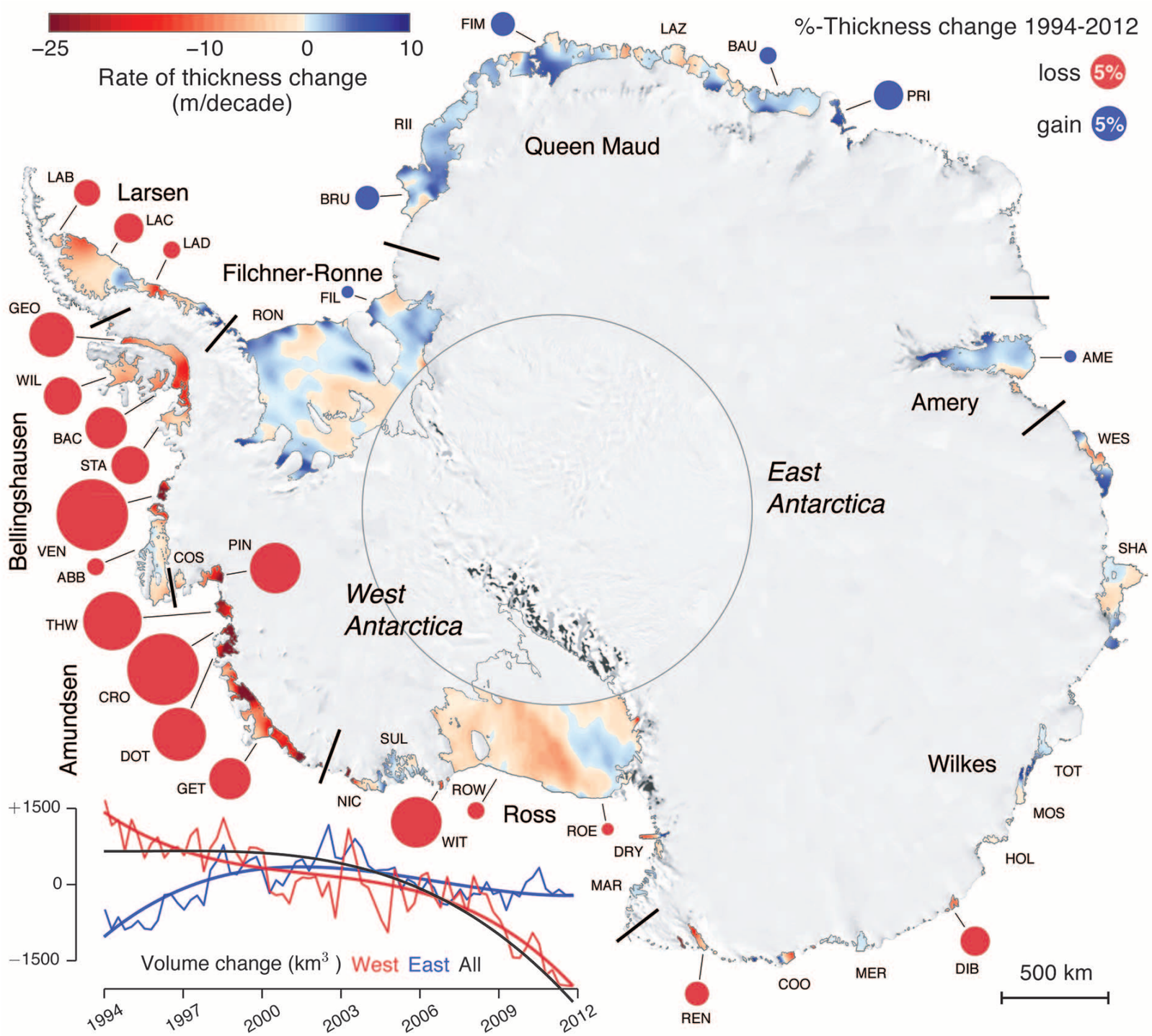
Ice Shelves: Interactions with the Ocean

Ice and the Ocean

Ice shelves in Antarctica and Greenland are being melted from below/the side by warm ocean water (thermodynamic influence)



Paolo et al. 2015

Ice Shelves and the Ocean

- **The ocean also influences ice shelves mechanically through**
  - **Tides**
  - **Waves**
  - **Sea ice/melange**

ARTICLE

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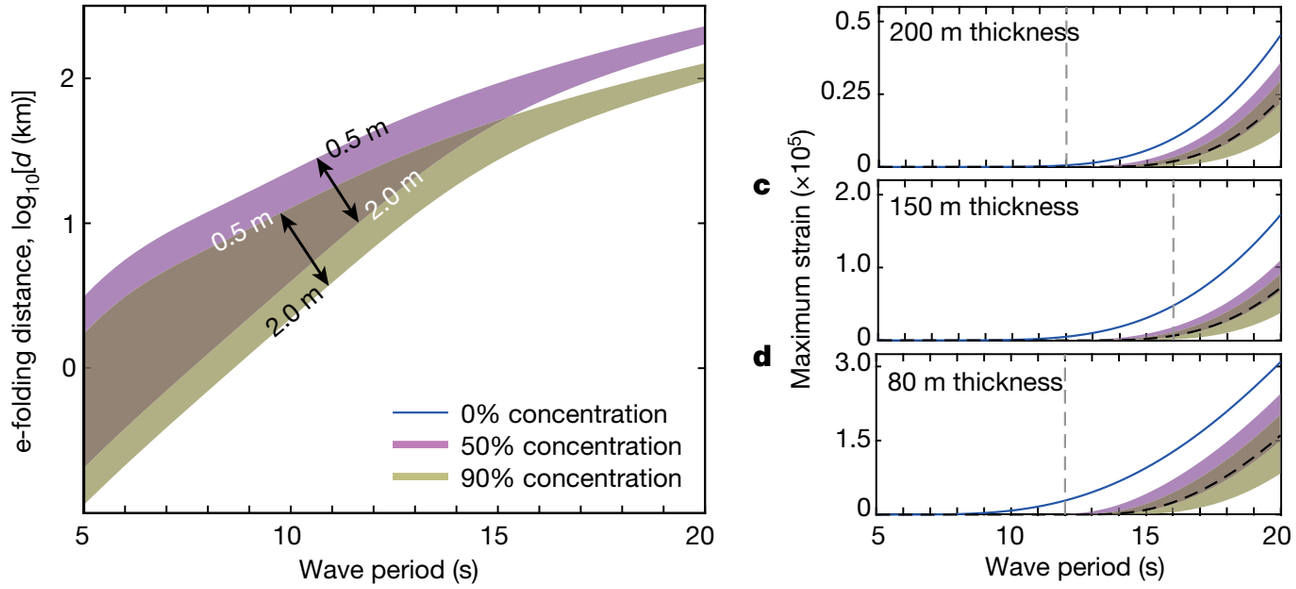
Antarctic ice shelf disintegration triggered by sea ice loss and ocean swell

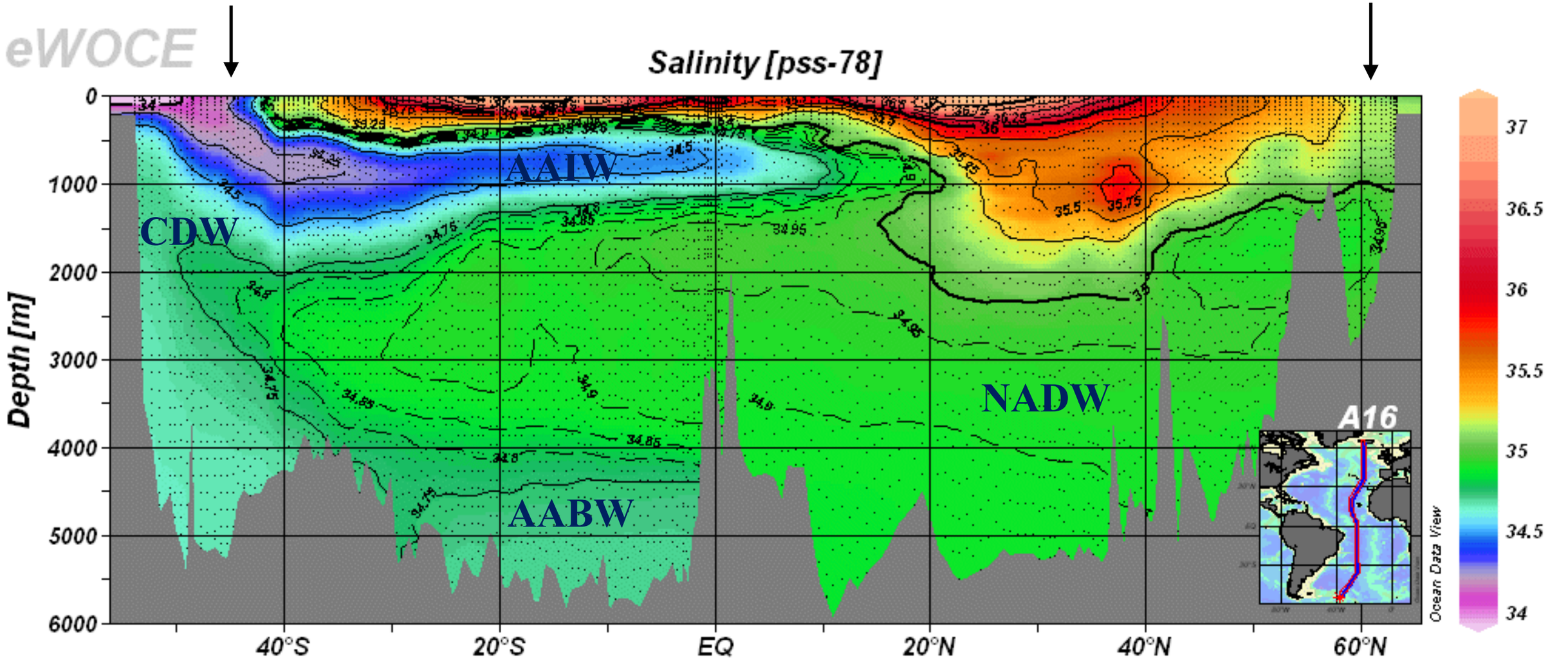
Robert A. Massom[1,2*], Theodore A. Scambos[3], Luke G. Bennetts[4], Phillip Reid[2,5], Vernon A. Squire[6] & Sharon E. Stammerjohn[7]



How ice sheets influence the ocean circulation

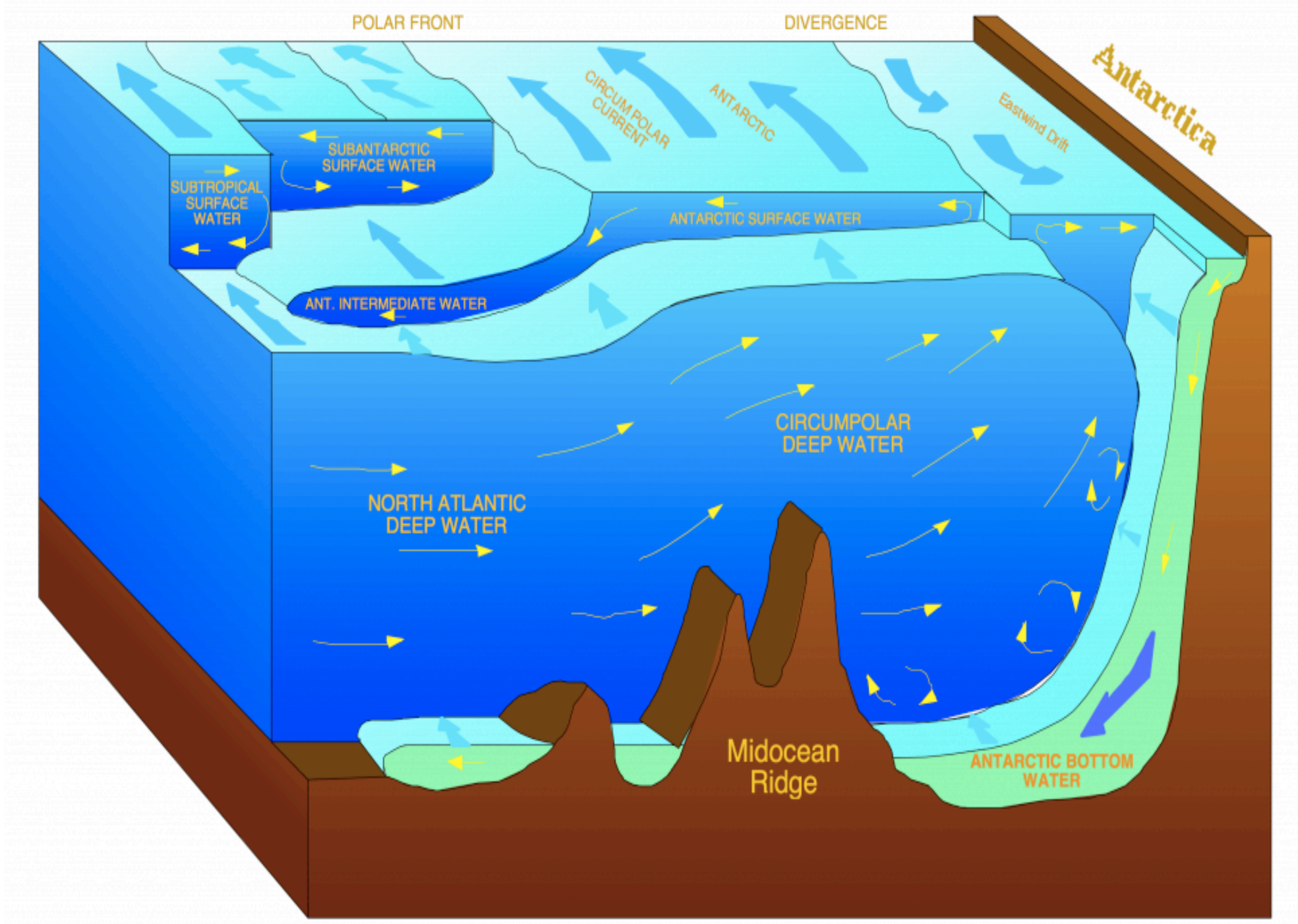
Sea ice formation and ice shelf melt around Antarctica

