

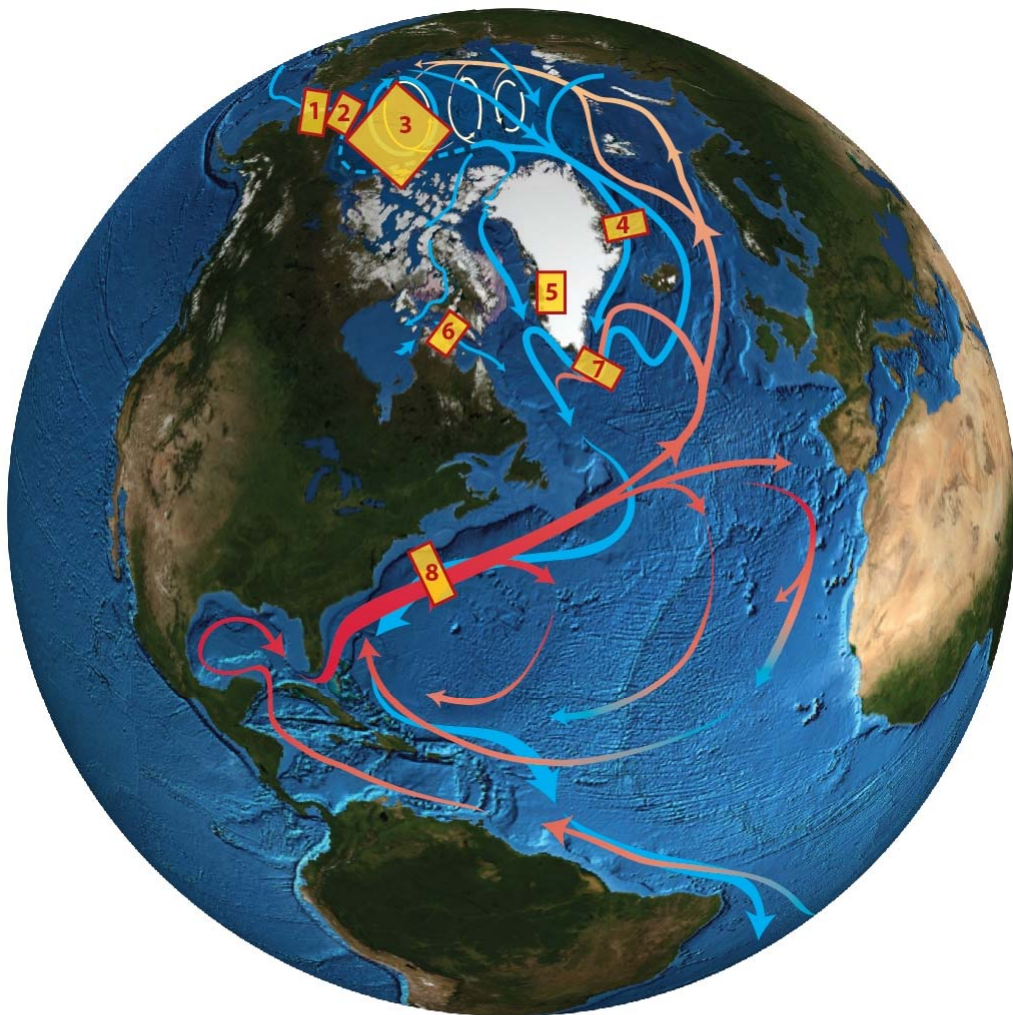


WOODS HOLE OCEANOGRAPHIC INSTITUTION

Report to

THE COMER SCIENCE AND EDUCATION FOUNDATION

March 2011



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Background Summary

In 2002, two decades of research had led climate scientists to the conclusions that Earth's climate can change abruptly and dramatically. Observed in the geological record, the changes can cause widespread regions to become much colder, warmer, wetter or drier within a few decades. It was also becoming clear that the circulation of the North Atlantic played a key role in these climate changes by abruptly changing its mode of circulation. Nearly always the changes in circulation were associated with a change in North Atlantic salinity – rapid melting of ice sheets and discharge of ice bergs reduced the salinity of the surface waters and inhibited deep water production, which in turn reduced the northward flow of the warmer waters that are responsible for the unusual warmth of the circum-North Atlantic region.

At the same time, oceanographers who study the modern ocean were observing unprecedented changes in the salinity of the North Atlantic. Since the 1960s, North Atlantic subpolar waters had become steadily fresher, while the tropical Atlantic surface waters had become saltier. Although analogous to the freshening associated with the abrupt climate changes in the geological record, it was unclear if the present-day rates of change were large enough to cause disruptions to the circulation of the North Atlantic in the near future. The prospect of continued global warming and the increased melting of the ice on Greenland and in the Arctic Ocean made the study of this system extremely important for predicting changes in climate over the next few centuries.

WHOI Actions

To stimulate creative scientific thinking on these issues and devise a research strategy to address them, the Ocean and Climate Change Institute (OCCI) at Woods Hole Oceanographic Institution (WHOI) planned an Ocean Forum on Abrupt Climate Change in the fall of 2002.

With support from The Comer Science and Education Foundation, the OCCI invited four leading scientists in the field of abrupt climate change to Woods Hole as Visiting Summer Scholars. Their broad range of expertise and perspectives complemented those of WHOI scientists. The Ocean Forum Scholars included: Richard Alley (Pennsylvania State University), David Battisti (University of Washington), Mark Cane (Columbia University), and Robert Dickson (Centre for Environment, Fisheries and Aquaculture Science, UK). In the fall of that year, the Visiting Scholars and numerous other climate scientists convened for the forum in Woods Hole to summarize their work and to develop strategies to accelerate advances in abrupt climate change research, and outline specific initiatives WHOI could launch to contribute most forcefully to this overall effort.

