

GFD 2017 Lecture 1: Introduction to Ice-Ocean Interactions

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June 19, 2017

1 Introduction to Glaciers and Ice Sheets, *Andrew Fowler*

1.1 The long view of polar caps

The ice caps that we have today indicate that Earth is currently in the middle of an ice age. There are two ice sheets, one on Antarctica in the Southern hemisphere, and one on Greenland in the Northern hemisphere. Both cover almost the entire landmass that they are on. However, the ice sheets that we see today are not permanent features of the Earth system. There have been many times in Earth's history when the caps were altogether missing, and many times when the caps expanded to be much larger than they are today and fill the entire globe.

The Milanković cycles describe the different variations in solar insolation due to variations in the orbit of the planet. There are several cycles: a cycle of obliquity with a period of 41,000 years, a cycle of axial precession with a period of 22,000 years and a cycle of apsidal precession with a period of 100,000 years. The exact details of the cycles are unimportant; what is important is the apparent synchronization between the paleoproxy records of temperature and insolation values (figure 1). The paleotemperature record is characterized by large sawtooth oscillations with sudden onsets and slow declines, with an approximate periodicity of 10^5 years.

This observation suggests a simple theory of ice ages - when there is relatively high insolation the ice sheets melt and when there is relatively low insolation the ice sheets grow. The observed cycles are somewhat at odds with this theory however (figure 1). Although there is a 10^5 year cycle present in the insolation, it is not the strongest cycle. This suggests that the Milanković cycles may not be the driving force behind the changing ice cover, but instead may set the phase of an oscillation which already exists. Further support comes from comparing the temperature record with the CO_2 , which shows a strong correlation. This implies that the sawtooth oscillations in temperature that we observe could be an oscillation of the coupled climate system. Interestingly, the paleo temperature record also reveals a coupling between Greenland and Antarctica near the transition, according to

$$G = -\frac{dA}{dt},$$

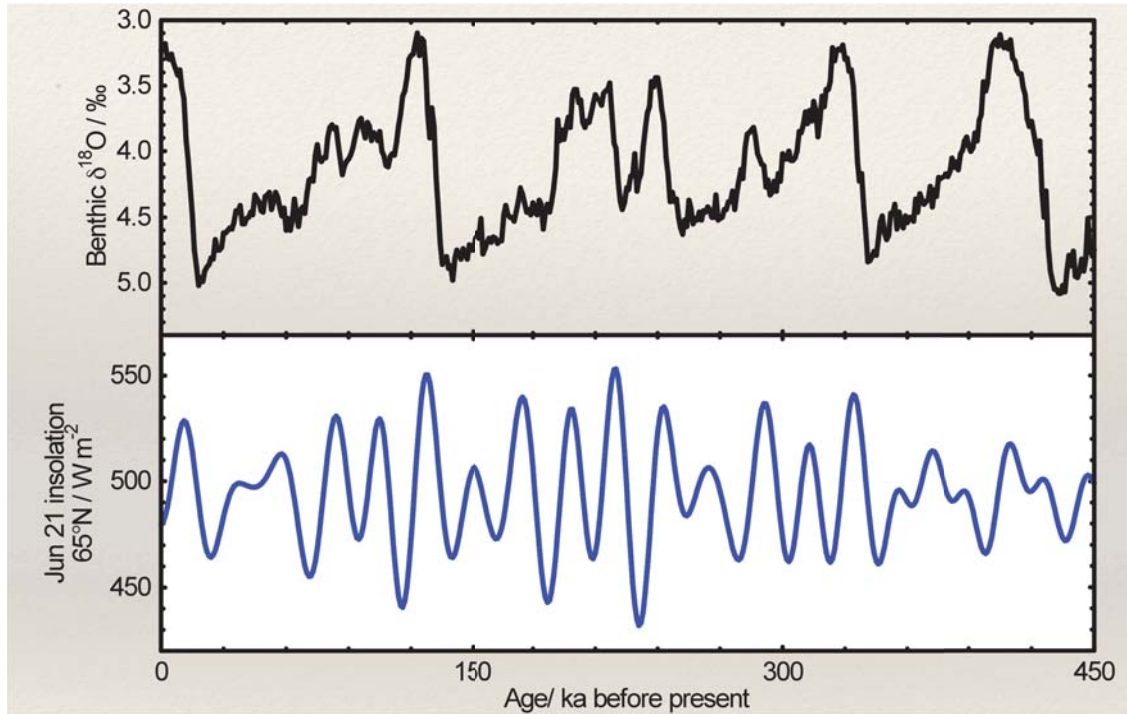


Figure 1: Top: a paleo oxygen isotope record constructed from sediments. Since O^{16} evaporates more rapidly and condenses more slowly than O^{18} , it is preferentially deposited into ice masses, which leaves the ocean enriched in O^{18} . A higher O^{18} value therefore represents more land ice. This isotopic signature is incorporated into the shells of living organisms and turned into sediment. Thus, relatively high δO^{18} values correspond to cold periods and relatively low δO^{18} to warm periods. Bottom: the variations in insolation calculated using the Milanković cycles.

where G is the temperature over Greenland and A is the temperature over Antarctica. Apparently the two ice masses are able to communicate, either through an atmospheric teleconnection or ocean heat transport.

It is believed that northeastern North America has been previously covered in ice, referred to as the Laurentide ice sheet. When this sheet collapses large quantities of icebergs raft sediments into the North Atlantic ocean, referred to as Heinrich events. Some of these sediments have been shown to originate in Hudson Bay, suggesting that there was an ice dome over Hudson bay. There is some partial synchronization between the Heinrich events and the Dansgaard-Oeschger events, sudden change in Greenland surface temperature over decades, suggesting that these sudden changes in air temperature could be linked to the collapse of the ice sheet.

The initiation process of an ice sheet has also been studied, particularly for Antarctica. The Earth has been cooling since 50 Ma (although this is being opposed currently by anthropogenic climate change), and the Antarctic ice sheet began growing at approximately 34 Ma. Modeling studies suggest that the ice sheet begins as mountain glaciers, which grow until they are able to join together and form an ice sheet over the eastern half of the continent.