Sea ice formation and glacier melt around Greenland



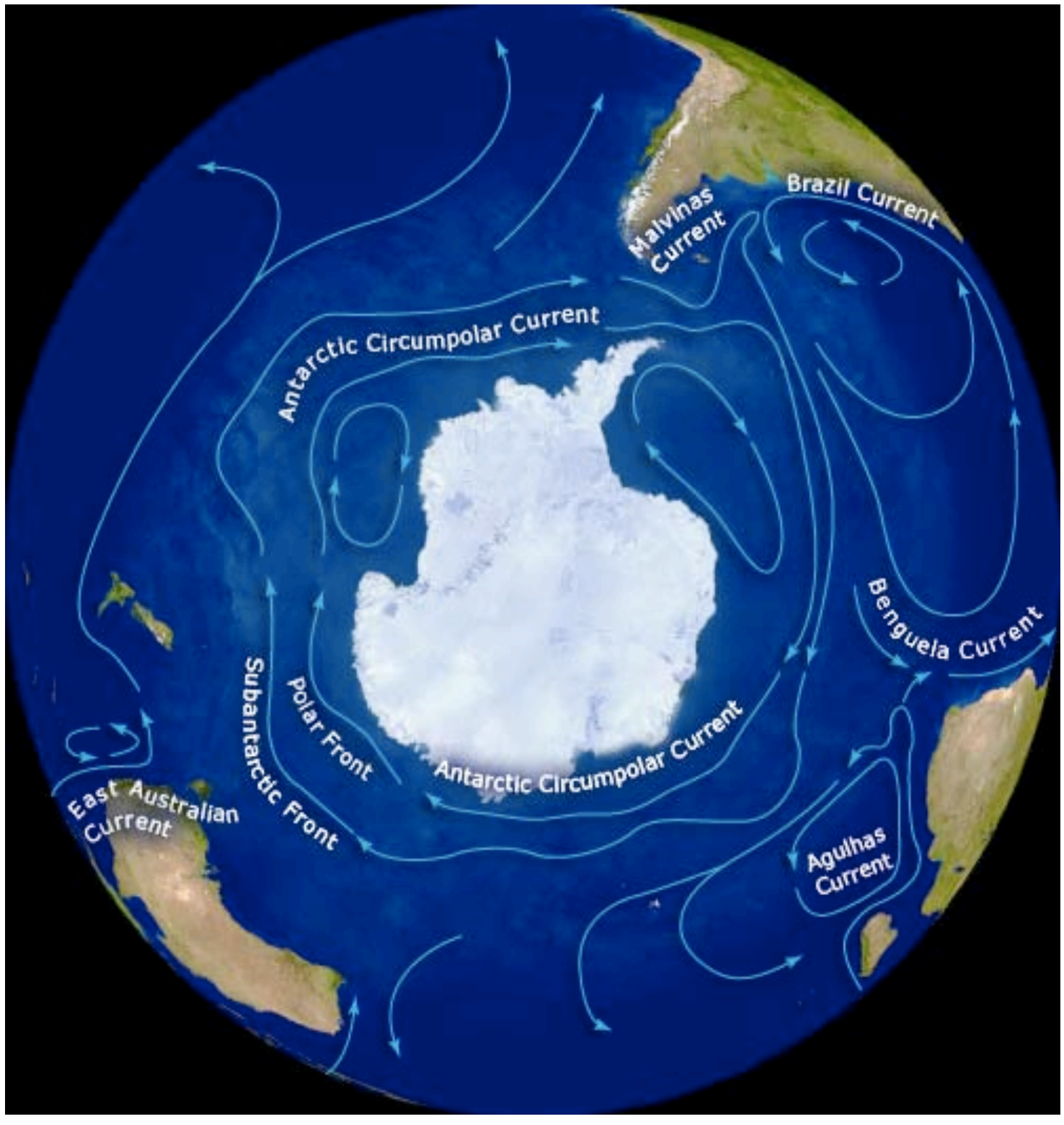
The ice sheets play a major role in setting the properties of pretty much all water below the top few hundred meters of the ocean

The global ocean overturning circulation



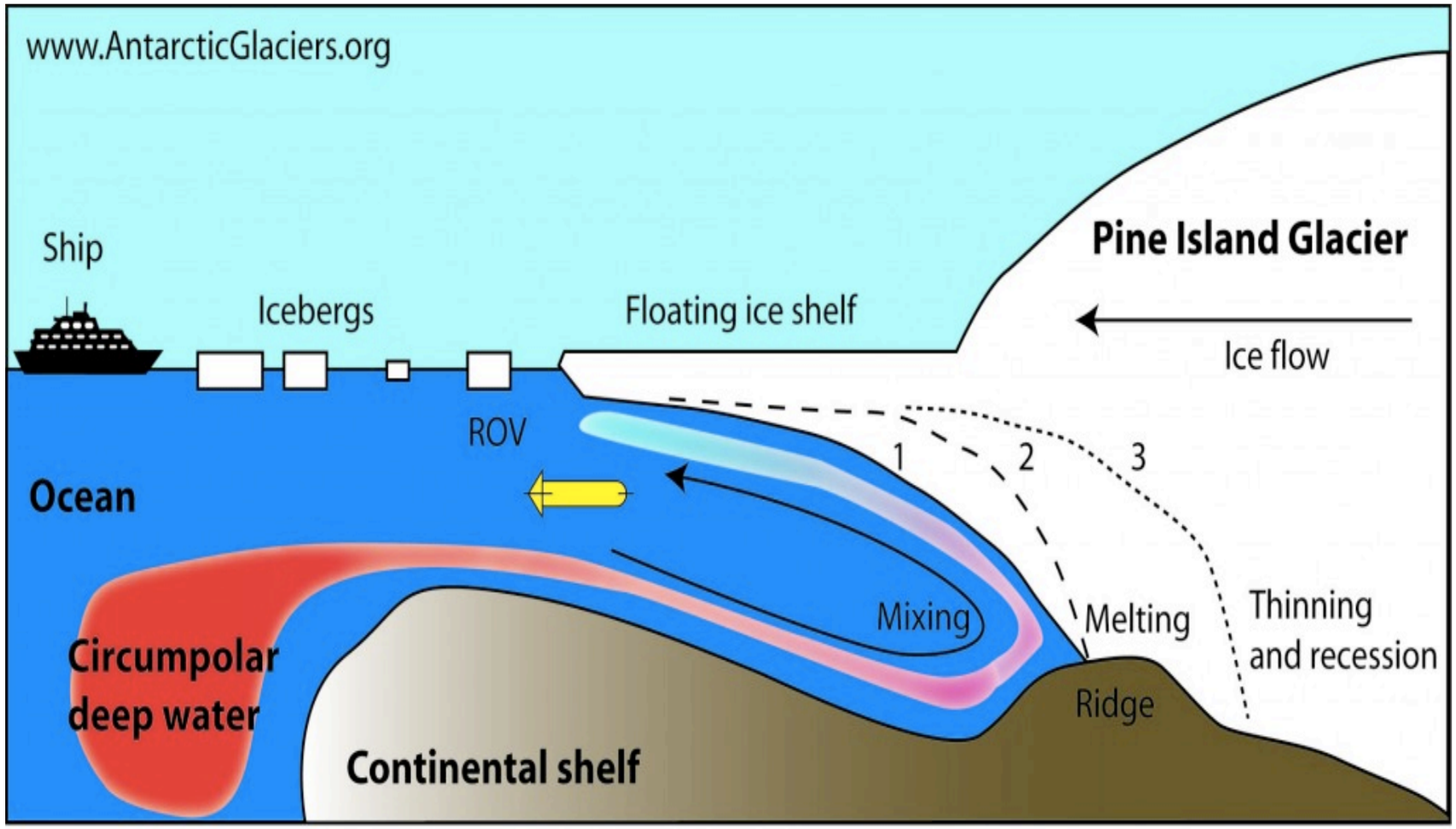
Antarctica and ocean circulation

Antarctic Circumpolar Current (ACC) connects all the other non-polar ocean basins, and thus is an important mechanism for moving heat, salt and icebergs around the world. It also acts as a climatological "barrier" which prevents North-South propagation of climatic signals to Antarctica



Antarctica and ocean circulation

Much of the ACC is comprised of warm and salty (>3.5 C) circumpolar deep water (CDW) which resides at a few hundred meters below the surface (below AAIW). It must get up onto the continental shelf to affect thick ice shelves

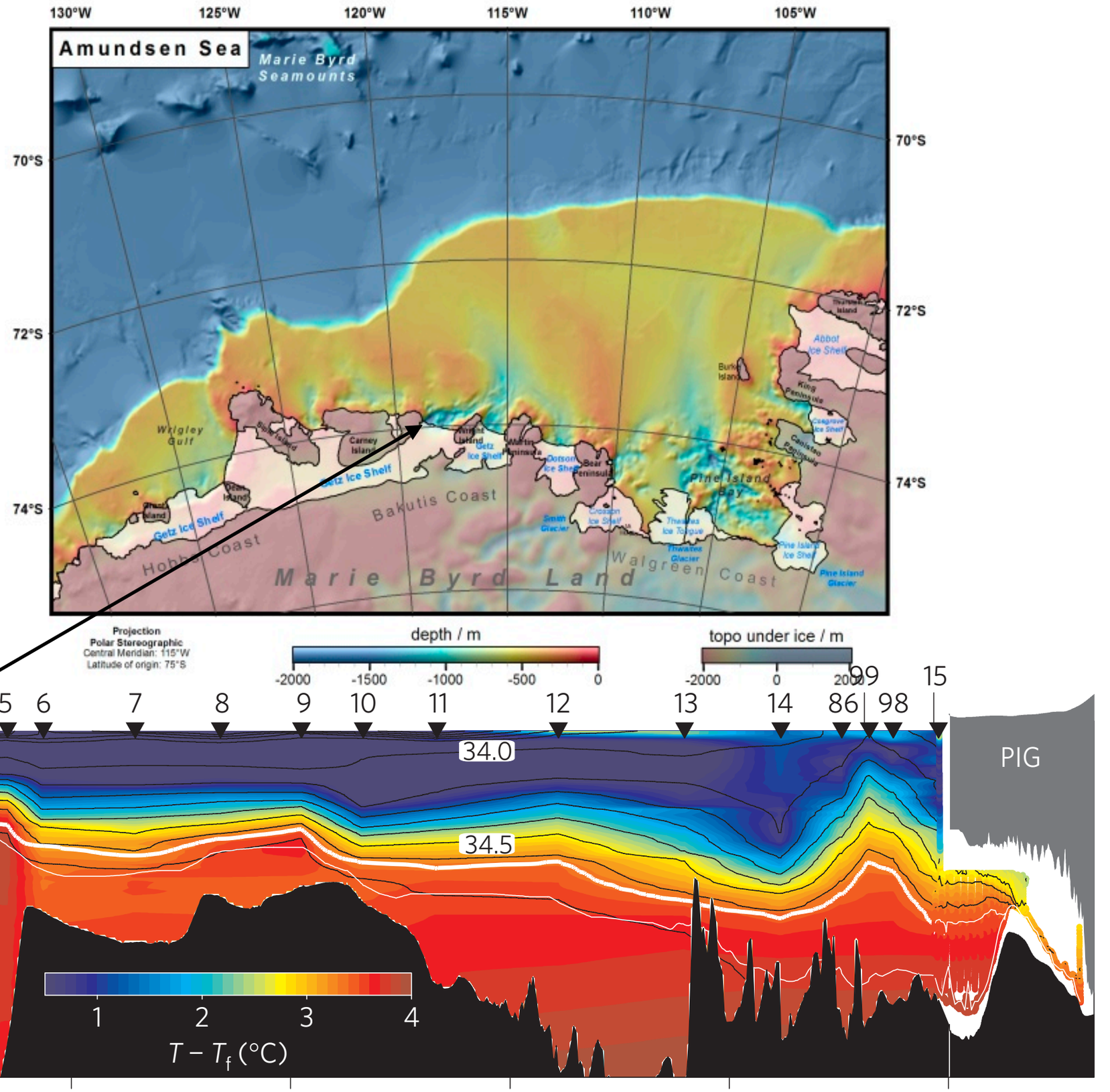


1. Early 1970s. Pine Island Glacier is grounded at a bedrock ridge.
2. Warm, inflowing Circumpolar Deep Water melts the base of the glacier. The glacier steepens and accelerates.
3. Present day, observed by a remotely operated vehicle (ROV). Glacier is thinning and receding.