The results of these activities are summarized in the booklet included with this report:

“The Critical Role of the North Atlantic and Arctic Oceans in Abrupt Climate Change – A Scientific Strategy.” This research strategy dominated the scientific agenda of WHOI's OCCI for the next nine years, and a significant amount of research was



accomplished with support from The Comer Science and Education Foundation through two major grants: \$1 million in 2002 to WHOI specifically for OCCI, and \$5 million in discretionary funds in 2003, which WHOI used primarily for climate change research. Between 2002-2008, 34 WHOI PIs and two international researchers were awarded funds from The Comer Science and Education Foundation to work on 34 different projects. Results are still being produced from those investments.

Accomplishments over the past Nine years with Comer funding:

First and foremost, funds from The Comer Science and Education Foundation have enabled the establishment of a set of essential (many permanent) observing systems in critical areas of the Arctic and North Atlantic Oceans to monitor changes in climate. These systems cover nearly every major gateway and pathway for flow of freshwater from the Arctic to the North Atlantic Ocean (see the map on the cover).

These observing systems include stations:

- north of the Bering Strait to study the exchange of water between the Pacific Ocean and the Arctic – including the development of a new mooring system for under ice measurements
- north of Barrow, Alaska – including the development of a new generation of vehicles capable of navigating beneath sea ice in the Arctic ocean
- in the Beaufort Sea where sea ice accumulates before it is ejected from the Arctic Ocean (now a permanent observing system supported by the National Science Foundation)
- at several locations along the east coast of Greenland, where ice bergs and freshwater flow southward toward the locations of North Atlantic deep water formation
- in the Hudson Strait, another pathway for fresh water flow to the North Atlantic
- on the top of the Greenland ice sheet to measure surface melting, ponding of meltwater, and ice sheet fracturing
- across the Gulf Stream-Deep Western boundary current system southeast of New England (Line W – now a permanent observing system supported by the National Science Foundation)

Observations from these systems and others have revealed the following key insights:

- 1) While the North Atlantic waters continue to freshen, the rate of Greenland melting due to warming and the decrease in North Atlantic salinity are not yet rapid enough to cause the kind of abrupt climate changes observed in the



- geological record. However, future melting of the Greenland ice sheets could accelerate significantly due to the effect of warmer Atlantic waters entering the Greenland fjords where glaciers are expelling ice into the ocean. As the ice melts in the fjords from underneath, it destabilizes the glacier and speeds up the slide of the glacier into the ocean, raising the sea level and adding additional fresh water to the ocean. This is an area of new, emerging research on the relationship of oceans and ice sheets.
- 2) The warm Atlantic waters that enter into the Arctic are so far having little impact on the Arctic sea ice. The extremes observed in summer sea ice melting result more from warming of the atmosphere and shifting winds than from heat exchange from below. Atlantic waters continue to warm, however, so their impact on the Arctic may increase with time.
 - 3) The Atlantic Meridional Overturning Circulation (MOC, which carries warm upper waters into far-northern latitudes and into the Arctic and returns cold deep waters southward) is much more variable than previously thought. Researchers are still working on the implications of this observation, but one consequence may be that short term oscillations in its flow may have little impact on climate. We have observed this behavior from the wealth of data obtained by the RAPID program, a joint UK-US research program to study the MOC. The Line W observing system is an important part of the Rapid program.

In addition to these major scientific findings, funds from The Comer Science and Education at WHOI helped launch or significantly boost the professional development of numerous early career scientists and postdocs at WHOI. Nine Assistant Scientists dedicated to climate change research have benefited by Comer support, and the majority of them have been promoted to Associate Scientists already. These young scientists have accomplished research that provided some of the key findings of the past decade that have come out of Woods Hole Oceanographic Institution. These scientists include:

Fiamma Straneo (now Associate Scientist in Physical Oceanography at WHOI)
Mary-Louise Timmermans (now Assistant Professor at Yale University)
Peter Winsor (now Associate Professor at University of Alaska, Fairbanks)
Jeff Donnelly (now Associate Scientist in Geology and Geophysics at WHOI)
Sarah Das (now Associate Scientist in Geology and Geophysics at WHOI)
Mark Behn (now Associate Scientist with tenure in Geology and Geophysics at WHOI)
Laura Robinson (now professor at Bristol University, UK)
Ilya Buynevich (now Assistant Professor at Drexel University)
Andrew Ashton (Assistant Scientist in Geology and Geophysics at WHOI)

The following detailed reports cover just a few of the many projects supported by The Comer Science and Education Foundation at Woods Hole Oceanographic Institution in recent years. (These were funded specifically by the discretionary funds allocated between 2005-2008.)



