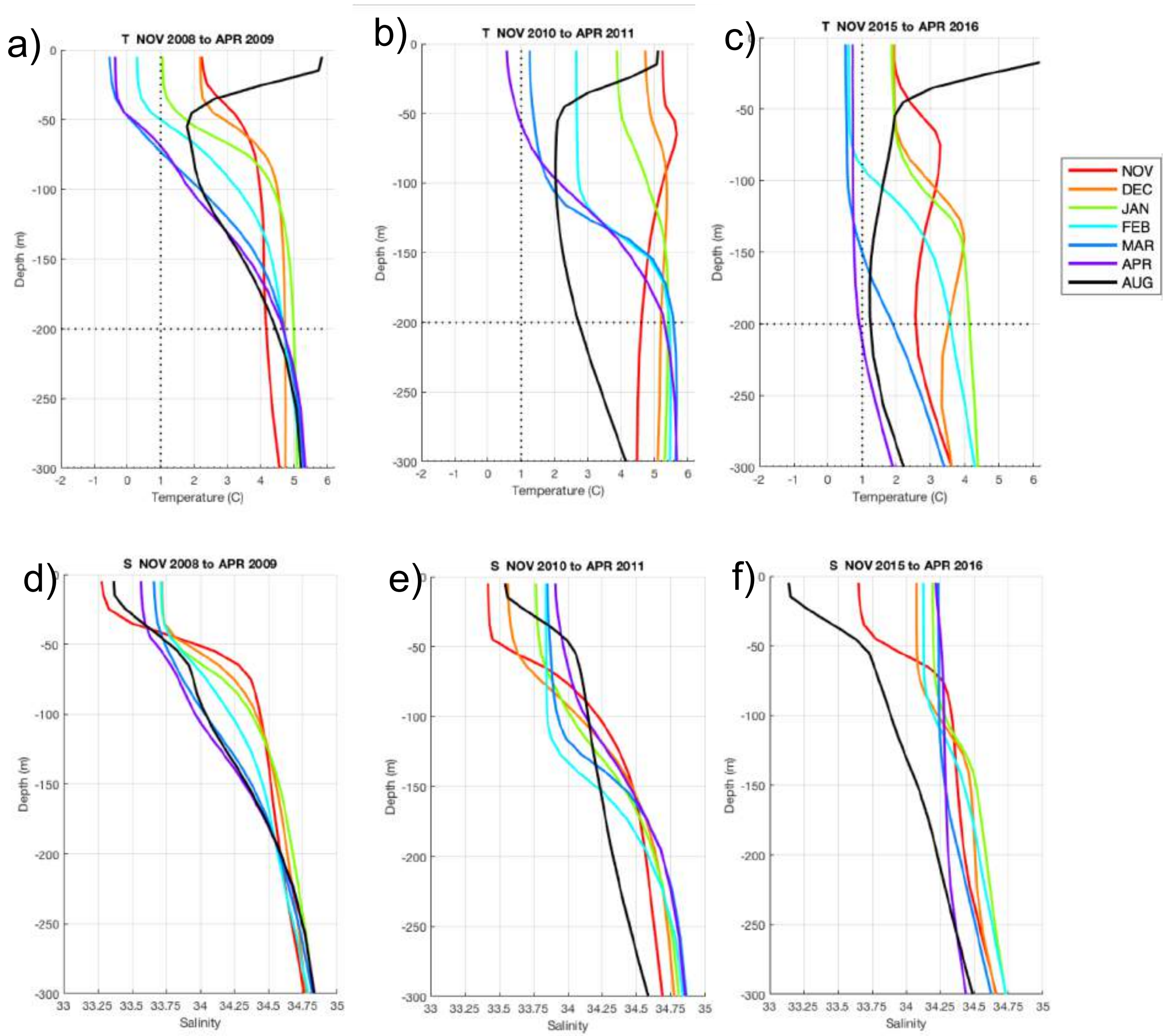

Nov 2011 - Apr 2012: T, S and rho evolution from Nov-April from the ECCO state estimate. Initially greater than average upper ocean stratification (fresher) leading to shallow wintertime convection and mixing. Maximum wintertime mixed layer depth of ~125 m (Jan). Cooling by ~4C in upper 50 m, gradually decreasing to zero at ~200 m, warming of waters below (through the arrival of warmer waters from upstream)

Jakobshavn Isbrae has been the single largest source of mass loss from the Greenland Ice Sheet over the last 20 years. During that time, it has been retreating, accelerating, and thinning. Here we show that since 2016 Jakobshavn has been re-advancing, slowing and thickening. We link these changes to concurrent cooling of ocean waters in Disko Bay that spill over into Ilulissat Icefjord. Ocean temperatures in the Bay's upper 250 m have cooled to levels not seen since the mid 1980s. Observations and modeling trace the origins of this cooling to anomalous wintertime heat loss in the boundary current that circulates around the southern half of Greenland. Longer time series of ocean temperature, subglacial discharge and glacier variability strongly suggest that ocean-induced melting at the front has continued to influence glacier dynamics after the disintegration of its floating tongue in 2003. We conclude that projections of Jakobshavn's future contribution to sea level rise that are based on glacier geometry are insufficient, and that accounting for external forcing is indispensable.

- OMG sees a major cooling event in the deeper waters in Disko Bay from data collected in 2016. Colder through the column than during the last cold water seen in DB seen in early summer 2010. Before that, water this cold was not seen since the late 1980s.
- We know that Atlantic Water flows north through Davis Strait. Examine mooring data in WGC at 200 and 250 m depth (instrument depths changed through the years but difference between the two is actually fairly small.)
- Davis Strait shows very interesting time series. Cooling in 2015 (greatest cooling over past 20ish years) followed by basically no recovery of warm waters through the rest of that year. When winter of 2016 comes, which has about average intensity along the W. Greenland coast, temperatures drop by the amount that they normally do, but this time to ~ 1C.
- What is the cause of this signal?
  - compare with ECCO state estimate.
    - Model Agrees fairly well at DS. Sees 2016 cooling.
    - Has slight bias, probably due to resolution of the narrow BC in this resolution (~11 km in the region)
    - Very good in salinity by the way)
  - Origin could be from BB or could be from further upstream or could be local.
    - If it were purely “local” in the sense of high air-sea heat fluxes in that winter then we would expect the signal to be lost in a matter of a few months when waters upstream arrive. We can show that it originates upstream by analyzing the state estimate
- Trace it further upstream
  - Model state estimate qualitatively agrees with mooring from D to C and less so from C to B.
  - Cold 2015 winter = weak recovery of warm waters in the BC
  - Agreement at C with DS mooring is extremely good despite that it is 300 km upstream
- See clear evidence of cooling in this year
  - 300 km (about 1 month at 10 cm/s)
  - This year also started out cooler than normal by about 0.6 C, this we can attribute to cooling upstream at A. time integral of air-sea heat fluxes near A match upper 600 m temperature anomalies at *A* very closely. This cooling signal is seen at B which we see in the model after about a one month lag.
- 2015 Winter was very severe, leaving the waters in the BC in the SPG and upstream of A by about ~0.*5* degrees colder than normal. Less heat survives on the BC by the time winter comes at C. When 2016 winter begins, weaker than normal stratification, convection to 220 m, August temperatures 1°C, which is what is seen in Disko.
  - Match is not perfect