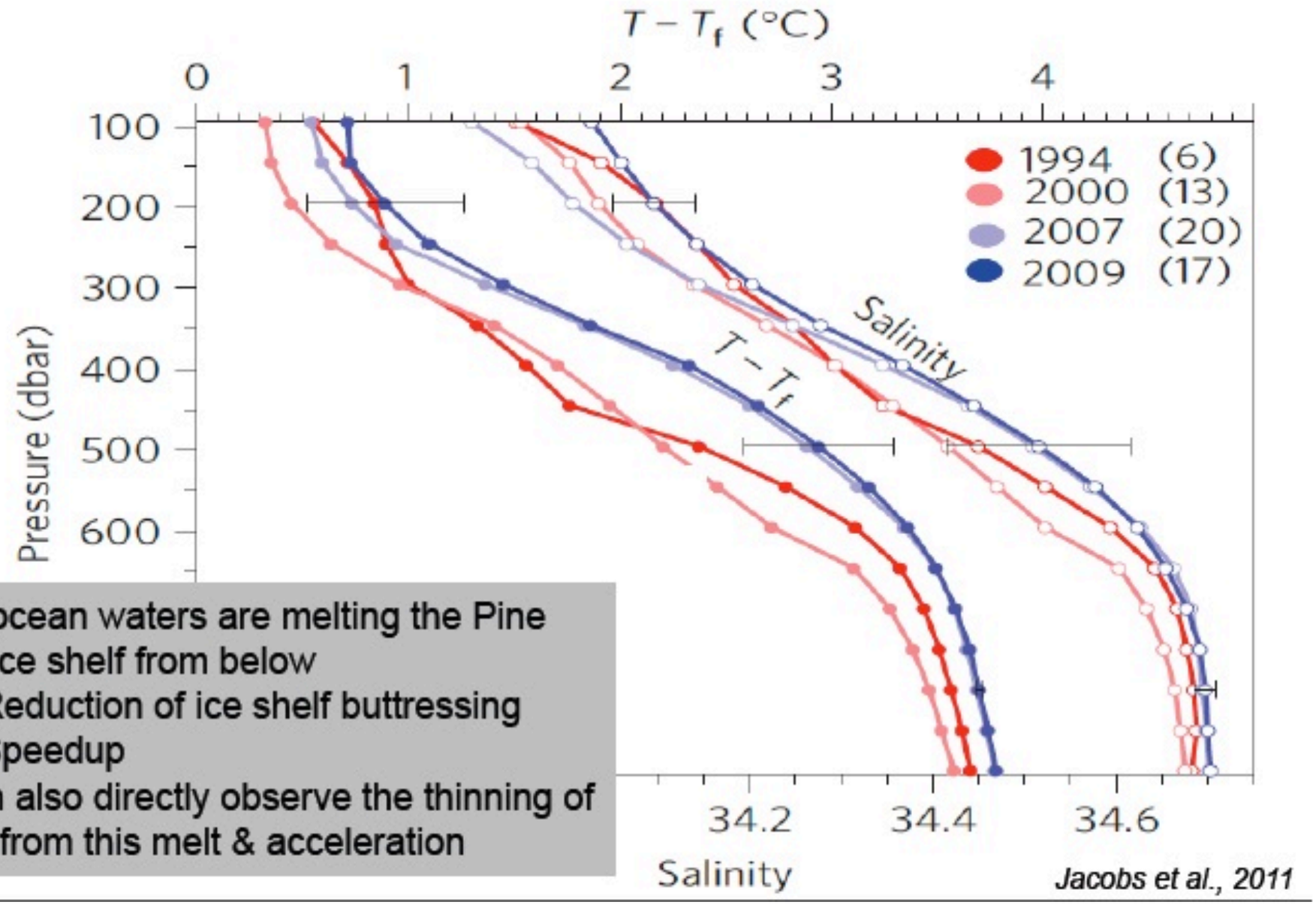
Antarctica and ocean circulation

In practice, determining whether CDW will reach underneath an ice shelf is difficult due to the complicated bathymetry of the ocean bottom and fluctuations in depth of CDW[a]

Past extent of ice stream, erodes deep trough in continental shelf that makes it much easier for CDW to reach ice sheet



Antarctica and ocean circulation



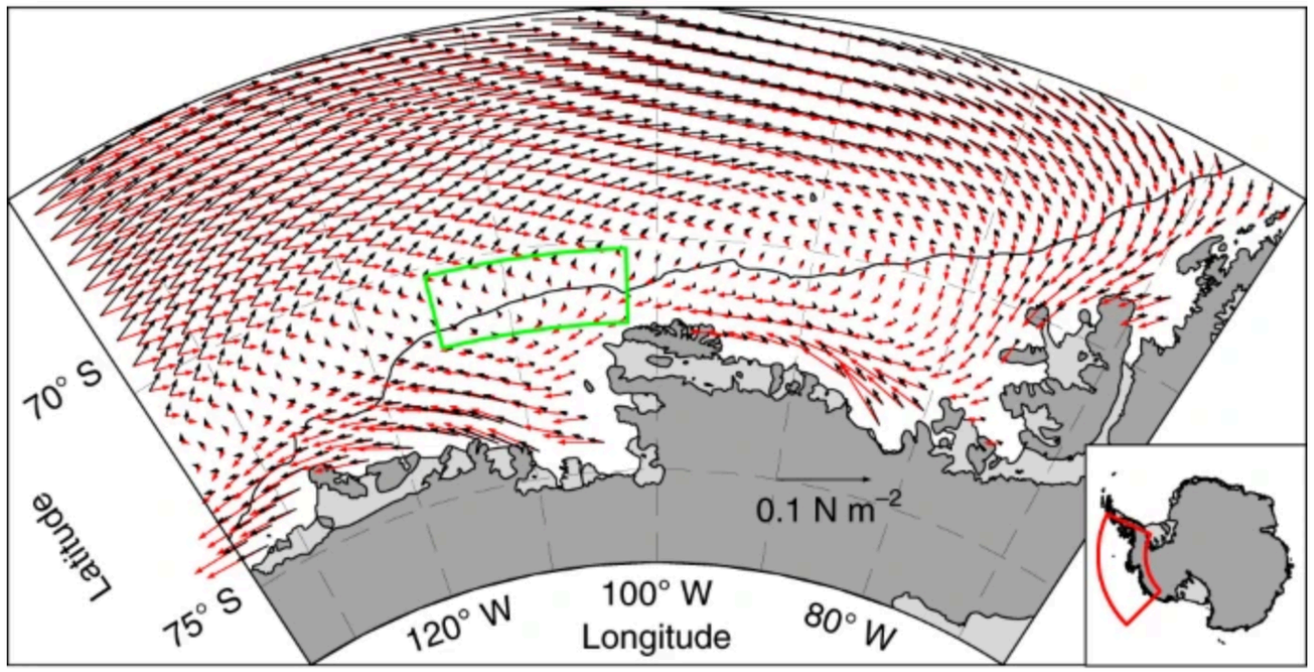
Warm ocean waters are melting the Pine Island ice shelf from below

- Reduction of ice shelf buttressing
- Speedup

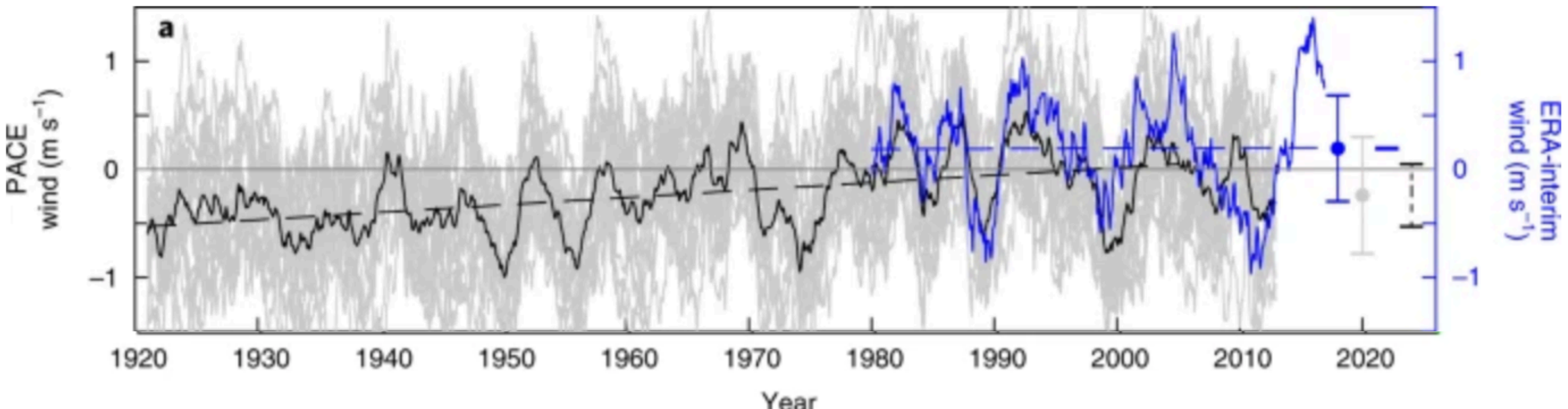
We can also directly observe the thinning of the ice from this melt & acceleration

Waters underneath the ice shelf at Pine Island Glacier (West Antarctica) have been warming over the last 20+ years, coincident with thinning of the ice shelf. There is an ongoing debate as to the cause.

Antarctica and ocean circulation

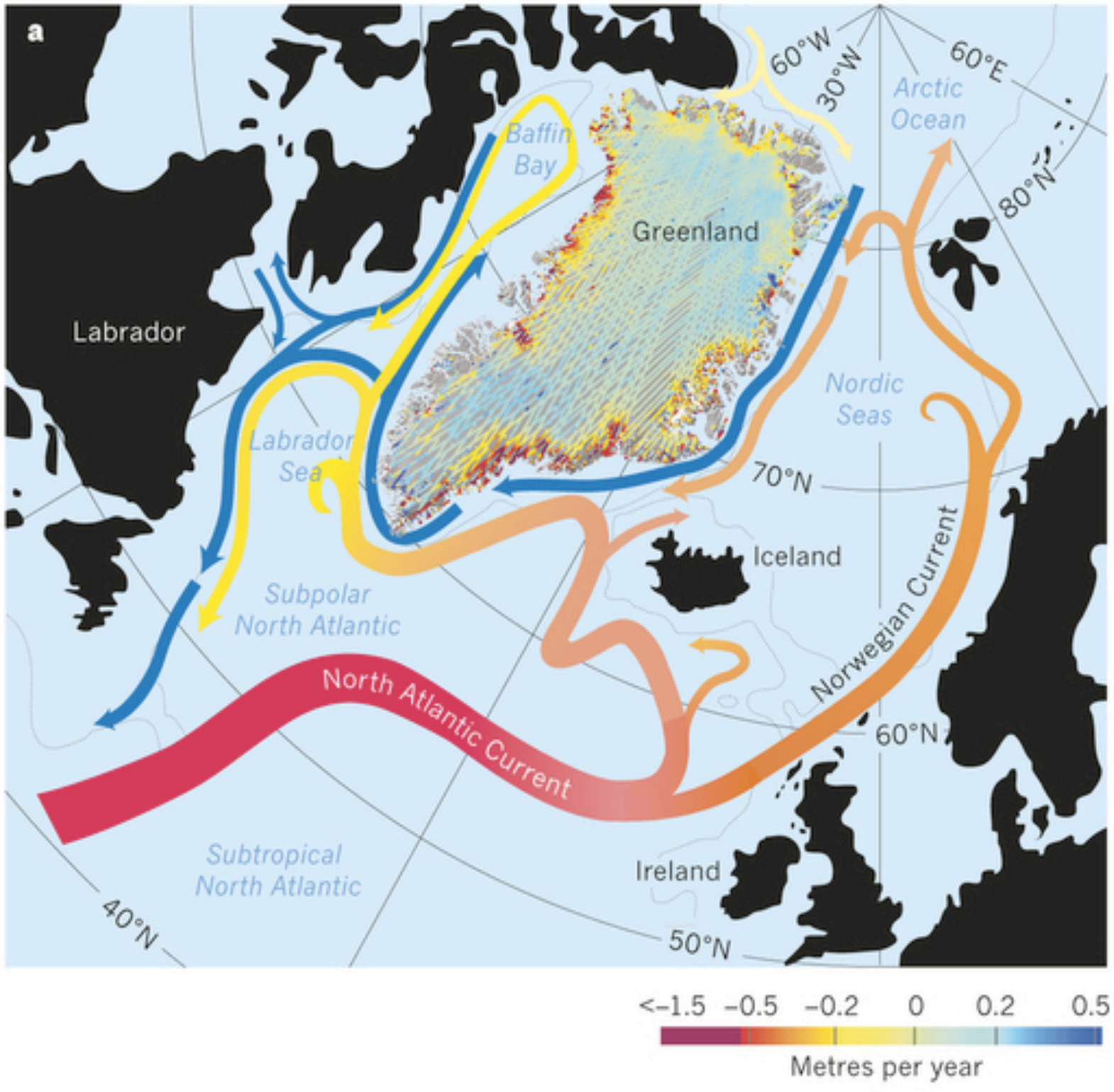


Winds in the Amundsen Sea may shift and change the flow of Warm CDW either along or onto the continental shift. The balance of wind direction is very subtle and changes are modulated by both variability and climate change (Holland et al. 2019)