Where the Arctic meets the North Atlantic

Robert S. Pickart

Physical Oceanography Department

Denmark Strait, the narrow strip of ocean between Greenland and Iceland (Figure 1), is a critical “choke point” in the northern hemisphere’s system of currents. Here, much of the dense water formed in the Arctic domain enters the North Atlantic and subsequently sinks to depth. This process is a critical part of the Atlantic Meridional Overturning Circulation (MOC), which helps regulate the climate of our planet. Not surprisingly, the dense outflow through the strait (called Denmark Strait Overflow Water, or DSOW) has been the topic of a great number of studies spanning more than half a century. The present understanding is that, after the plume of deep water passes over the sill of the Denmark Strait, it descends the continental slope into the Irminger Sea and entrains ambient water to form a substantial current known as the Deep Western Boundary Current. This deep current (after merging with another branch further south) proceeds to flow past the equator into the south Atlantic, and into other parts of the world ocean. It is important to understand the sinking process at Denmark Strait – where and how the sinking happens and to what depth the water penetrates – in order to understand the ramifications on the MOC and hence on climate.



Figure 1: Denmark Strait is located between Greenland and Iceland.

A number of years ago we conducted the first high-resolution hydrographic/velocity transect south of Denmark Strait that extended from the east Greenland shelf into the deep part of the Irminger Basin. Surprisingly, not only did we observe the deep plume of DSOW near the base of the continental rise, but also we discovered a new current on the upper slope. This jet was also transporting dense water southward, but it was extremely narrow – and extremely fast. We hypothesized that the dense water in the shallower jet did not emanate from the deepest part of Denmark Strait (i.e., with the main overflow plume) but instead spilled over the continental shelf south of the strait to form the current. Consequently, we named the feature the “East Greenland Spill Jet.” If this feature is permanent, then it represents a new paradigm for part of the dense water exiting the Arctic into the North Atlantic. With this data, we posed the question, “Does a significant fraction of the DSOW remain on the continental shelf (instead of sinking with the deep plume) and subsequently spill over the shelf-edge farther south?” If so, this raises a host of new and important questions about the fate and impact of a portion of the deep MOC.

These results motivated a new field program to investigate the existence and source of the East Greenland Spill Jet. The desire of my colleagues and I was to deploy a mooring array across the current (and the deeper DSOW plume as well) to obtain year-long timeseries of the flow and its hydrographic properties. However, such a venture was



risky and expensive. The risks were threefold: icebergs pass through the region, it is a site of commercial trawling, and our initial results indicated that the currents were extraordinarily strong. All of these risks could damage or destroy moorings, making this project difficult to fund via traditional sources. However, with support from the Comer Science and Education Foundation, and through WHOI's Ocean and Climate Change Institute, we were able to deploy the array. Moreover, this seed funding subsequently enabled us to obtain a grant from NSF to recover the array and analyze the data.

In the summer of 2007, on the Icelandic fisheries vessel *Arni Fridriksson*, we deployed seven moorings that spanned the Spill Jet as well as the traditional (deeper) Deep Western Boundary Current (Figure 2). We went to great efforts to contact fishing companies around Greenland and Europe to ask them to steer clear of the array. To sample at shallow depths and minimize the risk posed by icebergs, we deployed a "sacrificial" sensor 50 meters above the main top float of the mooring. Our reasoning was that if an iceberg snagged the shallow sensor, the weak link between the sensor and the mooring's main top float (situated at 100 meters) would break and we would lose the shallow sensor, not the entire mooring.

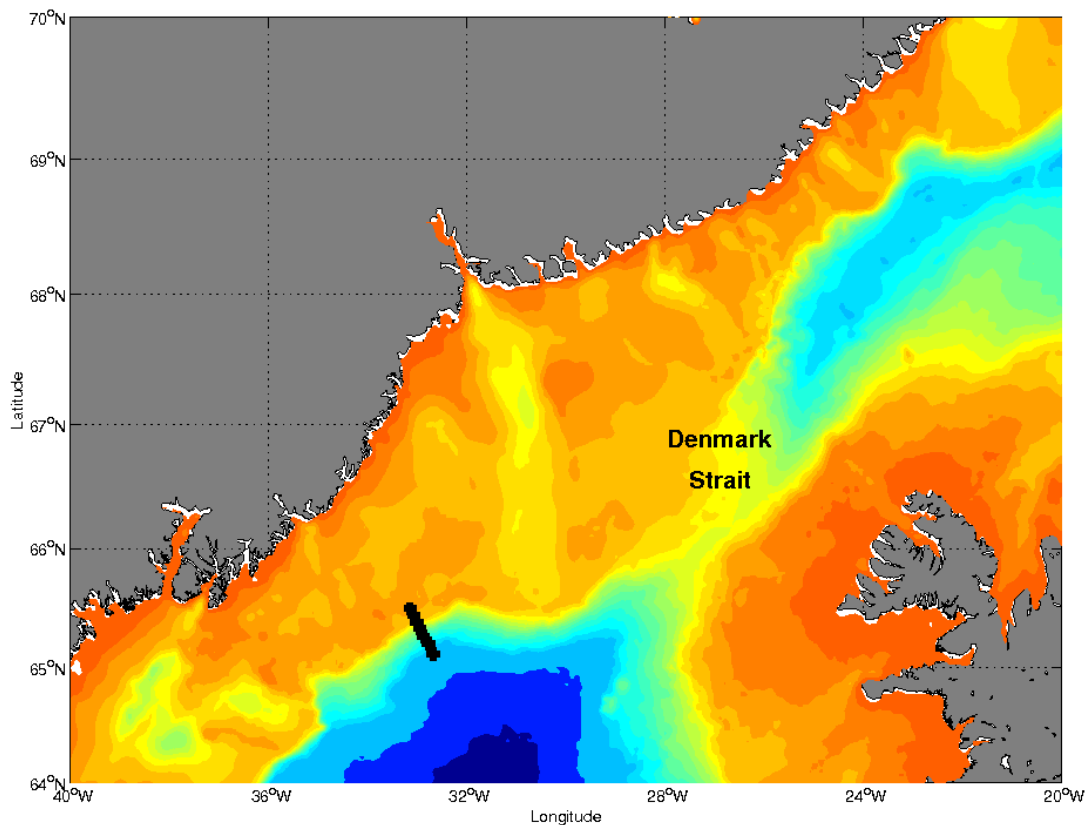


Figure 2: Mooring array (thick, black line) extending from the edge of the East Greenland shelf to the continental rise of the Irminger Sea south of Denmark Strait. The array was deployed from September of 2007 through October of 2008.