1.2 A taxonomy of ice flows

Ice can be modeled as a viscous fluid. Frequently the ice will move quite rapidly; in a glacier this causes surges to occur and in an ice sheet it causes ice streams to form. Glaciers and ice sheets both refer to masses of grounded ice; the difference is in their size. Ice sheets cover entire landmasses while glaciers can be any size. Parts of an ice sheet can be referred to as glaciers.

The ice flow moves ice from areas of accumulation to areas of ablation. If the ablation is sufficient to terminate the ice sheet over land, the boundary of the sheet is referred to as a dry margin. If the ablation is not enough to remove all of the ice over land, the ice will flow into the ocean. The boundary between the ice and the ocean is called a wet margin in this case. Wet margins can further be categorized into tidewater glaciers, where the glacier rests on the bed, and ice shelves, where the ice extends itself by floating into the water. The endpoint of an ice mass determines some of the behavior of the ice motion, and so it is advantageous to classify glaciers by the nature of their termination.

Antarctica is split between the west and the east by the trans-antarctic mountains. The East Antarctic Ice Sheet is a continental ice sheet: if it were removed, the ground would be largely above sea level. The West Antarctic Ice Sheet, on the other hand is a submarine ice sheet; most of its base is below sea level, and it contains large ice shelves. Antarctica is also characterized by large numbers of ice streams (figure 2), which accomplish a large fraction of the ice transport, which brings mass from the central mass accretion zone to the outlying ablation and loss zones.

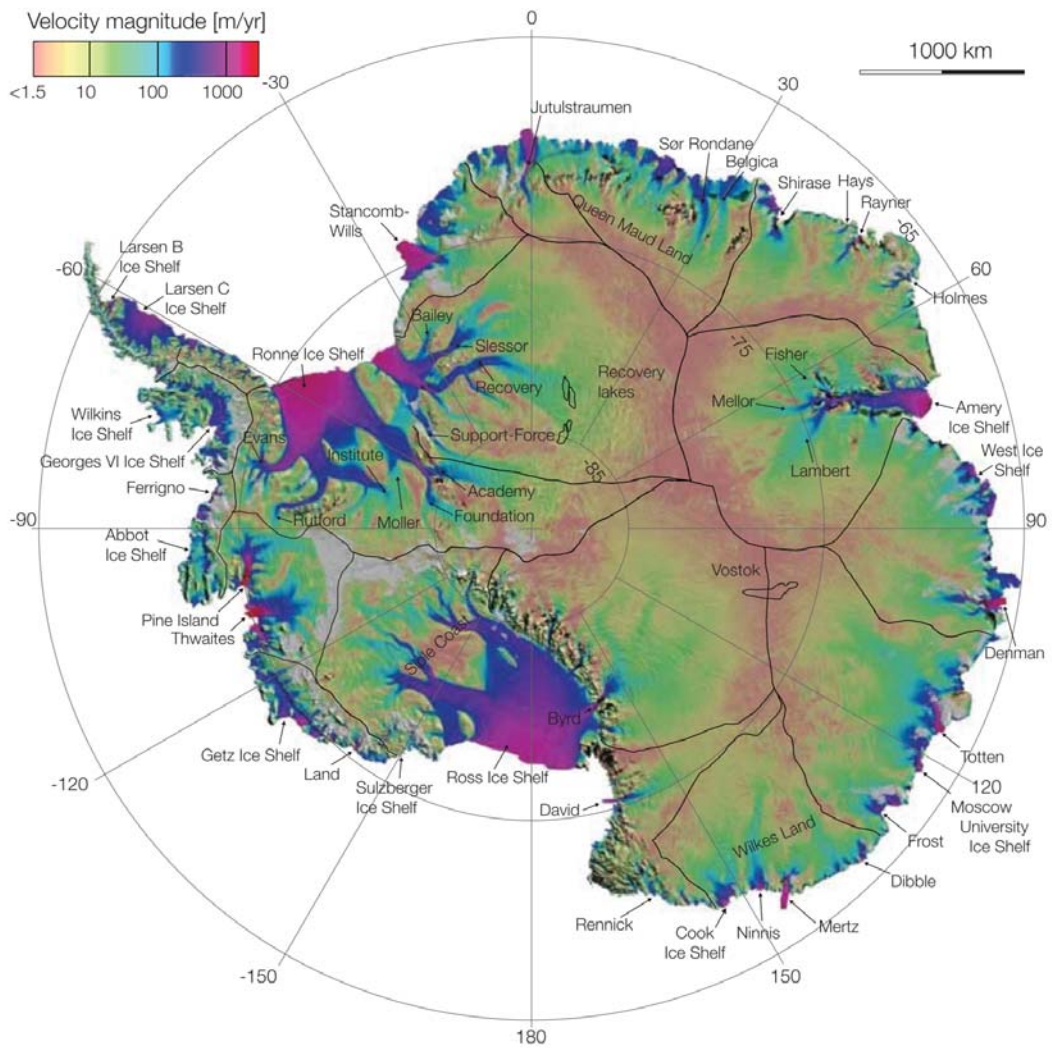


Figure 2: Ice speeds in Antarctica, from [13]

2 The Antarctic Ice Sheet and the Southern Ocean: An Introduction, *Adrian Jenkins*

2.1 Marine ice sheets and sea level

Marine ice sheets sit on bedrock that falls below sea level. At the edges of these ice sheets, floating ice shelves form where the ice is not thick enough to maintain contact with the bed. Antarctica sits on average 500m below sea level due to several factors: Antarctic topography, the weight of the ice sheet, tectonics and erosion of the continental shelf by ice flow. As a result, most ice shelves are found in Antarctica, where they cover an area comparable in size to the Greenland ice sheet > 1.561 million km². These are particularly found in West Antarctica where the ice is grounded in water 2km deep, in contrast to East Antarctica which is mainly sitting on a bed above sea level. Ice shelves form only 11% of the Antarctic ice sheet but control 80% of the outflow from the continent. Therefore, understanding the behavior of ice shelves is important for understanding the 0.5mm/yr contribution Antarctica makes to global mean sea level, 97% of which is contributed when ice crosses the grounding line.