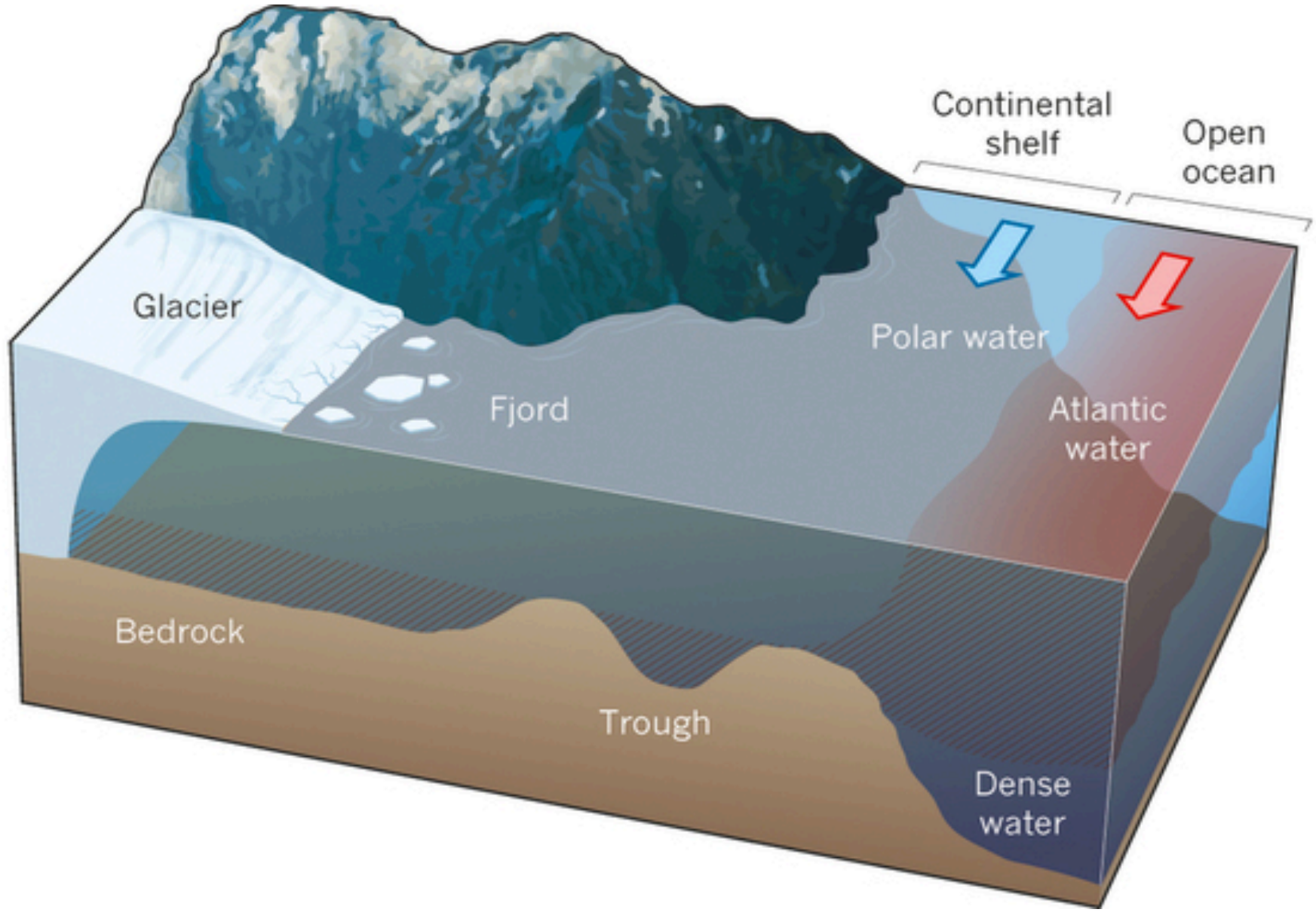
Greenland and ocean circulation

Strong winds coming off the ice sheet drive polar water around Greenland in a coastal current called Sub Polar North Atlantic (SPNA) waters. The larger scale the North Atlantic current is driven by wind stress over the North Atlantic and brings warm water from the subtropics.



Greenland and ocean circulation

SPNA waters encircle Greenland in the West Greenland Current and buffer warm waters from reaching the ice front of glaciers within fjords



Greenland and ocean circulation

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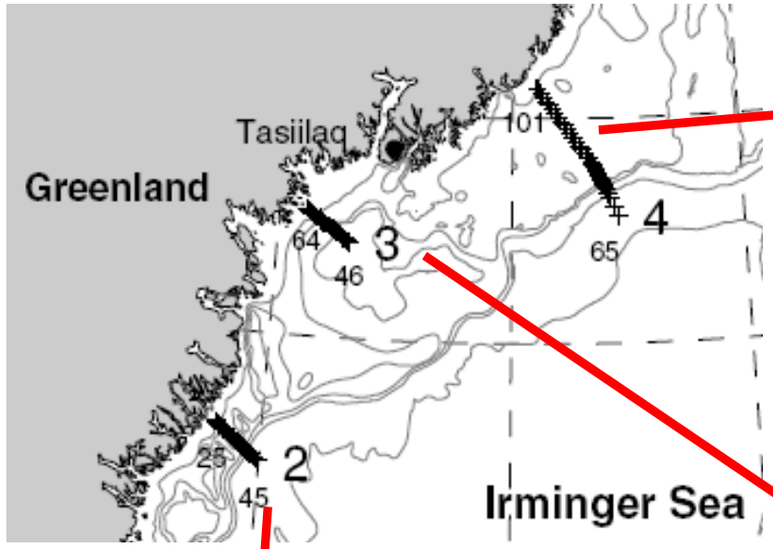
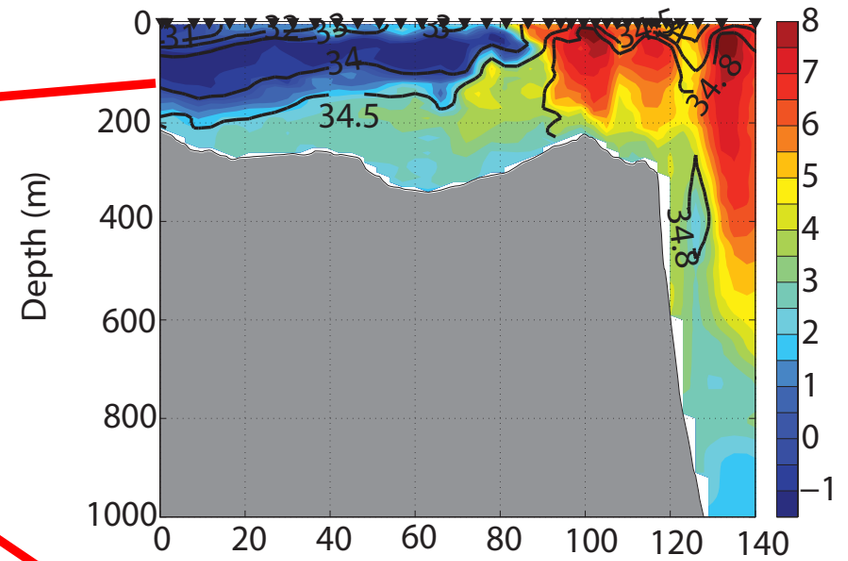
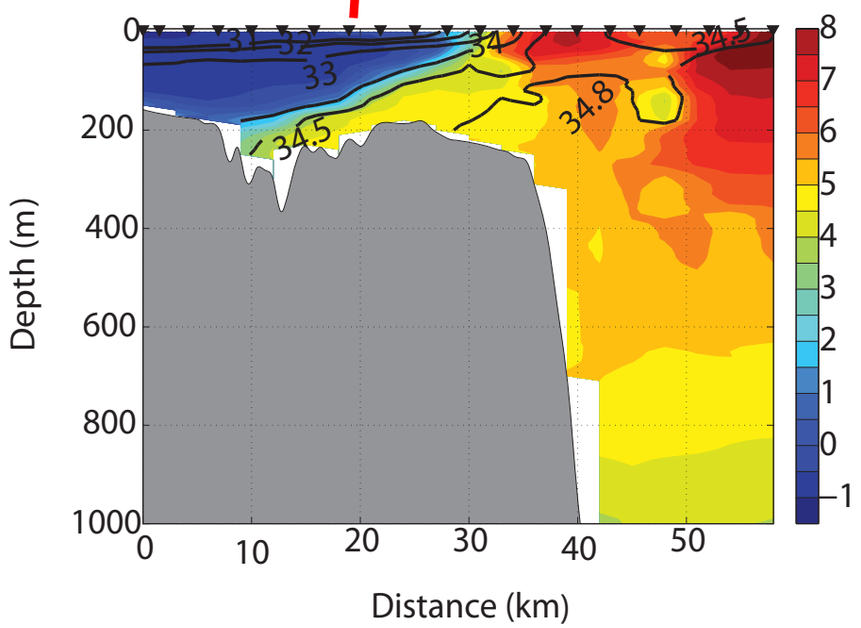
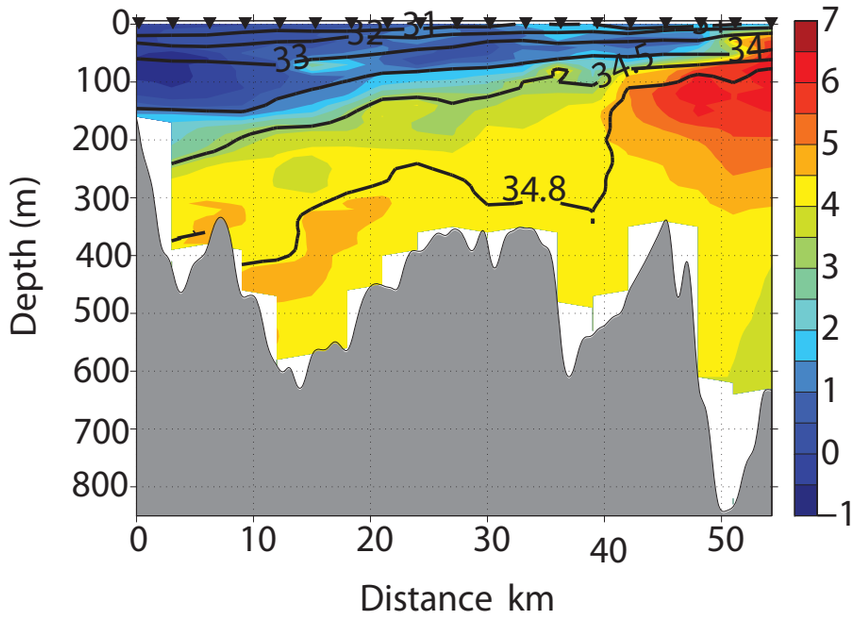