After a year of keeping our fingers crossed, we recovered the mooring array on the R/V *Knorr*. The good news is that all of the moorings were still intact. However, there were some issues. Firstly, none of the sacrificial sensors remained above the top float. This was not the result of icebergs, but rather the strong currents – we underestimated the strength of the Spill Jet. It is the most intense current that I have ever measured, and the small floatation units used on the 50-meter sensors were shaken so violently that they fell apart within weeks of the deployment. Secondly, as the year progressed, one by one the moored profilers within the center of the jet stopped functioning. This was also most likely the result of the energetic environment. Finally, even when the profilers were working, there were often strong flow events that bent the moorings over and caused a temporary disruption of the data collection. In short, the moorings took a beating. However, compared to the information we had previously (a handful of snapshots from ships) obtained, the new data we acquired was more than enough to answer the questions we had posed.

Our hypothesis stated that the spilling of dense water off the shelf to form the Spill Jet was caused by two different phenomena: instabilities (natural variations) of the shelf flow, and wind-driven off-shelf transport due to storms. The region near Denmark Strait is one of the stormiest places in the world ocean, situated directly beneath the North Atlantic storm track. As storms progress northward, the northeasterly flow at the leading edge of the storm collides with the high topography of Greenland's coastline causing a "barrier wind." We surmised that these intense winds paralleling the coast – often near hurricane strength – could force dense water off the shelf. During the recovery of the moorings, we encountered such a barrier wind event (Figure 3), giving us a unique opportunity to experience this phenomenon and collect atmospheric measurements from the ship.



Figure 3: R/V *Knorr* negotiating high waves during the barrier wind event near the mooring array.



Barrier winds are common in the region of Denmark Strait. Using data from the European Centre for Medium-range Weather Forecasting (ECMWF), we constructed a composite average of all of the high speed barrier wind events during the course of the mooring deployment (Figure 4). As the figure shows, the enhanced winds were adjacent to the coast of Greenland, both in the vicinity of the array and farther to the north. During the course of the 15-month deployment there were 42 barrier wind events during which the wind exceeded 20 ms^{-1} (45 mph). Although not evident in the mean composite, sometimes the winds were strongest near the array site, and other times the highest winds were to the north.

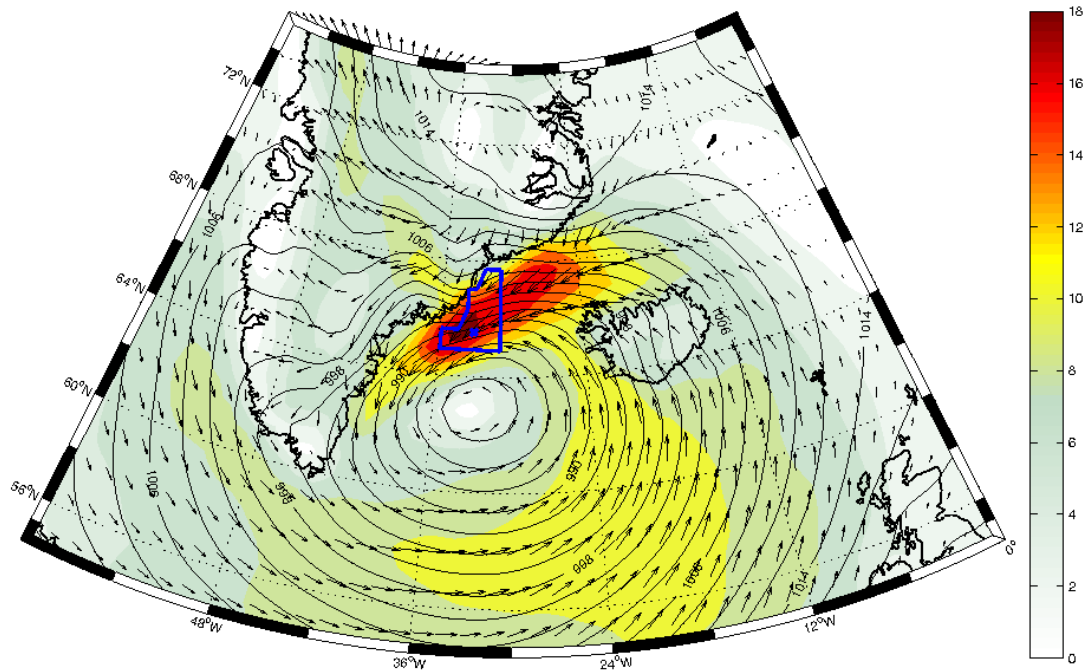


Figure 4: Composite of the barrier wind events when the mean wind speed within the blue polygon exceeded 20 ms^{-1} . The blue asterisk marks the location of the mooring array. Wind speed is indicated by color, and the flow vectors are overlaid. The contours denote sea level pressure.

