Final Report

ARI: The water-mass signature and pathways of Greenland Ice Sheet meltwater in the Arctic and North Atlantic as inferred by an inverse method

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Nearly all Greenland outlet glaciers show thinning, retreat, and acceleration of ice flow over the past few decades. This project has addressed two **primary questions**: 1) can the rate of melt of Greenland be inferred from already-collected ocean observations, and 2) what is the fate of the meltwater in the ocean. Recently, observations from satellite stereo imagery, laser altimetry, and elastic uplift of the crust show the accelerating ice loss from the Greenland Ice Sheet. Unfortunately,the interpretation of these observations requires a difficult calculation in which the melt rate is the difference of large numbers with large uncertainties. For this reason, we pose question (1), and we show that ocean observations may provide key information. Question (2) depends upon the tracking of the path of meltwater in the open ocean, a quantitative estimate of its dilution in ambient waters, and a large-scale view of how coastal meltwater is mixed into the ocean interior. The ocean circulation may passively move meltwater, but meltwater may also change circulation patterns in an active way. To answer both primary questions, our goal is to reconstruct the location of the sources of meltwater, including the particular fjord and the depth of the injection, which has important implications for understanding submarine melting at the ice-ocean interface. Furthermore, the total volume of meltwater from each location can be ascertained, and with the addition of circulation rate constraints, the meltwater rate is recovered.

The project has clear **implications for society**. The Intergovermental Panel on Climate Change (IPCC) issues projections for 21st Century climate that suggest that sealevel will rise by up to 3 feet over the next century, with obvious consequences for low-lying island nations, developing nations that have millions of inhabitants of the coastal zone, and the effect of storm surge during hurricanes such as Sandy. Much of today’s sealevel rise is due to the warming and expansion of the ocean, but such an effect is limited to just a few feet. The potential big surprise in the projections comes from the fate of ice trapped on Greenland. If it melts, sealevel will rise up to 25 feet, swamping any other effects. The rate at which this could happen is not captured by the IPCC projections, although they do acknowledge the possibility that Greenland’s collapse could be rapid.

The processes that surround the melt of Greenland ice is **significant for the research of others in the field**. Greenland’s outlet glaciers terminate in the multitude of fjords that ring Greenland, where contact with warming ocean waters may contribute to the observed recent changes. Besides the effects of the ocean on the Greenland ice, large quantities of meltwater are supplied to the ocean in the fjords, leading to the transformation of the properties of seawater with consequences for the ocean circulation.

The properties of the meltwater are quite distinct: very cold, fresh, super-saturated in dissolved oxygen, and with an abundance of light oxygen-isotopes. Such waters are present in relatively small volumes in the open ocean, but the distinctness of the signal gives hope that their influence on seawater properties can be tracked far from the source region. The pathways are critical because they have been fingered in circulation models as a link between ice sheet melt and the basin-wide Atlantic circulation, a process implicated in both the Ice Ages and future climate scenarios, but we have relatively-little observational information to determine the validity of that view. In summary, the project has relevance to physical oceanographers, glaciologists, and paleoceanographers.

This **key tool** of this project is a mathematical framework that allows the fusion of models and observations in the Arctic, with an eye toward including in-situ information from other ARI projects in one synthesis. This is a means of adding value to new and existing data sets. Here we build upon a new statistical technique (Total Matrix Intercomparison, TMI) that combines hydrographic information collected from research cruises during the World Ocean Circulation Experiment (WOCE) and a numerical model of ocean pathways. Previously, this method quantified the volume of ocean water that originates from the global sea surface with over 10,000 unique water sources, and here we extend the method to include sources of water from the Greenland outlet glaciers.

This research **was conducted in a number of locations over the last two years.**
In 2010, I organized a summer school on Ice Sheet-Ocean interactions that was held in Norway at 70 degrees North latitude. An ongoing collaboration with Adrian Jenkins at the British Antarctic Survey was forged at that school. Preliminary results were first discussed at the International Glaciological Society meeting at their 2011 annual meeting held at the Scripps Insitute of Oceanography. WHOI Summer Student Fellow Joseph Wenig carried out the bulk of research on the topic in 2012 while in residence at WHOI. His outstanding work was rewarded by being one of just five Summer Student Fellows to be awarded a trip to present his work at an international conference. He chose to attend and present the work on ice sheet melt at the American Geophysical Union Fall Meeting in San Francisco, 2012, as part of a specific session on ice sheet-ocean interaction. His research is chronicled in more detail next.