Sutherland et al. 2008

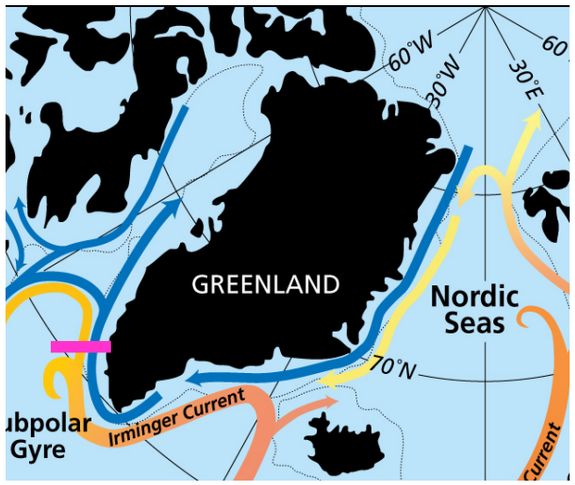


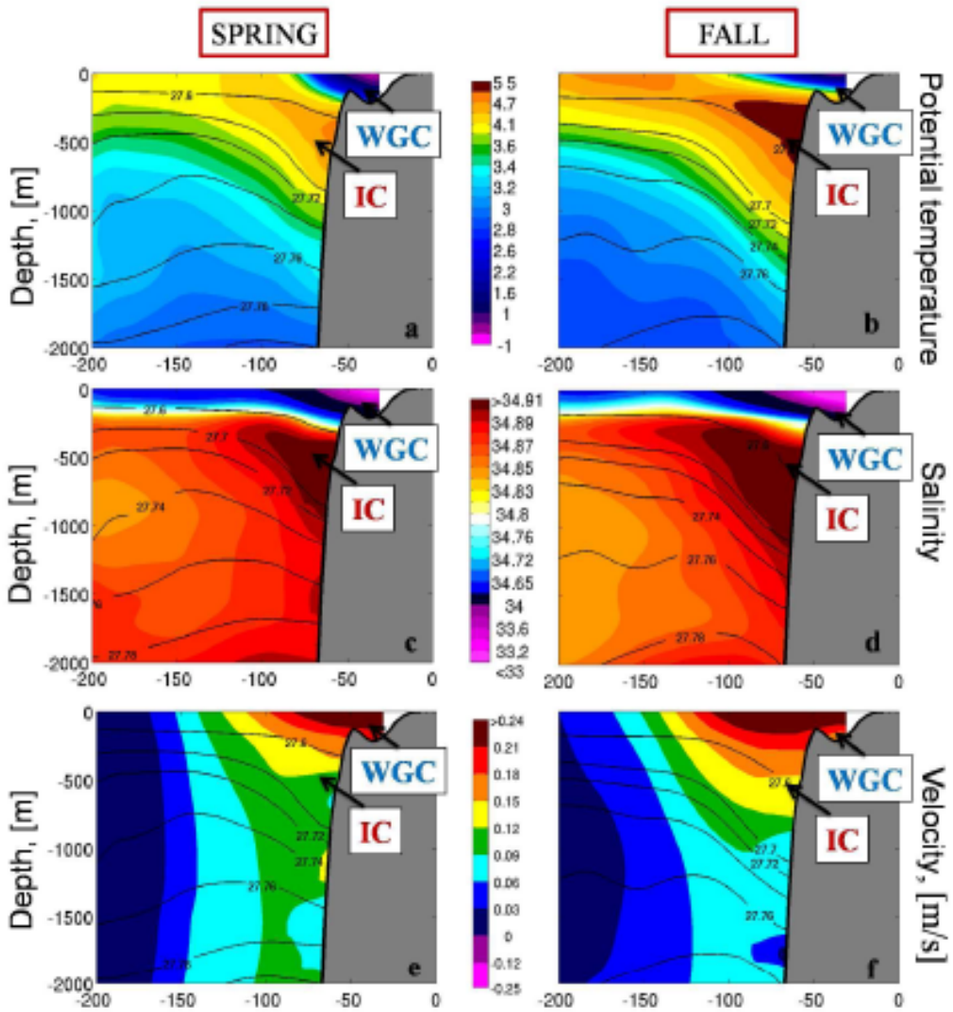


Greenland and ocean circulation

West Greenland – Labrador Sea Side

SPNA waters encircle Greenland in the West Greenland Current and buffer warm waters from reaching the ice front of glaciers within fjords



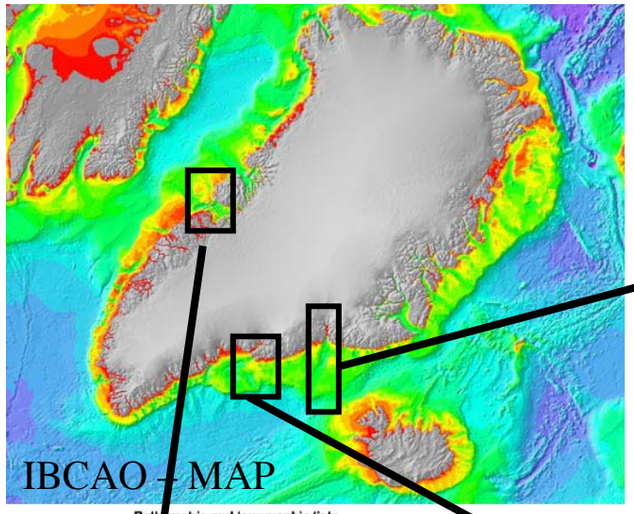


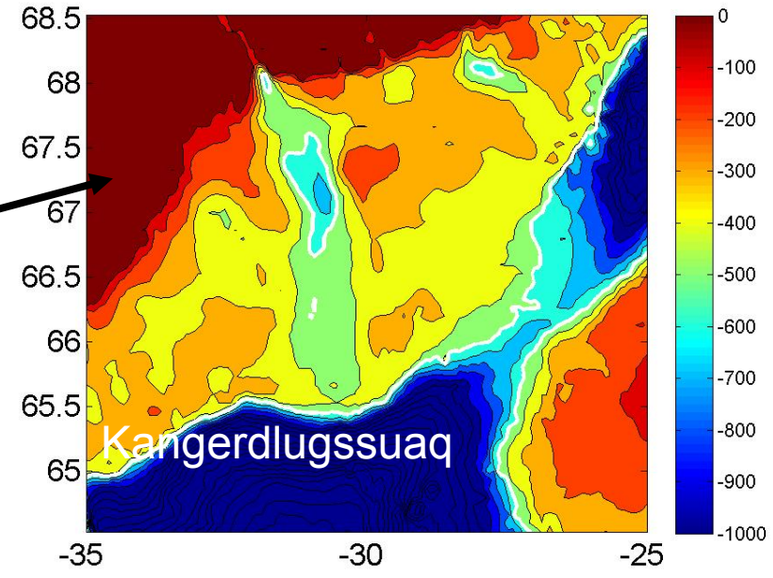
Rykova et al. 2015

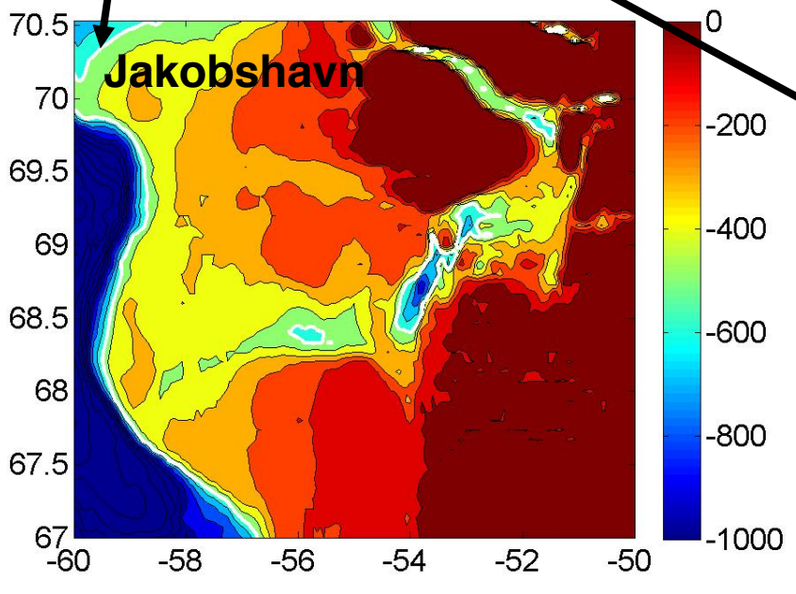
Greenland and ocean circulation

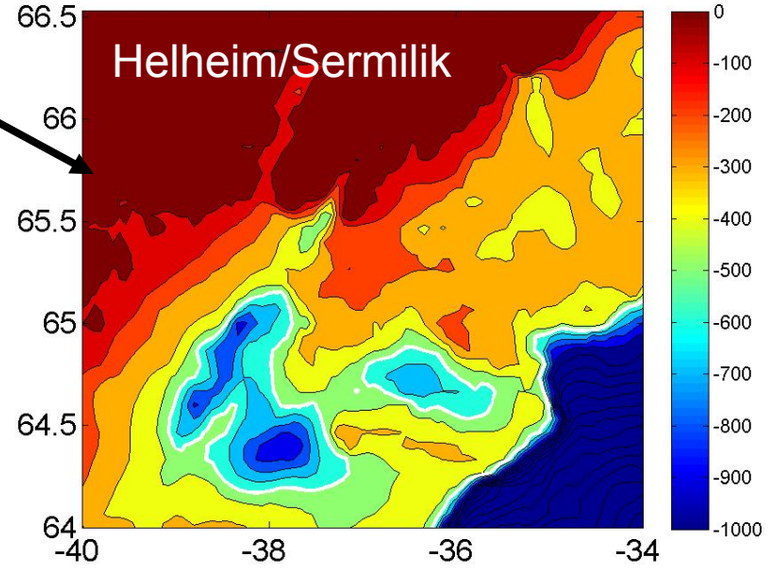
SPNA waters encircle Greenland in the West Greenland Current and buffer warm waters from reaching the ice front of glaciers within fjords