On a rotating planet, the oceanographic response to such high winds near a coast is typically enhanced flow in the direction of the wind, in this case towards the southwest. This is referred to as the primary flow. In addition, the flow should be directed to the right of the wind (in this case onshore) in the surface layer, while at depth there should be a component of flow directed offshore. These onshore/offshore currents are called the secondary circulation. Hence, if dense water is located near the bottom of the shelf – in particular any DSOW that remained on the outer shelf – it might be forced offshore by the deep secondary flow. This in turn would cause the dense water to sink once it passes over the edge of the shelf, thereby feeding the Spill Jet. Our mooring records revealed the presence of such a secondary circulation pattern during barrier wind events, driving dense water off the shelf.



Figure 5 shows the lagged correlation between the wind and the primary (alongshore) and secondary (cross-shore) velocity from one of the moorings located at the outer shelf. The left-hand panel shows a strong positive correlation throughout the water column between the winds and the alongshore flow, at near-zero lag. This means that the alongshore flow increases quickly as the wind blows. The right-hand panel shows a positive correlation near the surface (i.e., onshore flow) and a negative correlation at depth (i.e., offshore flow) also at near-zero lag. Hence, these results imply that the barrier winds drive part of the spilling. Interestingly, Figure 5 also reveals a second peak of strong alongshore correlation 3-4 days after the storm, along with enhanced negative offshore correlation at depth during this same time period. We believe that these latter peaks are due to a delayed response from remote winds via wave propagation (recall that the barrier winds are often strongest north of the array). We are presently investigating this finding more carefully with the mooring data and attempting to simulate this process using a numerical model.

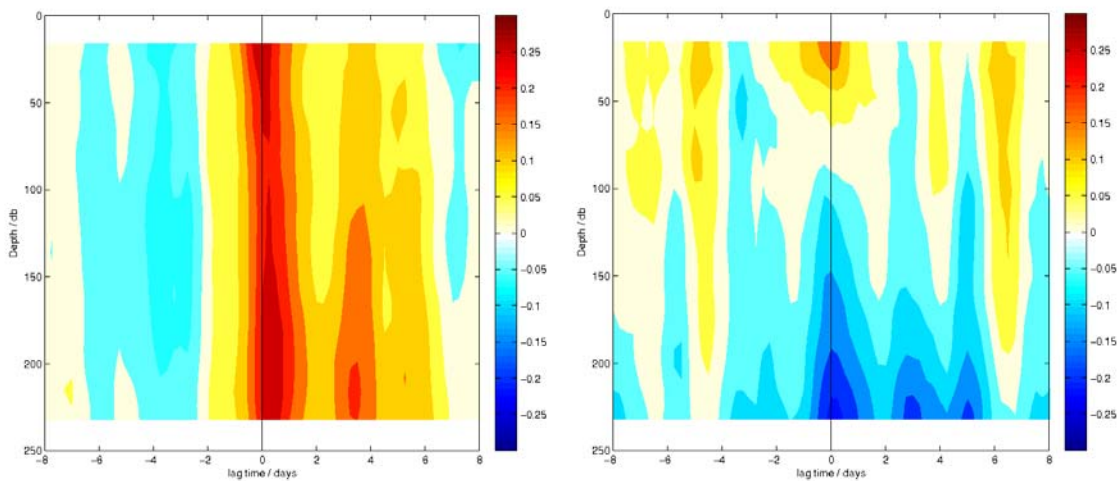


Figure 5: Lagged correlations (indicated by color) between wind speed and the velocity timeseries from one of the moorings on the outer shelf. Left-hand panel: correlation between the wind and the alongshore velocity as a function of depth. Right-hand panel: correlation between the wind and the cross-shore velocity as a function of depth.

Although part of our hypothesis was that the spilling of dense water would also be caused by instabilities (natural variations) of the alongshore flow, it is becoming apparent that this idea is not supported by the data. However, the data does indicate that there is a second mechanism (aside from the wind) that drives spilling. This other process is caused by the offshore circulation. Specifically, the deeper DSOW plume tends to form massive eddies (counter-clockwise swirls) every few days. As these eddies propagate southward it appears that they “graze” the shelf and draw dense water offshore. This seems to be the dominant mechanism responsible for the spilling. Ongoing research is being conducted to characterize this process and investigate its dynamics.

In addition to the mooring data, we conducted a comprehensive hydrographic survey of the region on the R/V *Knorr* after recovering the array. I am presently working with a post-doc and a graduate student using the hydrographic data, and with two other graduate



students using the mooring data. One paper has been submitted to *Nature Geoscience*, and another will be submitted shortly to *Journal of Physical Oceanography* (the first draft is complete).

The process of DSOW spilling off the shelf south of Denmark Strait and forming an intense jet along the upper continental slope constitutes a new paradigm for sinking in the MOC. We will continue to investigate some of the important ramifications involving the mixing and the vertical distribution of transport in the lower limb of the MOC and what this means for our climate system.

I am greatly indebted to the Comer Science and Education Foundation for making this exciting research possible.



Freshwater Flow Through Hudson Strait

Fiamma Straneo
Physical Oceanography Department

The Hudson Bay System, which includes the Hudson, James and Ungava Bays, Foxe Basin and Hudson Strait, is a large and very fresh arctic basin due to the input of freshwater from large rivers and to the inflow of Arctic Ocean waters. Freshwater cycles through the Hudson Bay System and, eventually, is exported to the North Atlantic, along the southern side of the Hudson Strait (Figure 1), where it is thought to play a significant role in modulating the Labrador Sea's deep convection and, thus, the climate of the North Atlantic. Indeed, the contribution from Hudson Strait is thought to be the third largest source of freshwater for the North Atlantic – even though the net freshwater flow through Hudson Strait had never been observed.