Unlike terrestrial ice sheets where accumulation of snow directly balances the melting of ice at lower elevations, for marine ice sheets the mass balance is intimately linked with ice dynamics, where ice is lost to the ocean through iceberg calving and basal melting. Figure 3 shows the basal melt rates of Antarctic ice shelves where, in total, basal melting is the largest ablation process with basal melt of 1325 ± 235 gigatons per year (Gt/yr) versus 1089 ± 235 Gt/yr through calving [10]. Most of the current mass loss is balanced by the accumulation due to snow fall with the excess driving thinning of ice shelves, for example West Antarctica's ice shelves experienced a 134 Gt/yr mass loss during the period 2010–2013 [7]. Reductions in ice shelf thickness reduce the buttressing of the grounded ice allowing flow across the grounding line to accelerate and hence increase the rate of ice sheet mass loss [8]. The observed rate of ice loss is highest near the grounding line. This suggests ice shelf thinning in response to an increase in ocean-induced basal melting due to increased flux of Circumpolar Deep Water (CDW) onto the continental shelf. This increase in ocean-forced melting may have caused grounding lines to retreat onto a reverse slope which can trigger a runaway Marine Ice Sheet Instability (MISI).

Another possible process of ice sheet retreat is the Marine Ice Cliff Instability (MICI) [4] driven instead by atmospheric warming. Increased surface meltwater and summer rainfall on low topography can form ponds on the surface of the ice which drain into existing crevasses. It is thought that this allows water to penetrate into the ice causing it to fracture and eventually break off. An example of this is the Antarctic Peninsula's Larsen B ice shelf during its sudden break up in 2002. The Antarctic Peninsula is also one of the fastest warming regions in the world with an observed rise of $+0.53\text{C}/10\text{yr}$ pushing the surface temperature close to a critical threshold where the surface is warm enough to melt during the summer. Although most of the Antarctic sheet sees surface temperatures well below this threshold, trends of decadal atmospheric warming threaten to push the zone of melting further south towards larger ice shelves.

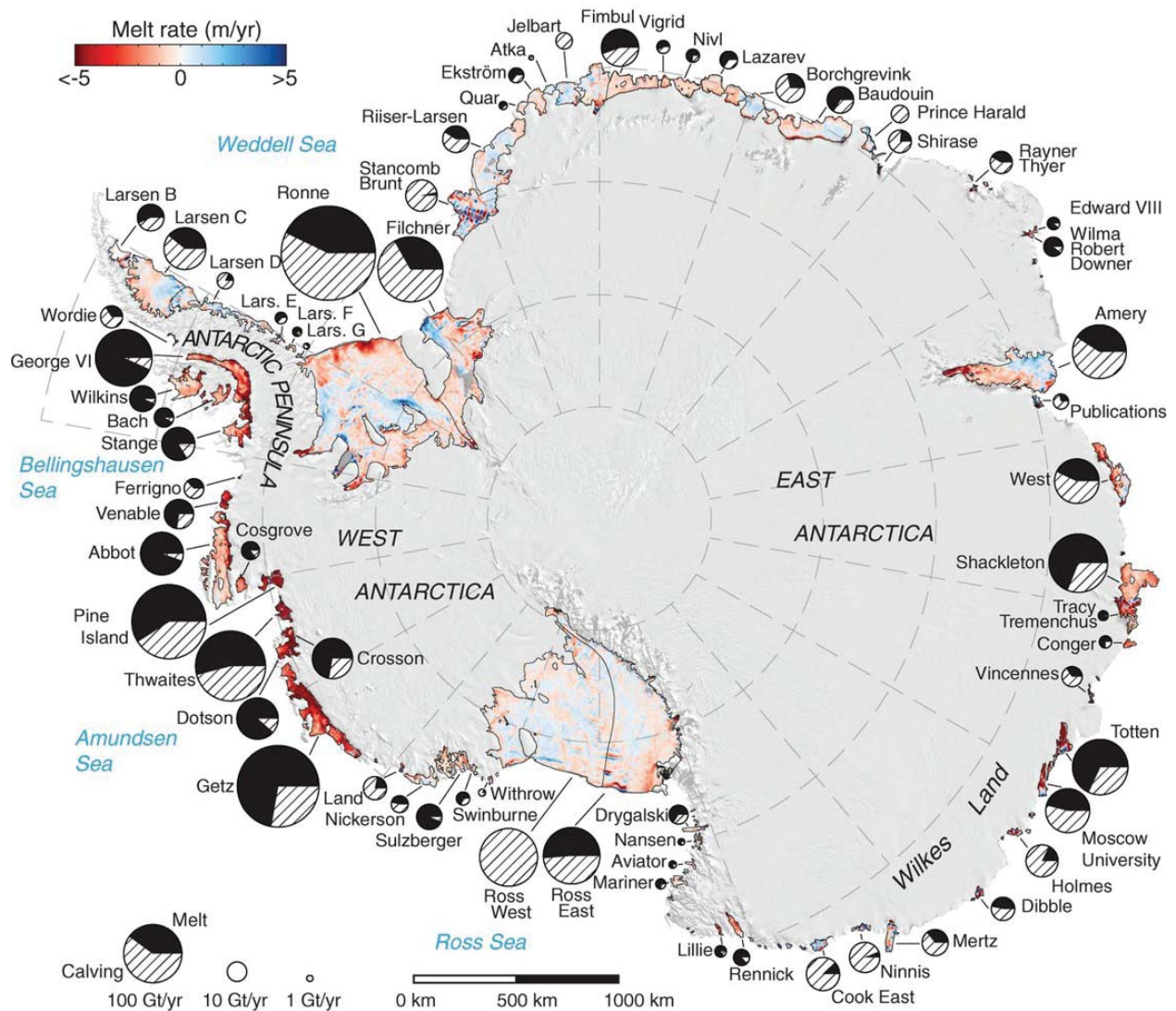


Figure 3: Basal melt rates of Antarctic ice shelves. Each circle graph is proportional in area to the mass loss from each shelf through ice-berg calving (hatch fill) and basal melting (black fill) [10].