Deep troughs leading to major outlet glacier/fjord



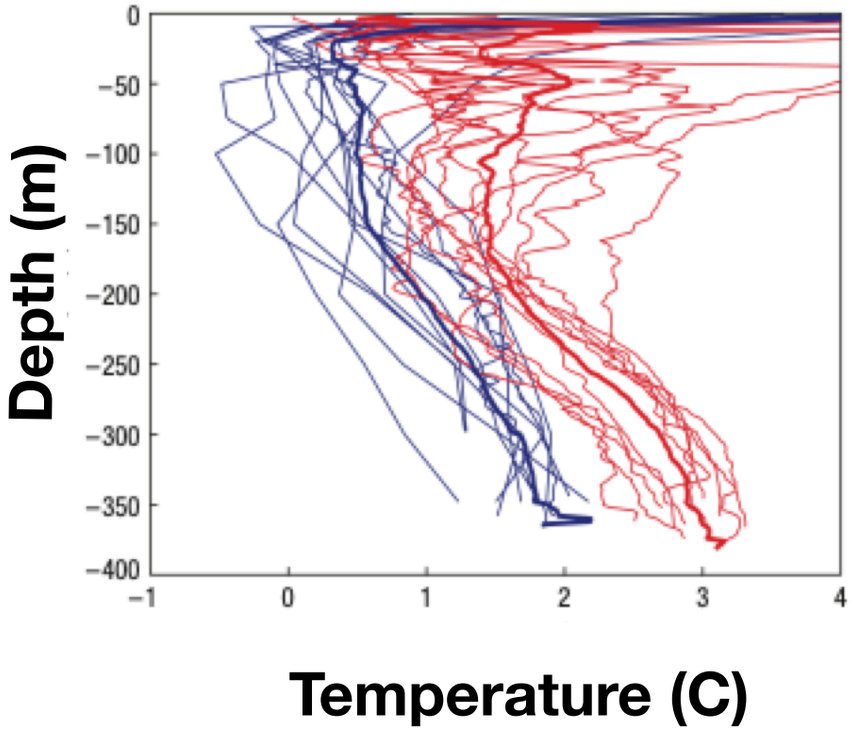


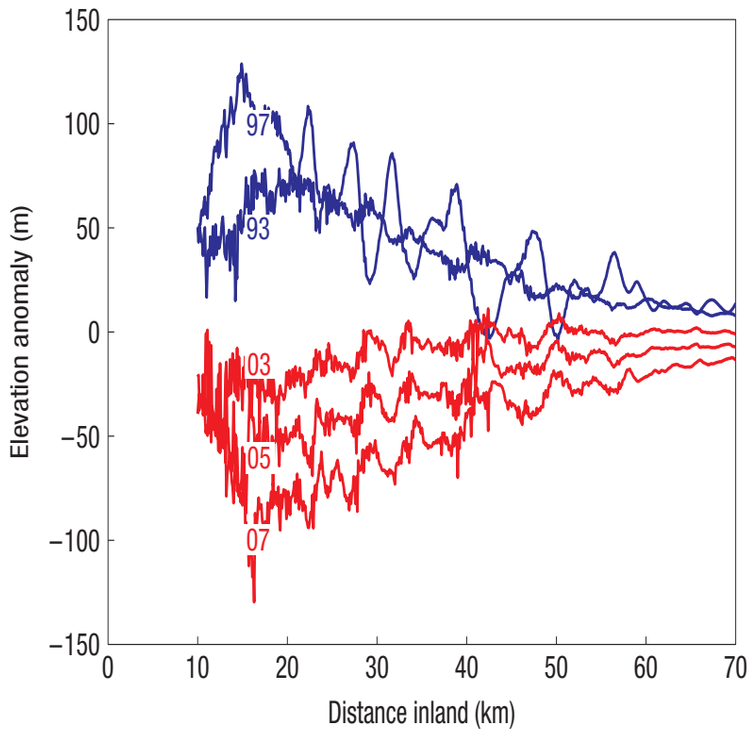


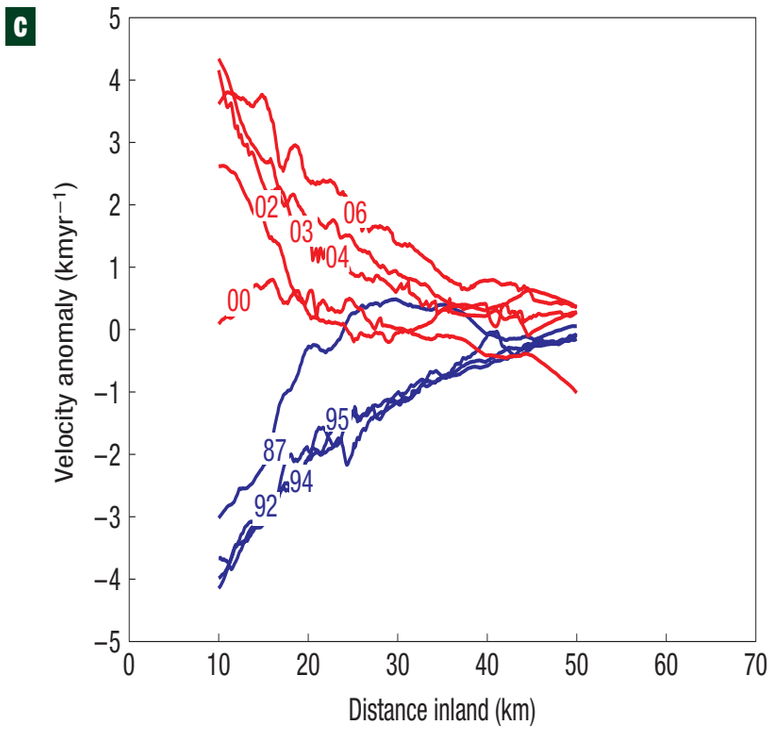


Greenland and ocean circulation

Jakobshavn Isbrae in W. Greenland



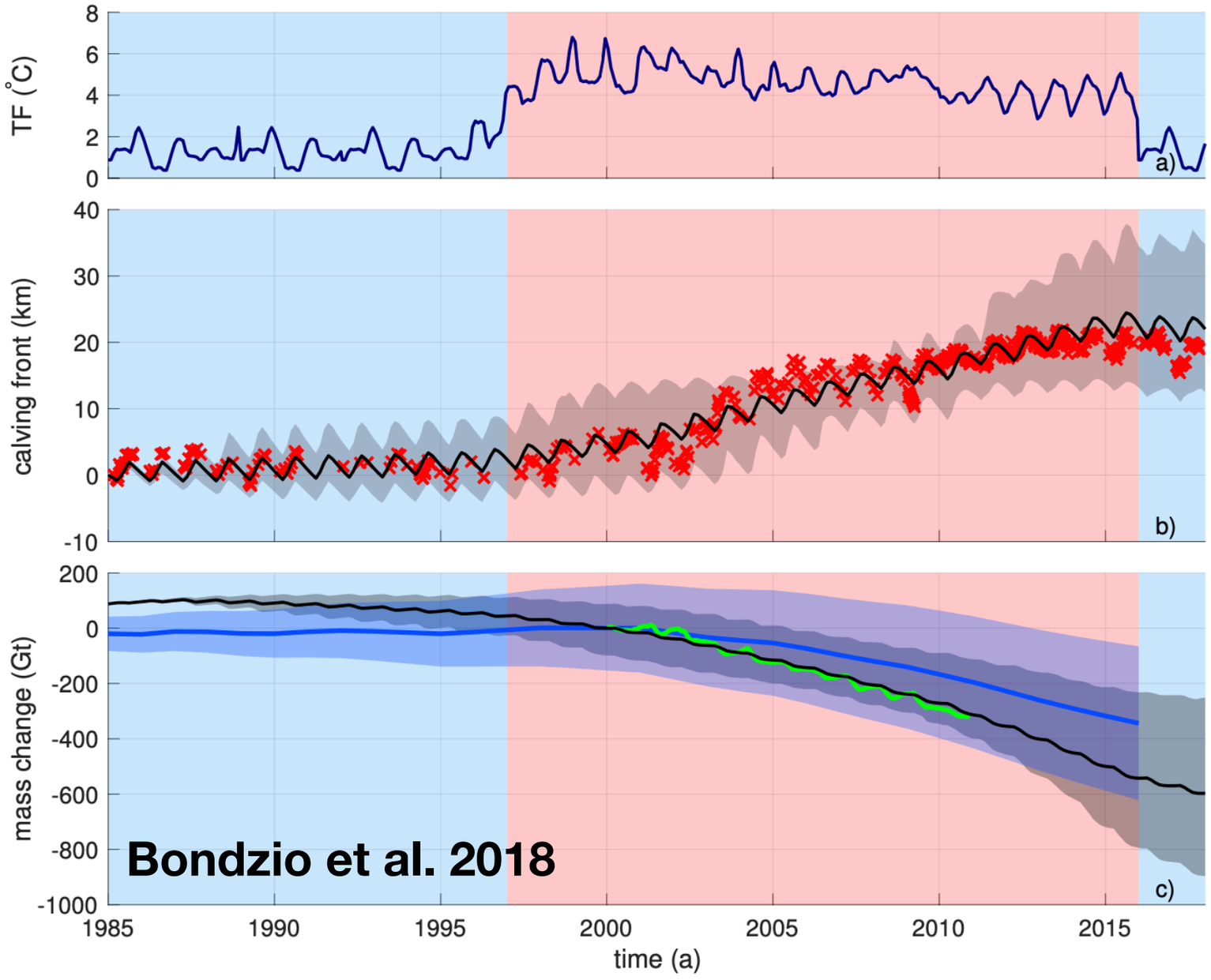




blue= depth profiles of ocean temperature 1954-2007
red=same 1997-2007
air temp for comparison

Cold water buffer has reduced and melting of Greenland glaciers by warm subtropical waters has increased in last ~20 years. But why? Still being debated.

Greenland and ocean circulation

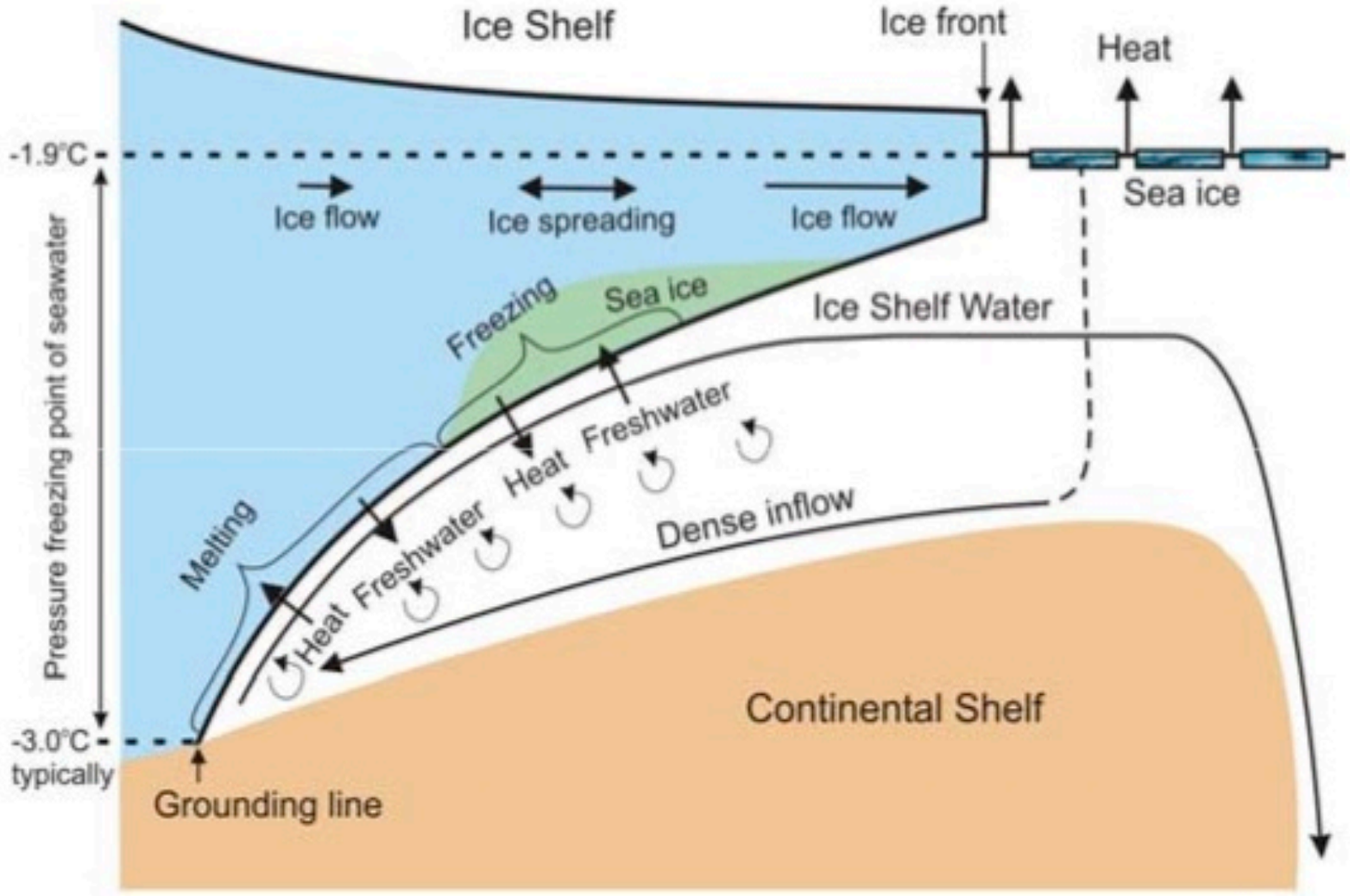


The world's fastest glacier (Sermeq Kujalleq, aka Jakobshavn Isbrae) sped up and retreat over the 2000-2015 period, coincident with warming of ocean waters nearby, but role of variability vs. climate change is subtle

The Ice Pump

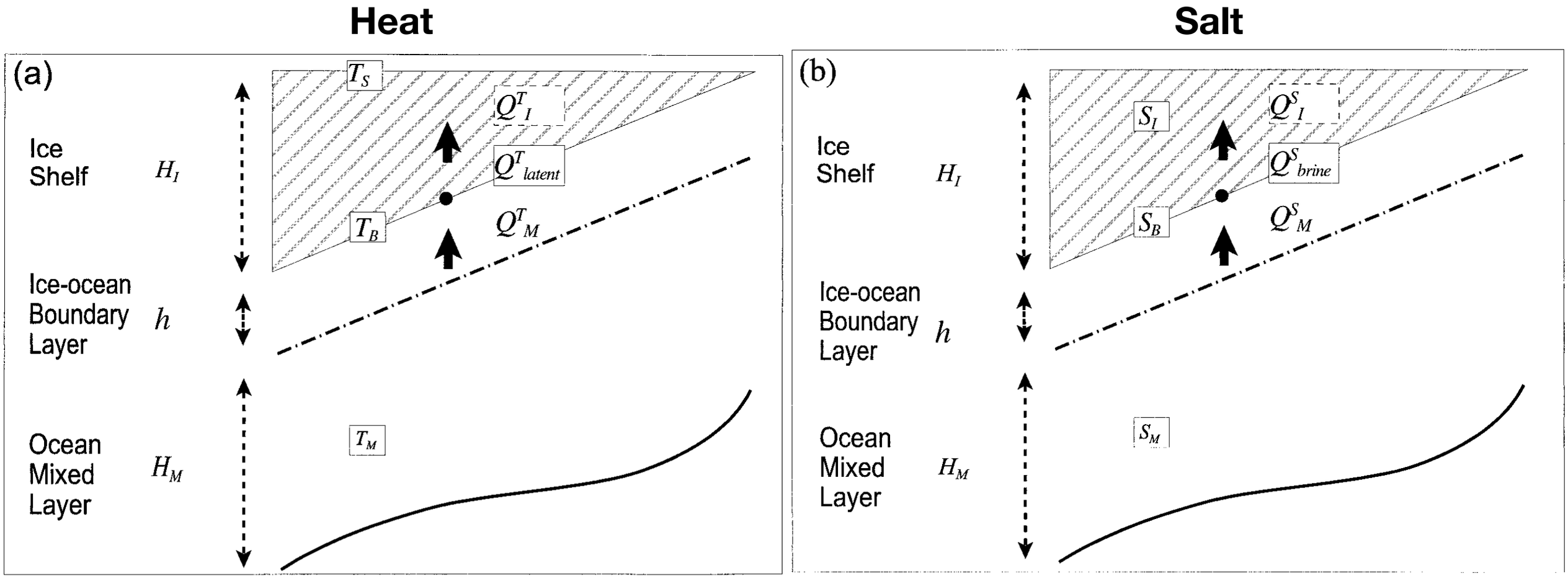
To the board!