In 2004, I set out to fill this gap by measuring how much fresh water is exported out of Hudson Strait along its southern side. Year-long mooring records revealed a much larger freshwater export than was expected. This excess freshwater could be a result of only two processes: 1) a larger than expected amount of Arctic Ocean fresh water enters the Hudson Bay System, or, 2) the Hudson Bay System has the ability to accumulate and release freshwater due to internal processes. Understanding the sources of this excess freshwater and, in general, the pathways of freshwater in this region is key to our understanding of what governs freshwater input into the North Atlantic and its variability – a crucial aspect of our climate system.

The objective of this project was, for the first time, to measure how much fresh water enters the Hudson Bay System from the Arctic Ocean (along the northern side of Hudson Strait) and how much freshwater exits into the Labrador Sea (along the southern side). To achieve this goal, my Canadian colleague, Professor Yves Gratton, from the University of Quebec, and I deployed four moorings across Hudson Strait. The moorings were deployed in August of 2008 and recovered in October of 2009. We retrieved close to 90% of the data – an astounding success – given the harshness of the environment, which includes large tides, icebergs and sea-ice cover over much of the year.

Due to the large amount of data collected from the moorings, the analysis of the 2008-2009 data is ongoing. However, several important results can already be seen from the

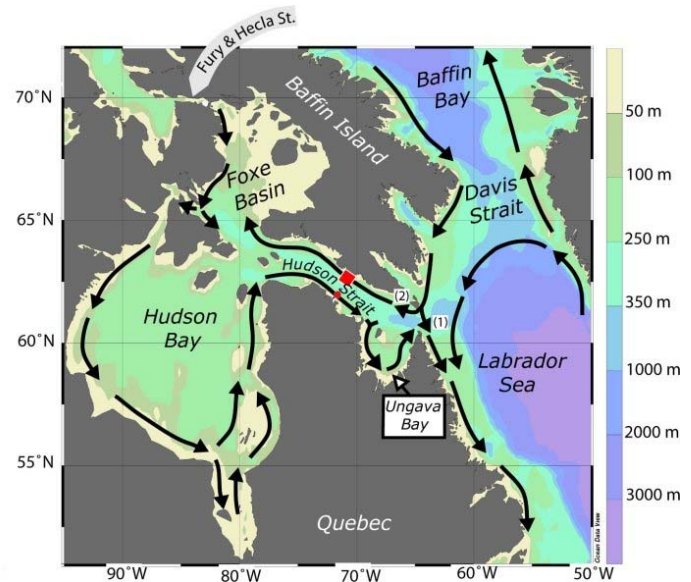


Figure 1: Freshwater pathways in the northwest Atlantic, Hudson Strait and Hudson Bay. The moorings were deployed across the section indicated by the red square (3 moorings across the inflow) and red circle (one mooring across the inflow).



preliminary data shown in Figure 2. The top panel compares the fresh water inflow and outflow on the two sides of the Strait (by simply comparing the salinity from instruments in the upper part of the water column). This simple plot shows that the inflowing waters (red) have a limited seasonal variability and a salinity of about 33, compared to the very fresh outflowing waters with a strong seasonal variability (blue). In the lower panel, furthermore, we compare the fresh water outflow using data from four years of mooring data. These reveal some large interannual variability and, in particular, indicate that 2008-2009 was a year of anomalously large fresh water export (with the freshest waters emerging from the Strait). This is in agreement with ongoing work which suggests that Hudson Bay had been accumulating fresh water during the last few years – becoming progressively fresher – and that this fresh water is now being released downstream into the Labrador Sea. This is the first time we have observed such large interannual variability and it has important implications on the variability of the ocean circulation downstream.