A complication in studying Greenland ice melt is the source of two types of meltwater: one from the surface and one from underneath ice cavities. The different melting processes have a big effect on the temperature and dissolved oxygen content of the water. To avoid this complication, SSF Wenig and I first concentrated on developing the key tools for Antarctic data where surface melting is minimal due to the cold atmosphere there. In this research, we used the ocean data from the World Ocean Circulation Experiment and an inverse method to build up ocean circulation pathways based on a steady state assumption. We unambiguously demonstrated a plume of Ice Shelf Water emerging from the Filchner Ice Shelf Front, primarily at a depth of around 400 m (consistent with prior observations, e.g. Nicholls et al. 2001). Under our newly-formulated model, the observed distribution of potential temperature is only fit within its published error (0.01 °C) if the Filchner Ice Shelf front is included as a source, indicating that the front is indeed a crucial source of water properties for the Weddell Sea and, by extension, the global ocean.

Products and References

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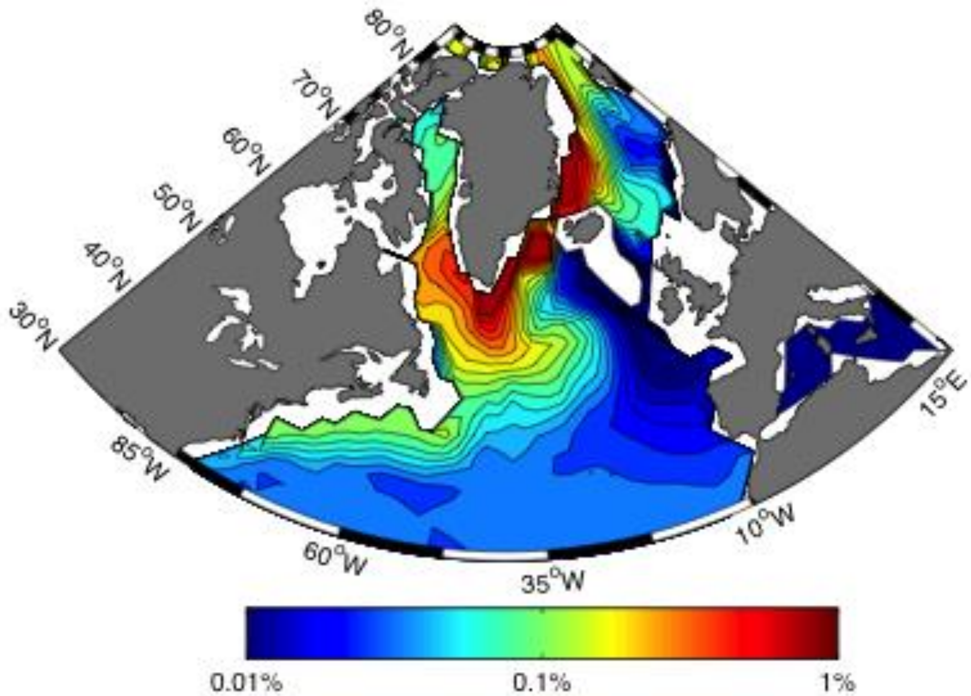

Figure 1: The equilibrium pathway of Greenland Ice Sheet meltwater injected along the East Greenland Shelf at depths of up to 500 meters, with the assumption that the volume of meltwater is 1% of seawater at the shelf break. (This spatial pattern is not sensitive to this assumption.) The figure shows the percentage of ocean water between the surface and 1000 meters that originated on the Ice Sheet. Meltwater is swept around the West Greenland Current and southward by the Labrador Current into the subtropics, but a large portion of meltwater is shunted into the interior of the subpolar gyre as well.

Figure 2. Meltwater concentration (parts per thousand) at 300 m depth in the Weddell Sea, calculated using our newly-developed reconstruction method. Already-collected ocean observations show the unambiguous signal of the melt of the Ronne-Filchner Ice Sheet, without the need of satellite data.