Buoyancy driven ocean currents



- **Many thing can drive ocean currents (take oceanography to find out more!)**
  - **Wind (mechanical)**
  - **Buoyancy (spatial density differences due to temperature or salinity)**
- **Underneath ice shelves (or near ice fronts), there is not much in the way of mechanical forcing, and a large potential source of cool, fresh water (the ice)**

The Ice-Ocean Boundary Layer



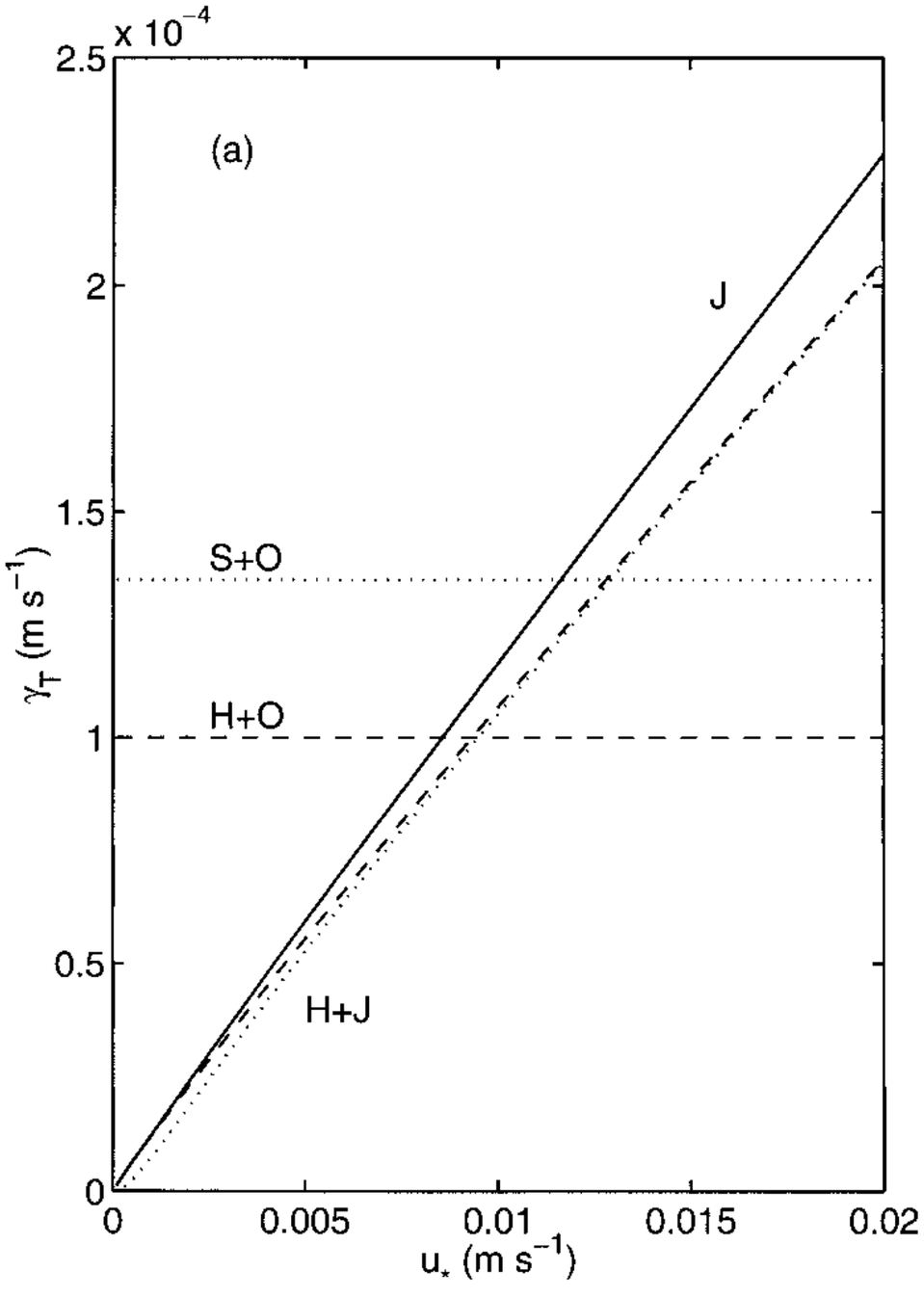
Holland & Jenkins 1999

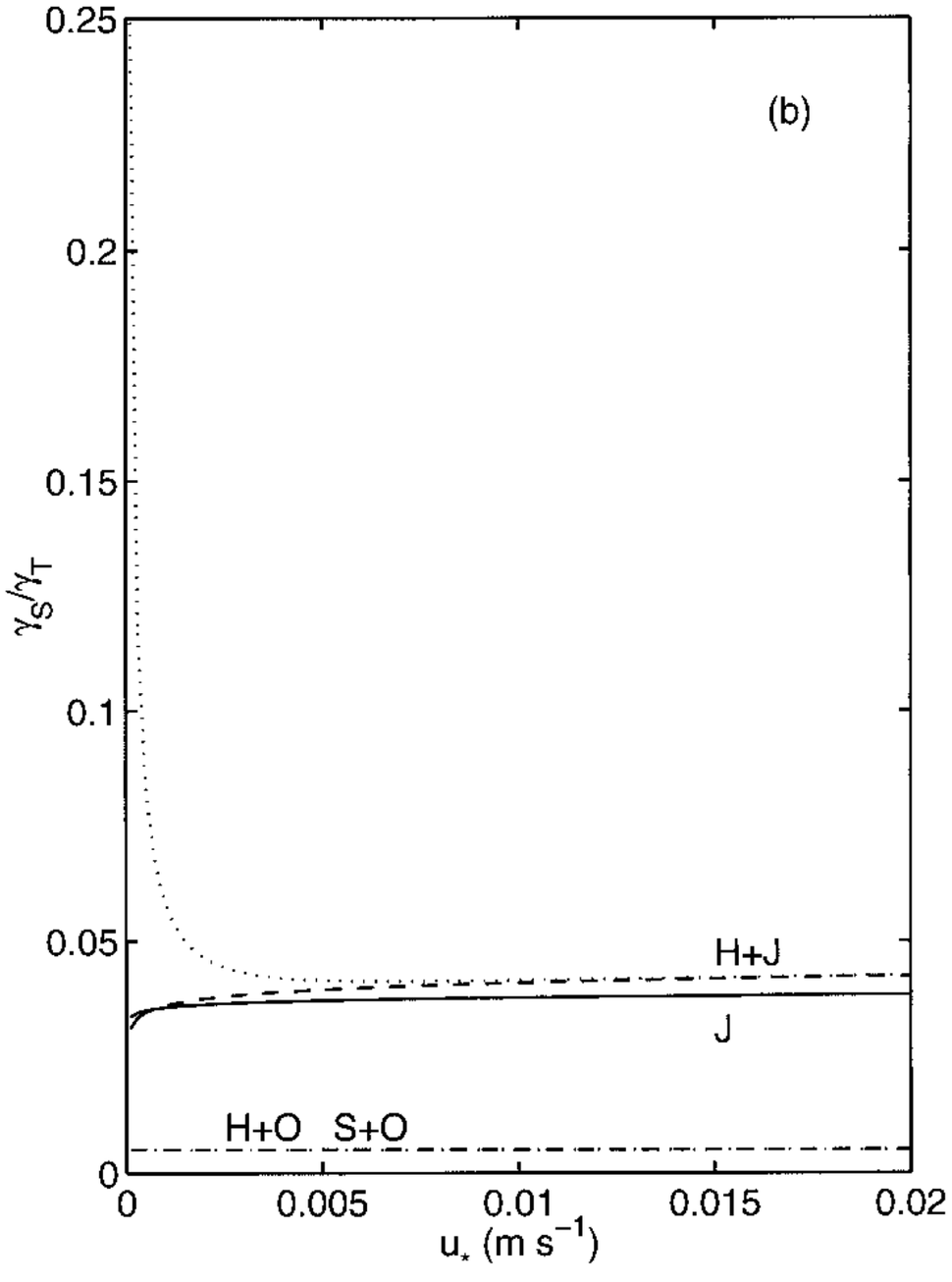
How do heat and salt move between the ocean and the ice shelf? This largely depends on the transition as you go from the far-field ocean properties and underside of the ice shelf - the transition happens in the <u>boundary layer</u>

The Ice-Ocean Boundary Layer

To the board!