The collapse of ice sheets due to atmospheric warming could lead to an instability when marine ice sheets have a depth of around 1km, > 90m of which is above sea level. As a result, the longitudinal stresses of the cliff face would exceed the yield strength of the ice (1MPa) leading to continued collapse until a reduction in temperature allows buttressing to reform. Again, if retreat moved the grounding line onto a reverse slope the MISI could take hold. This has been seen in Helheim and Jakobshavn glaciers in Greenland and Crane Glacier on the Antarctic Peninsula highlighting the importance of understanding the combination of MISI and MICI on an ice sheet. Figure 4 demonstrates these two methods of ice sheet retreat.

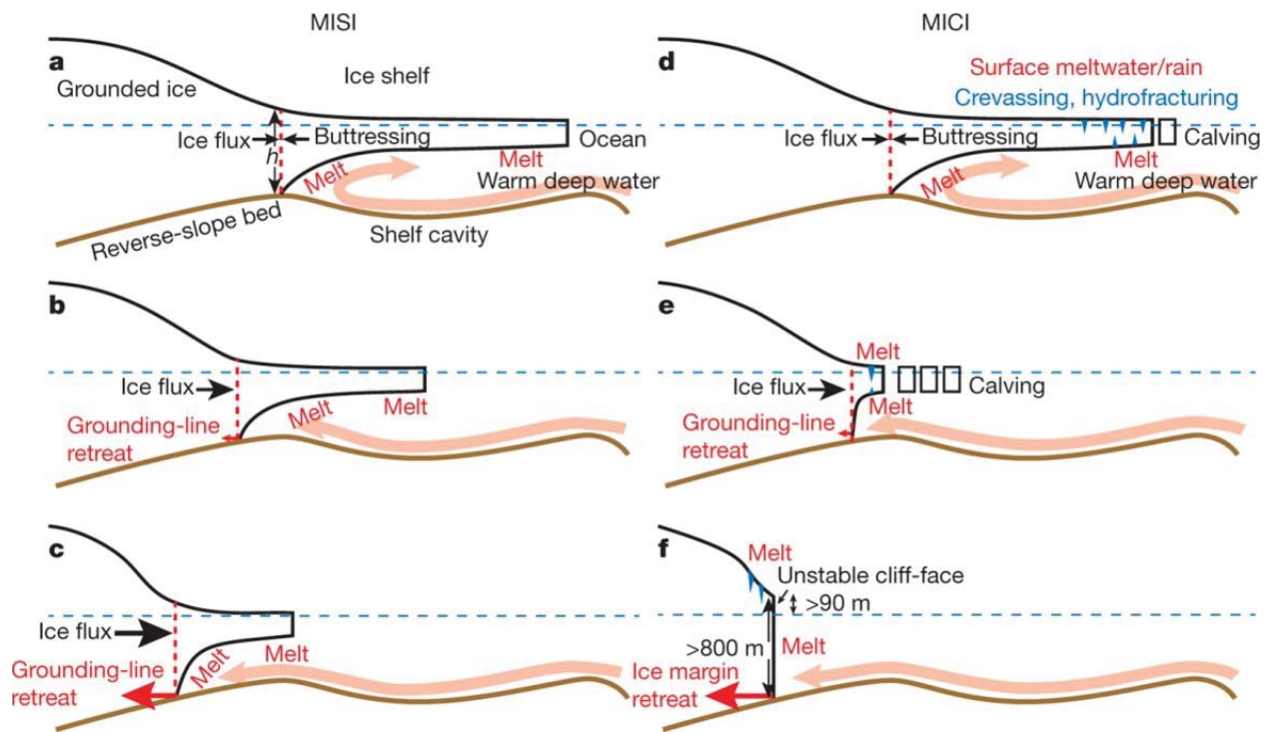


Figure 4: Schematic of MISI and MICI processes. (a-c) and (d-f) show ice retreat due to oceanic and atmospheric warming respectively. (a) Stable marine ice sheet with buttressing. Sub-ice melt rates increase with ocean warming and increased flux of the CDW onto the continental shelf. (b) Thinning of ice shelves due to sub-ice melting forcing the grounding line to retreat onto a reverse slope. (c) Grounding line positioned on a reverse slope triggers a runaway MISI. (d) Increased surface meltwater causes crevasses to fill up and eventually break off. (e) Increased calving provides another method of mass loss which, alongside MISI, causes the grounding line to retreat. (f) When continued calving breaks off the entire ice shelf, ice shelves with a height $> 800\text{m}$ with cliff face $> 90\text{m}$ become unstable and could collapse leading to further grounding line retreat leading to the MICI [4]

2.2 Ocean circulation near the Antarctic ice sheet and meridional overturning circulation

Differential solar heating causes vertical convection in the atmosphere which helps drive horizontal wind patterns with easterlies near the poles and in the tropics and westerlies at mid-latitudes. The westerly winds over the Southern Ocean are uninterrupted by land and so can drive the zonally continuous Antarctic Circumpolar Current (ACC), the largest wind-driven current on Earth, and the only current that connects the Atlantic, Pacific and Indian Oceans. These westerly winds coupled with the easterlies near the poles south of a minimum in mean sea level pressure drive surface divergence and upwelling of Circumpolar Deep Water (CDW). This water mass supplies heat and nutrients to the surface playing a key role in marine ecosystems in the Antarctic region. Similarly, north of these westerlies, there is a surface convergence which drives downwelling of fresh Antarctic Intermediate Water (AAIW). South of the ACC, salty water formed beneath sea ice then cooled beneath ice shelves sinks to form the Antarctic Bottom Water (AABW), the coldest, deepest water in the ocean, see Figure 5.