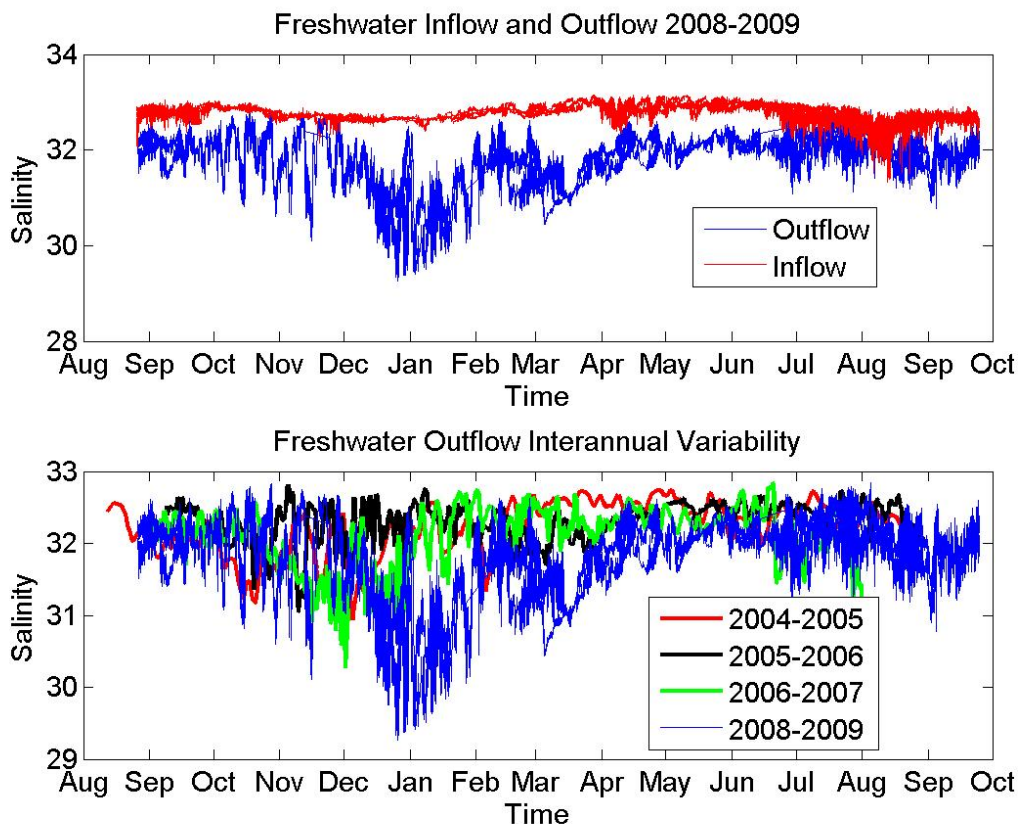


Figure 2: Freshwater through Hudson Strait. Top: Instruments located in the upper part of the water column clearly show the seasonal pulse of freshwater flowing out of Hudson Strait in late fall/early winter (blue) and the much smaller amount of freshwater entering with the inflow (red) throughout the year. Bottom: A comparison of the data from 2004 to 2009 shows the large interannual variability in the outflow and, in particular, the anomalously large export captured in 2008-2009.



The collection of these data, furthermore, has greatly contributed to the development of two important ongoing projects:

- 1) Synthesis of the Hudson Strait outflow. Thanks to the support from the Comer Science and Education Foundation in collecting these data, I have been able to obtain funding from the National Science Foundation to analyze the variability of the fresh water outflow from Hudson Bay and, also identify the driving mechanisms. This NSF project is supporting a student, post-doctoral fellow, and I and the grant continues through 2012.
- 2) Continued monitoring of Hudson Strait. Funding for this project has helped raise awareness for Hudson Strait and has established that monitoring of this important gateway is feasible. Presently, we are working together with our Canadian colleagues to establish a continuous monitoring program (funded by Canadian government sources) that will continue the work in the Strait. This is a major achievement and an important one for climate studies – and is an example of how a privately funded project can jump-start a much larger program.



Observing the Inflow of Pacific Water to the Arctic

Albert J. Plueddemann
Physical Oceanography Department

Although the importance of the Arctic in global climate change is widely recognized, a critical component of the Arctic system has been largely overlooked – the inflow of Pacific Water. Pacific inflow from the Bering Strait is a source of freshwater, carbon, and nutrients for the Arctic Ocean. However, before reaching the Arctic this water must first transverse the shallow Chukchi Sea (roughly 50 meters deep). Along its journey, Pacific water may be modified by air-sea interactions, input from rivers, mixing, and the freeze-thaw cycle of the ice. In addition, the inflow varies seasonally in both its rate and water mass properties. In particular, there is a need to understand the processes by which Pacific Water flowing through the Bering Strait is modified in the Chukchi Sea and then transported to the western Arctic basin. The most important transport is that which occurs in winter beneath the ice cover. This transport establishes the hydrographic conditions in the upper 200 meters of the Arctic basin, and may profoundly affect the thickness and extent of Arctic sea ice. The narrow passage between Point Barrow, Alaska, and the flank of Barrow Canyon is a critical “choke point” of the system, where a significant portion of the Pacific Water inflow is concentrated (Figure 1).

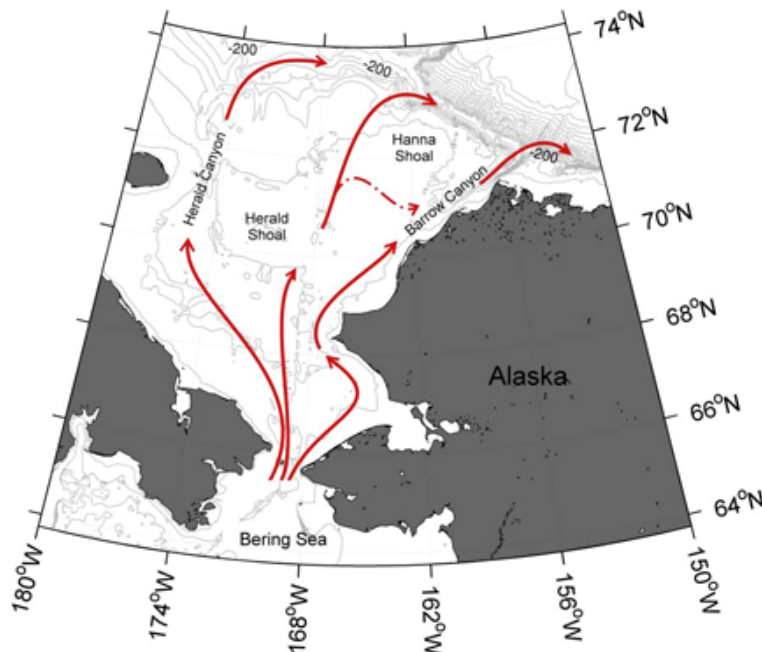


Figure 1: One of the pathways in which a significant portion of Pacific Water flows into the Arctic system is between the coast of Alaska and Barrow Canyon (far right arrow).