The Ice-Ocean Boundary Layer





Holland and Jenkins 1999

The Ice-Ocean Boundary Layer

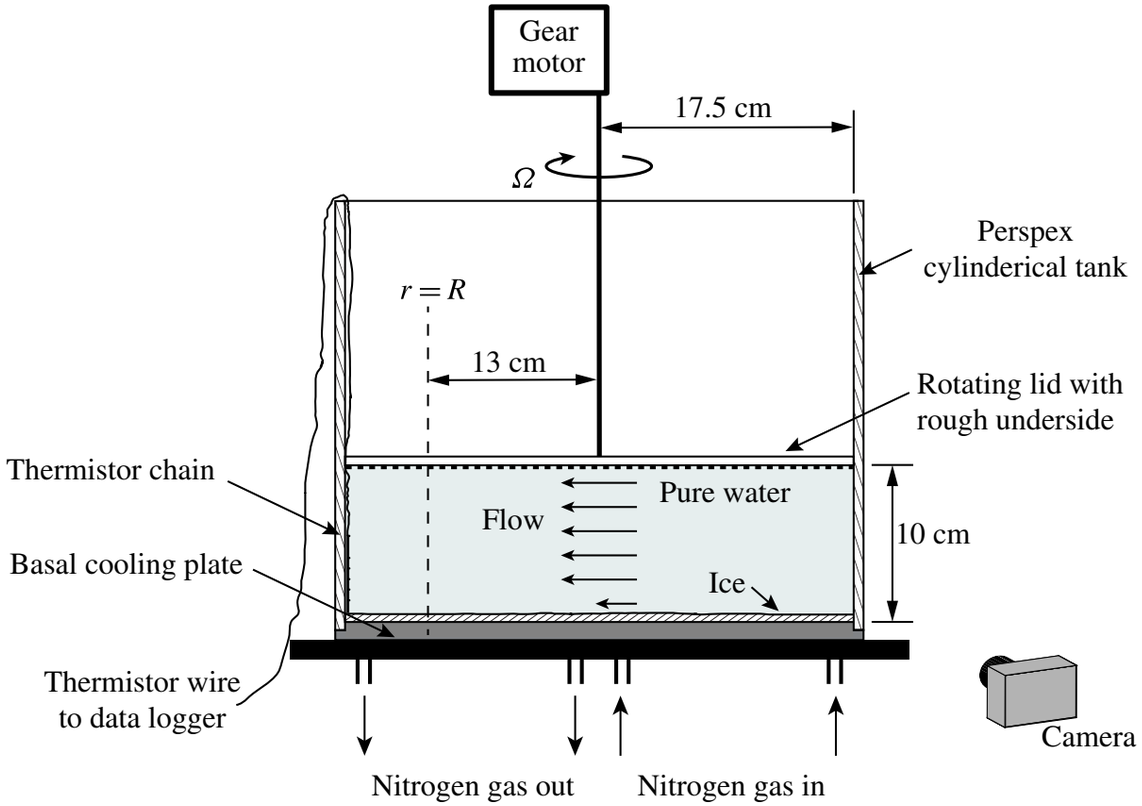
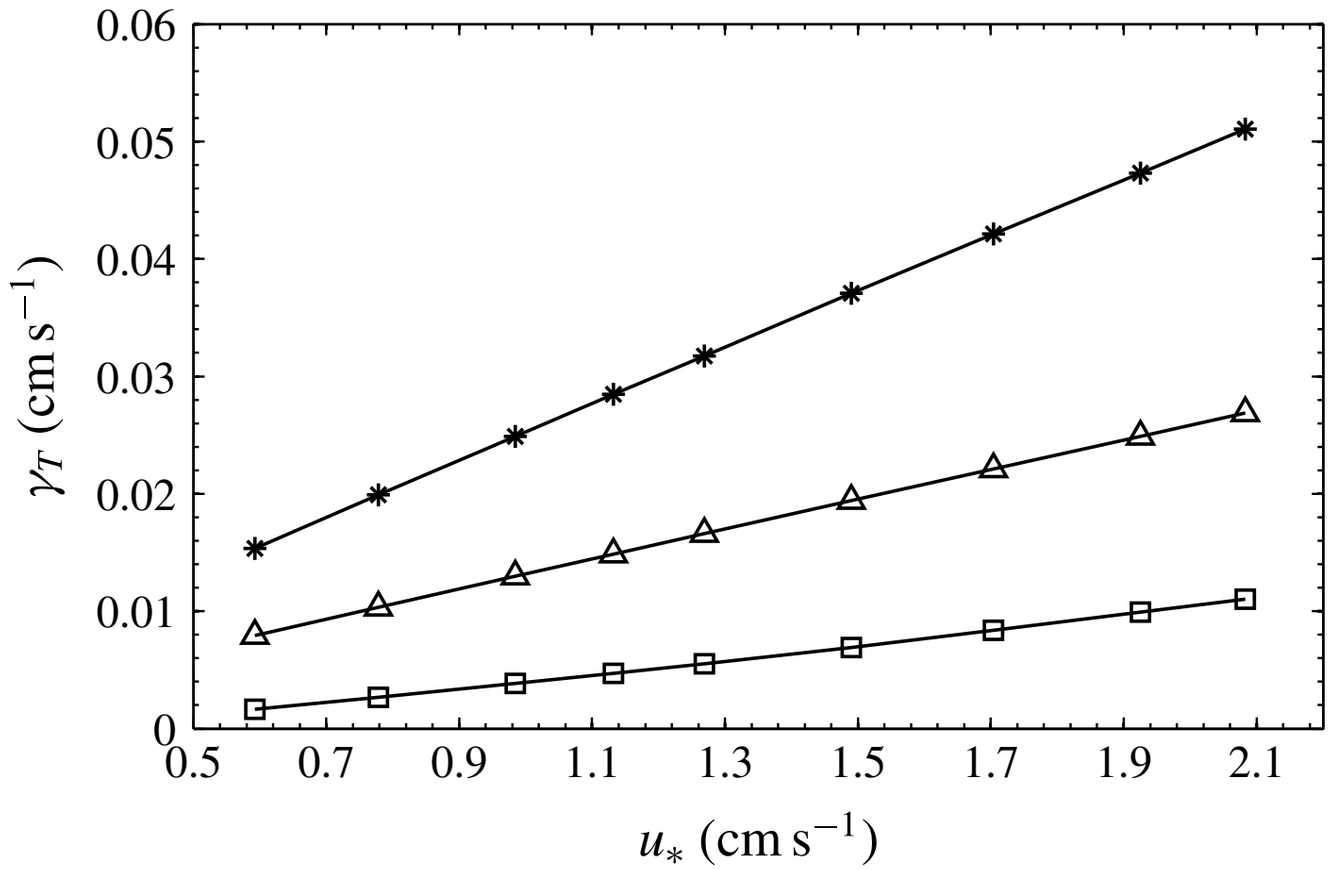
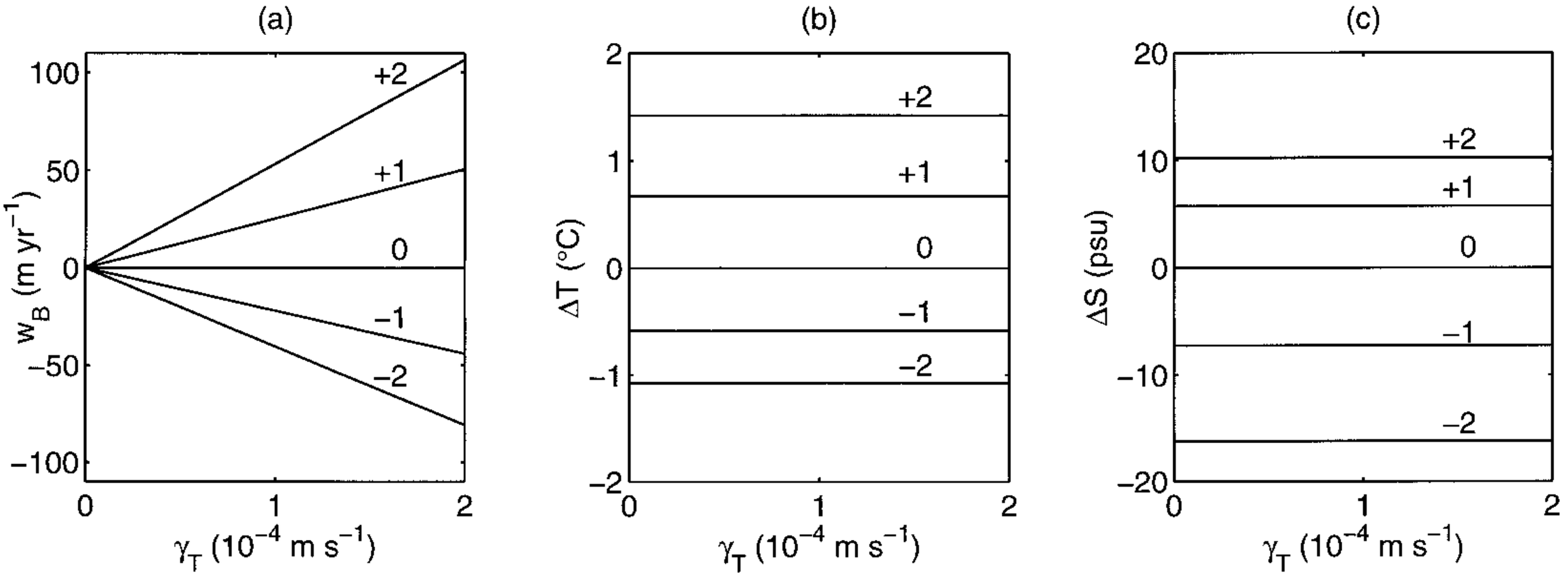


FIGURE 2. Schematic diagram of the apparatus.



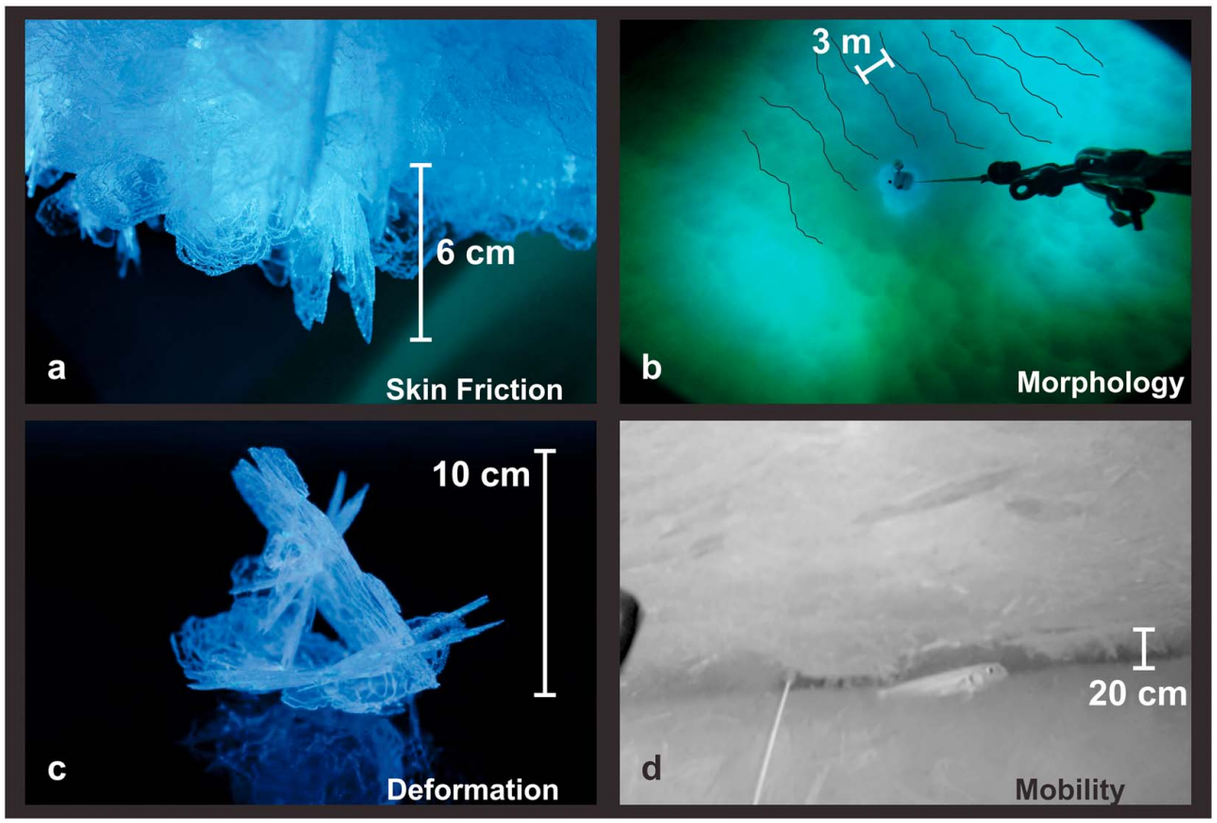
Ramudu et al. 2016

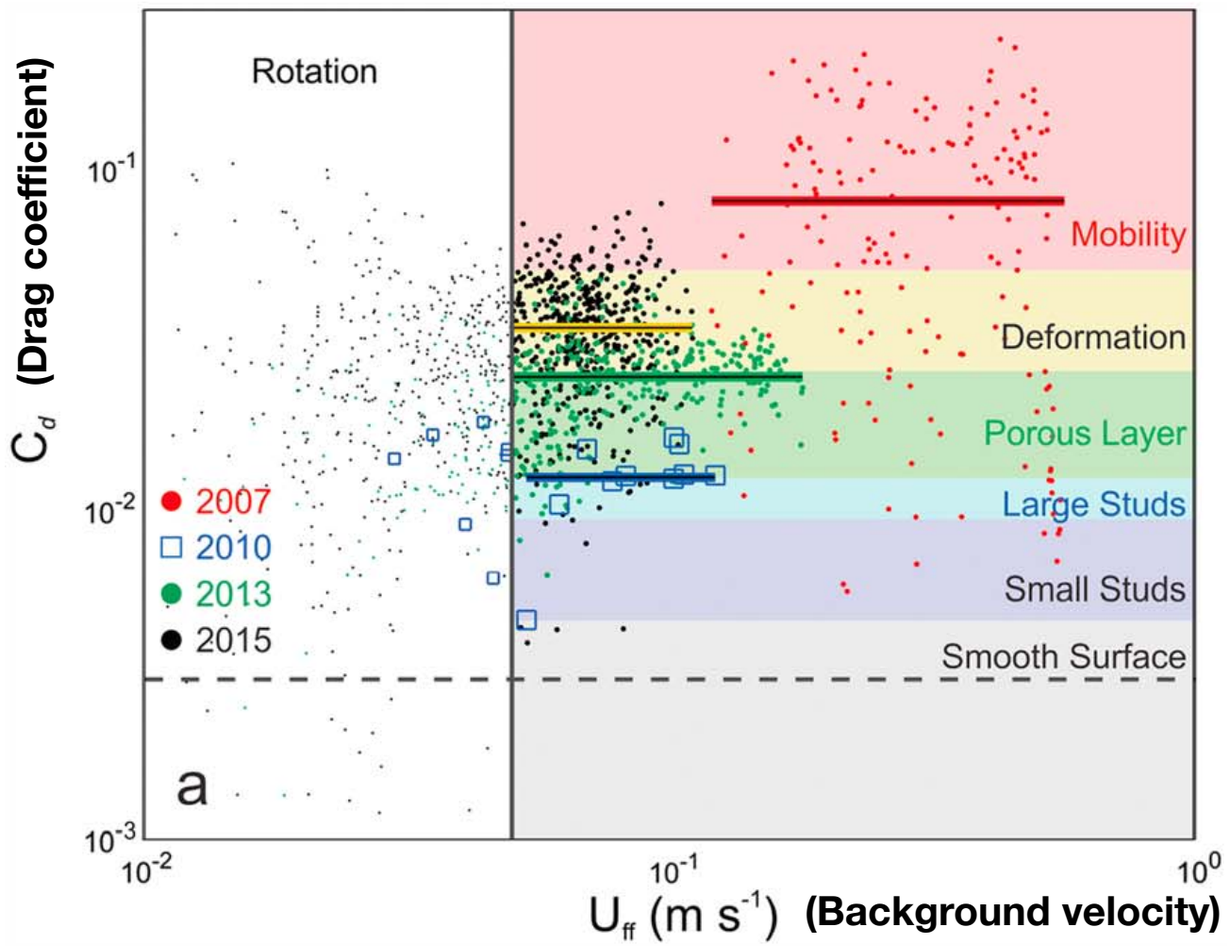
The Ice-Ocean Boundary Layer



Unsurprisingly, higher water temperatures cause higher melt rates, but the sensitivity depends on the exchange velocities, which are themselves dependent on velocity of water flow (and ice roughness). The result is a strongly nonlinear relationship between melt rate, temperature, salinity, water velocity

The Ice-Ocean Boundary Layer





Robinson et al. 2017

Also, the ice shelf bottom is not smooth - large affect on drag coefficient (and hence exchange velocity)