Similar to the Antarctic, cold North Atlantic Water sinks as North Atlantic Deep Water (NADW), which is transformed into CDW in the Southern Ocean. This upwelling brings saline water to the surface, which either freshens to form the downwelling AAIW, seen most notably on figure 6, or cools to join the fresh water from the continental shelf. However, further salt input from sea ice formed in the western Ross and Weddell seas is needed to increase the density of water sufficiently for the AABW to form.

North of the ACC surface water surrounding the Antarctic follows the meridional gradient, however south of the ACC subsurface temperatures on the shelf itself range significantly: from fresh water formed below floating ice shelves with temperatures below the surface freezing point, to warm waters from intruding CDW along the Pacific coast of West Antarctica with temperatures 3C above the surface freezing point.

3 Greenland Ice Sheet Changes: The Ocean as a Trigger and a Receiver, *Fiamma Straneo*

Greenland is changing rapidly and is losing mass at twice the rate of Antarctica. Observations from satellites have shown a loss of 2700 ± 930 Gt of ice between 1992 and 2011 from Greenland compared with 1350 ± 1010 Gt for Antarctica, contributing to a cumulative sea level rise of 7mm and 4mm respectively [14]. It is important to understand contributions to sea level rise and their uncertainties for informing future predictions (such as the IPCC report, which currently does not include ice sheet dynamics).

Greenland's increasing ice loss is also effecting many others processes. Maps of temperature data over the last century have shown an anomalous sub-polar North Atlantic cooling converse to the warming seen globally. This region of cooling compares well with climate models subject to a strong reduction in Atlantic meridional overturning circulation (AMOC) induced by adding a fresh water anomaly in the North Atlantic. If the climate models are forced further, an extension of the cooling region is seen causing a shutdown of the Labrador Sea convection, which has only briefly occurred so far [9]. Böning et al. 2016 [3] argue that

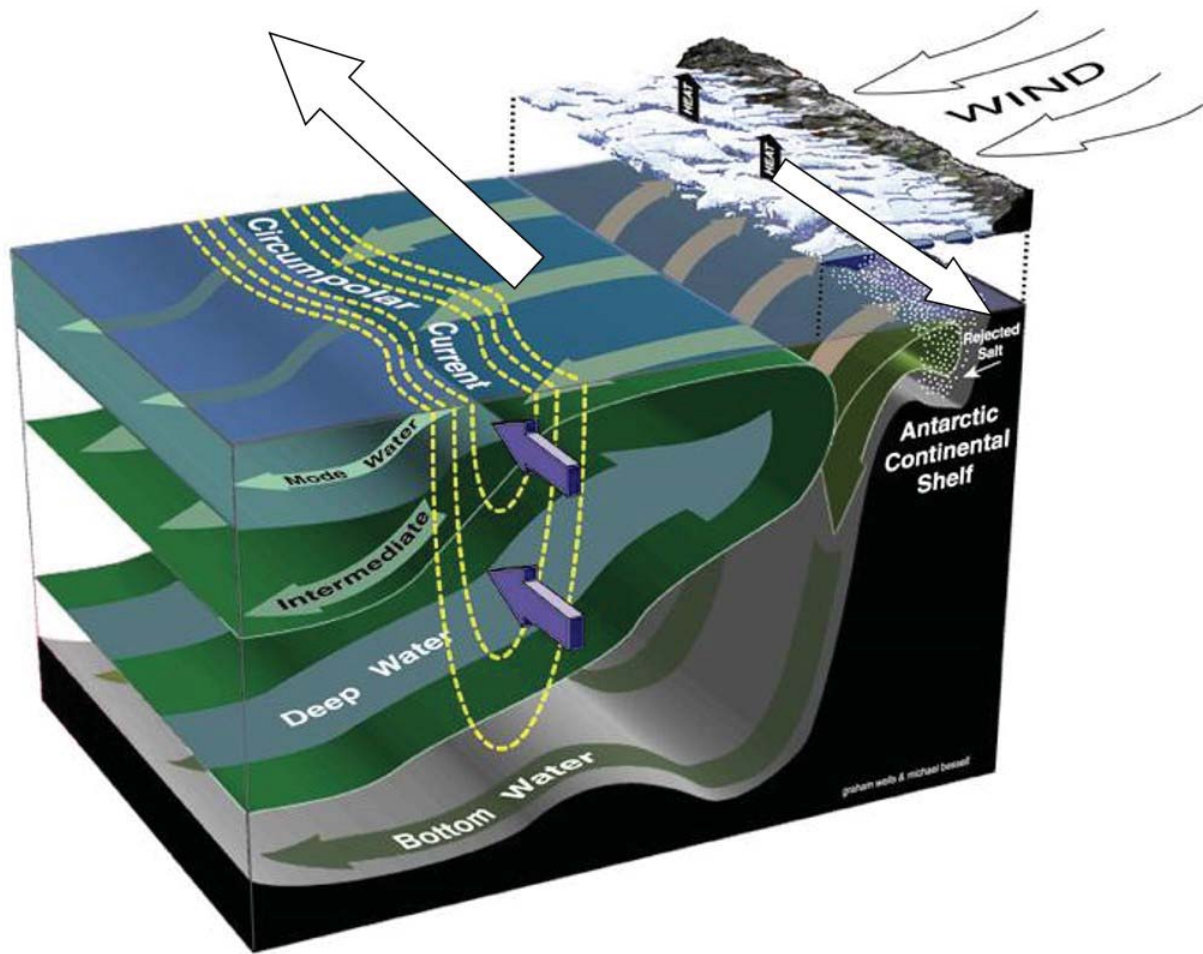


Figure 5: Schematic showing Ocean Circulation near the Antarctic Ice Sheet, particularly the upwelling of the CDW and downwelling of the AAIW and AABW in relation to the westerlies driving the ACC.

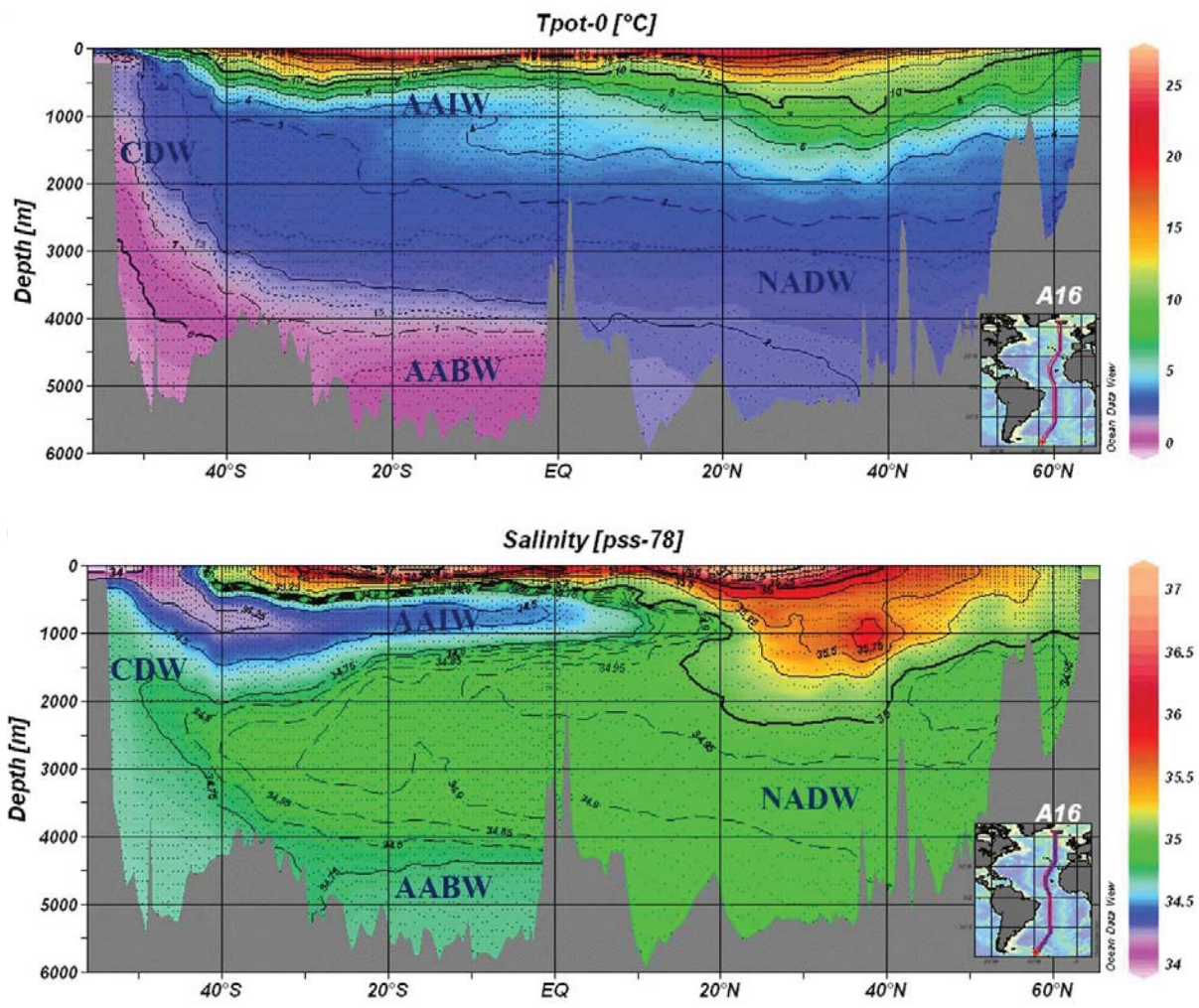


Figure 6: Cross sections of the temperature and salinity through the Atlantic.

the increased fresh water in the North Atlantic has currently not had a significant impact on the AMOC. However, continued freshening of the surface waters may begin to effect the formation of the NADW and hence the AMOC before clear signals are observed.

The peak in glacial discharge from Greenland occurs during the summer melt season, which coincides with the post-spring depletion of bloom nutrients. It is thought that Greenland's meltwater could be significant source of bioavailable iron and inorganic nutrients to the ocean through sediment at the base of glaciers. These would then form buoyant freshwater plumes allowing the maximum potential of primary productivity in the North Atlantic Ocean [2]. Increased aeolian Fe could explain recent evidence of a correlation between peak phytoplankton blooms and increased meltwater runoff from Greenland [5].

Freshwater anomalies have occurred previously. The Great Salinity Anomaly (GSA) in the 1970s caused deep convection to cease for three mild winters in a row and affected the Labrador Sea by freshening the surface layer. This increased ocean stratification and confined convective mixing to the top fresh layer. Very cold winters during 1971/1972 allowed convection to begin again to normal depths of around 1500m [6]. Currently the freshwater anomaly in the North Atlantic is about a third of the magnitude of the GSA with a cumulative freshwater output of $3200 \pm 358\text{km}^3$ since 1995 [1]. However, if the accelerating trend of increased fresh water discharge continues, it is estimated to exceed that of the GSA by 2025.

Ice sheet mass balance couples together the surface mass balance (SMB) due to accumulation, surface melt and sublimation and ice discharge (D),

$$\frac{DM}{Dt} = \text{SMB} - D, \quad (1)$$

where

$$\text{SMB} = \text{precipitation} - (\text{surface melt} + \text{sublimation}), \quad D = \text{ice bergs} + \text{ocean melt} \quad (2)$$

GRACE satellite data has recently shown that surface mass balance and ice discharge contributed roughly equally to the cumulative mass loss during the period from 1996-2015, with SMB accounting for between 40 – 60% loss and ice discharge the remaining 40% of loss [17]. In recent years, Greenland has had extreme melt years, for example in 2012 where the Greenland ice sheet was peppered all the way to the center with surface melt ponds. There has also been increased ice discharge moving ice from basins to the ocean. However, thus far models have struggled to constrain the contribution ice discharge makes.

During the last decade Greenland's large outlet glaciers have accelerated. Helheim glacier doubled its flow rate from 6km/yr to 11km/yr between 2002-2005 whilst Kangerlussuaq glacier almost tripled its flow rate from 5km/yr to 14km/yr between 2002-2005, with similar changes seen across the south of Greenland. These two glaciers had a combined mass loss of $208 \pm 15\text{km}^3$ during the period 2001-2005, or equivalently $51 \pm 8\text{km}^3/\text{yr}$. The increased flow rate increases longitudinal stresses in the ice and hence results in thinning rates of around 90m/yr contributing $0.31 \pm 0.07\text{mm}/\text{yr}$ to global mean sea level which is a significant portion of the 0.57mm/yr from Greenland as a whole [11]. This suggests that mass loss from glaciers in southeast Greenland is significant and hence understanding of the forcing that causes these rapid acceleration is important.

The Greenland ice sheet is influenced by waters originating in the North Atlantic (figure 7; red-yellow) and the Arctic (figure 1; blue). On the Eastern side of the continent the North

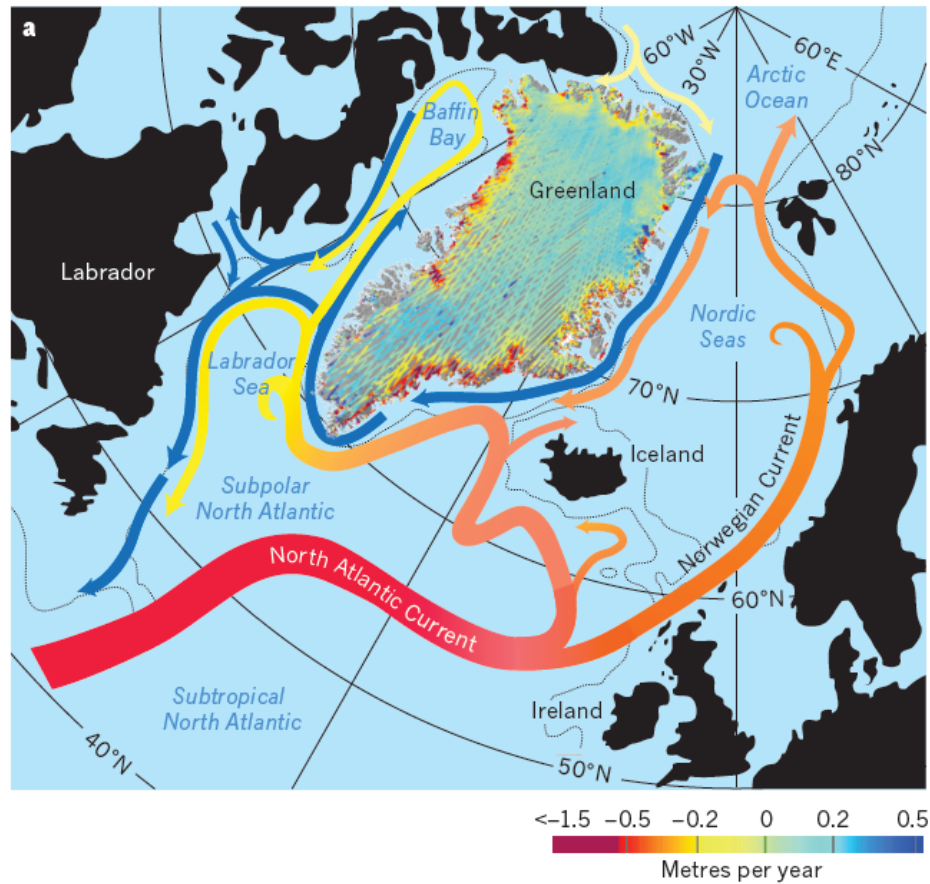


Figure 7: A schematic diagram showing the Ocean flow around Greenland overlain with the ice sheet elevation changes of the Greenland ice sheet. From [15]

Atlantic waters are much warmer than the Arctic water, but are separated from the land by a thin current of cold Arctic water. Without this layer of cold water the warm water would be able to melt the ice sheet.

Even with this layer however it is still possible for the warm Atlantic waters to reach ice shelves. This process occurs across many different scales. The large scale circulation determines the background temperature gradient and can be resolved by current models; mesoscale eddies that transport heat to the coast are significantly smaller; dynamics inside the fjords themselves are even smaller; heat transport between the water and the shelf occurs across a boundary layer that might be only millimeters to centimeters thick. Resolving the process across many scales is a major challenge for models.

Recent changes in the heat content of the North Atlantic appear to be driving changes in the glaciers surrounding Greenland. Observations of the subpolar Atlantic ocean show that there is a decadal variation in heat content, possibly related to the Atlantic Multidecadal Oscillation. Recently, the subpolar Atlantic ocean has seen the largest increase in temperature on current record. These changes are likely related to an inflow of warm subtropical

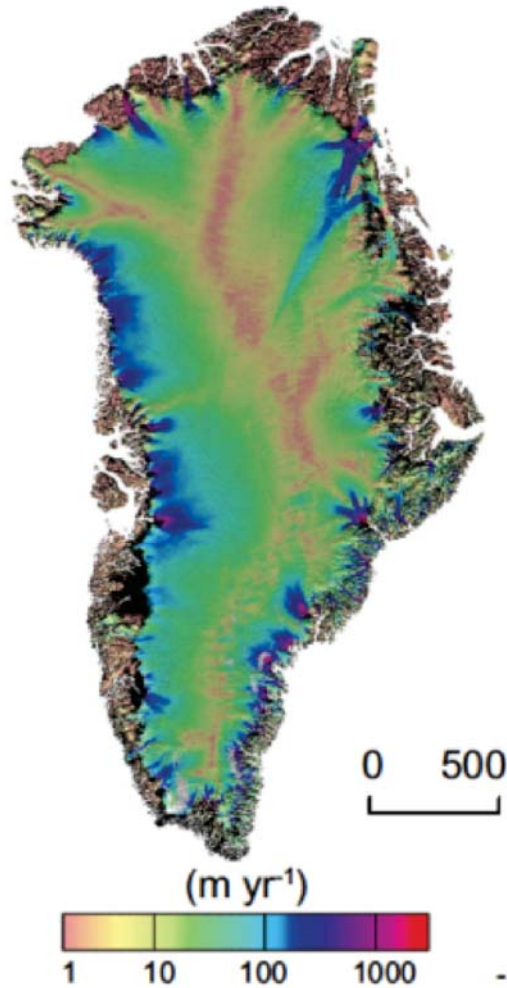


Figure 8: Ice velocity of the Greenland ice sheet. From [12]

waters. These waters have been warmed by increased atmospheric temperatures, but have not been able to propagate poleward into the subpolar Atlantic until the recent phase shift of the North Atlantic Oscillation.

Observations of ice velocity of the Greenland ice sheet show many ice streams carrying ice to the coast, especially on the southeast side (figure 8). Recent reconstructions of the surface elevation have shown that the Greenland ice sheet is not only losing mass, but that the ice rate itself is accelerating. The reconstructions are derived by differencing the observed elevation changes with the observed surface mass balance budget; the residual can be attributed to ice dynamics. The reconstructed data shows an acceleration in the ice, particularly on the southwest side of the continent. Although reconstructions and models have been able to provide us with important information, they have to be constrained by observations in order to provide reliable information since so many of the processes controlling the retreat of the ice sheet are small scale and parameterized in models.

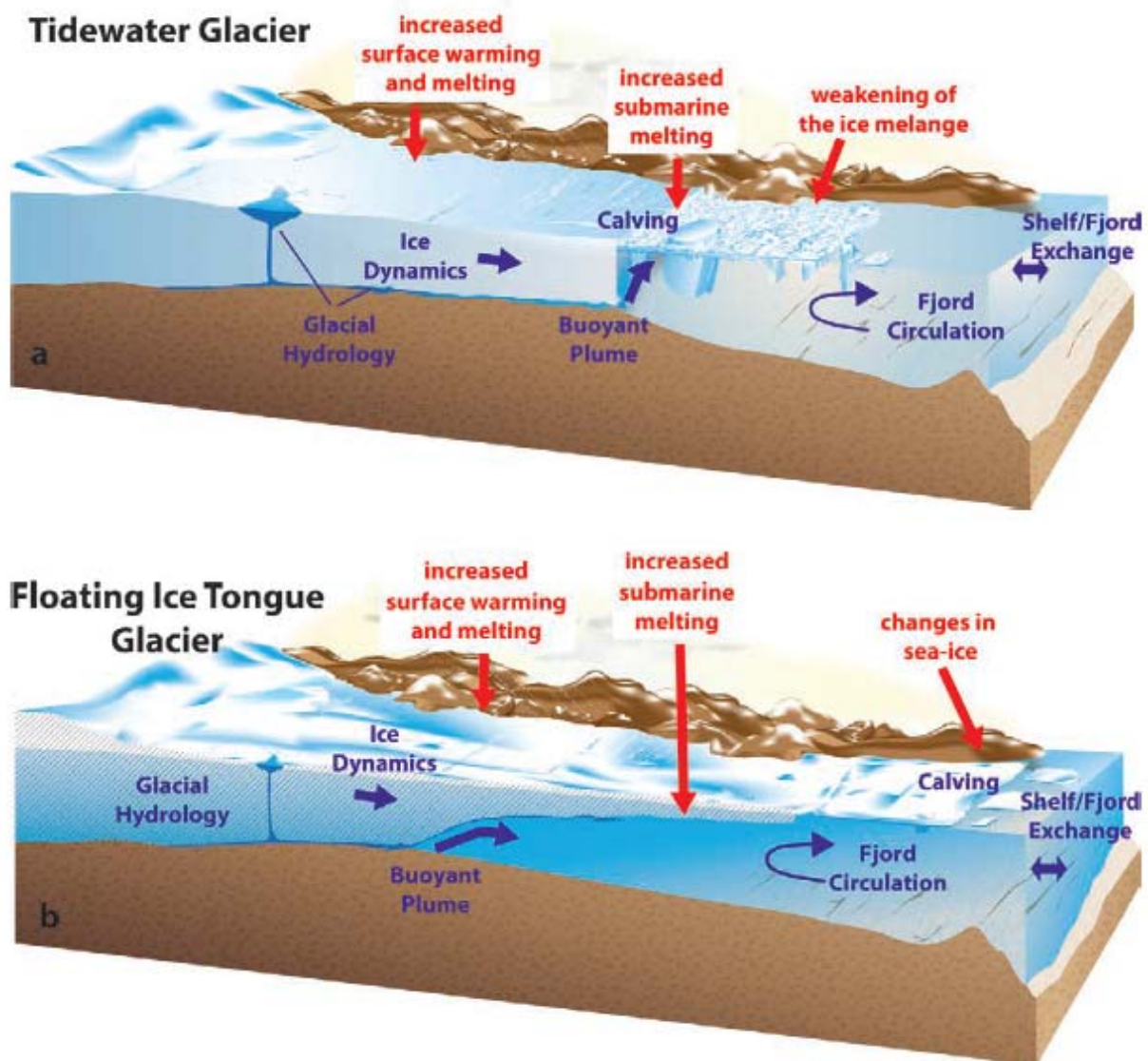


Figure 9: A: A schematic diagram showing the mechanisms by which a tidewater glacier is able to lose mass into the ocean. B: A schematic diagram showing the mechanisms by which a floating ice tongue glacier can lose mass. From [16]

In order to improve our understanding of the mass changes in the Greenland ice sheet we need to understand the different mechanisms for ice loss (figure 9) and their relative magnitudes. For both Tidewater glaciers and Floating Ice Tongue glaciers, increased surface warming from the atmosphere and increased submarine melting driven by warm Atlantic waters circulating in the fjord can cause an increase in ice speed. This could affect the two types of glaciers in different ways since the ice dynamics transporting ice to the ocean and the contact with the ocean look very different between the two cases. Since the problem of

melting Greenland glaciers touches many different subjects, including glaciology, oceanography, hydrology and geology, a multi-disciplinary approach is needed.

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