With funding from the Comer Science and Education Foundation we conducted a summer field project in 2005 to deploy an autonomous underwater vehicle REMUS (Remote Environmental Monitoring UnitS) to sample the water column across the choke



point. The goal of this initial deployment was to assess whether or not the vehicle would be potentially capable of operating under the ice cover in this region during the winter. There were several technical areas of concern, including the acoustic environment, strong currents and navigation issues. For example, due to the acoustic properties of the area, we found that we could only contact the vehicle when it was near the surface. This could have important implications for the winter work, where “homing” transponders deployed through ice-holes near the surface were envisioned, because they would likely have only intermittent contact with the vehicle. We also experienced problems with the navigation system. Despite the unanticipated technical problems, we were able to gather important scientific data, including measurements of temperature, salinity, pressure, velocity, acoustic, and fluorescence data.

The project period was extended to allow further technical developments, which were completed in 2007. Although we determined that the REMUS was well suited to be used in the harsh environment, improvements to the navigation system and the development of a through-ice launch and recovery system were necessary to allow the vehicle to operate successfully in winter. Based on the field experience and technical advancements of this project, the goal of under-ice AUV transects to measure the Pacific Water inflow to the Arctic in winter has been pursued in a follow-on project supported by WHOI’s Arctic Research Initiative.

Support from the Comer Foundation allowed us to pursue an innovative but risky new observational approach, put us ahead of the curve relative to the overall research community, and has leveraged several other research projects.



Greenland Ice Sheet: Surface Melting and a Slippery Bottom

Sarah Das, Mark Behn, Dan Lizarralde
Geology and Geophysics Department

Should the polar ice sheets melt in response to rising global temperatures, dramatic effects are predicted in the form of higher sea-level and the alteration of ocean circulation patterns. The Greenland Ice Sheet is more than a kilometer thick in most places, and until recently, many believed that it would take over a thousand years for temperature variations at the surface to reach the bed of the ice sheet.

Recent observations from Greenland, however, suggest that ice sheets have the potential to respond much more rapidly to climate change than was previously believed. New data show that ice-flow acceleration can occur within hours or days following the onset of melting at the surface. This surprising finding suggests that meltwater might be draining through the ice sheet rather than running off the surface, thereby rapidly lubricating and warming the bed. This would result in a quicker movement of the ice sheet toward the coast and ultimately into the ocean. If we are to fully grasp the effects of increased ice melting on ice sheet flow and its effects on sea-level change, we need to understand where and how the meltwater gets to the ice sheet bed.

One mechanism that has been proposed to quickly transport meltwater from the surface to the bed of an ice sheet is the propagation of water-filled fractures beneath lakes that form annually on the surface of the ice sheet. While theoretical models suggest that the draining of supraglacial lakes through fractures in the ice is a plausible transport mechanism, water-filled cracks that reached the bed had never been observed in the thick, subfreezing ice sheets. However, in an NSF-funded project to study the behavior of supraglacial lakes (see *Oceanus* article: Tracking an Ocean of Ice Atop Greenland) we found that large lakes do in fact drain rapidly—some in a matter of hours—through an apparent fracture-driven process (see front cover). This study represented the first glimpse into the pathways and time scales of surface-to-bed water flow.

Our next step has been to monitor the fracture process with field based measurements to determine the location and timing of fracture events and test our numerical model results.



Figure 1: Glaciologist Sarah Das contemplates a huge river of meltwater flowing on Greenland's ice sheet.



To accomplish this, we designed an observational network to measure seismicity around seasonally draining supraglacial lakes. Our experiment was designed to determine the rate and extent of water-filled crack propagation. We expected that crack propagation would be accompanied by enhanced seismicity near the crack tip.

During our field expedition in July 2007, we deployed a network of seismometers around two lakes on the Greenland Ice Sheet. We used Global Positioning System receivers and seismometers to measure ice movement, water pressure loggers to detect changes in lake levels, and meteorological sensors to precisely measure surface melting. Data from these instruments confirmed the water filling large glacial lakes can build up enough pressure to crack their bottoms, creating conduits that penetrate the ice sheet and could send torrents of water all the way to the bedrock. The water acts as lubrication between the ice and ground, speeding up the glacier's flow toward the ocean. Evidence collected from the instruments showed that cracks, reaching the bedrock, had suddenly drained the lakes. These measurements provided some of the first direct observations of the mechanisms behind rapid meltwater transport from supraglacial lakes to the bed of the Greenland Ice Sheet.



***Line W:
Sustained Measurements of the North Atlantic
Meridional Overturning Circulation***

John Toole, Ruth Curry, Terrence Joyce and Michael McCartney
Physical Oceanography Department

The global ocean plays a fundamental role in Earth's climate system by exchanging heat, freshwater, carbon, and other substances across the interface between air and sea at some locations and then transporting and releasing them back to the atmosphere in other places. A major agent in this transport process is the Meridional Overturning Circulation (MOC), manifested in the North Atlantic by the flow of warm surface waters (principally within the Gulf Stream) toward the poles and a return flow of colder, denser subsurface waters toward the Equator. The latter is concentrated in a current called the Deep Western Boundary Current (DWBC), which “hugs” the U.S. Eastern Seaboard.

The Line W Program is dedicated to obtaining a ten-year record of changes in transport by the DWBC at a logistically-accessible site southeast of Woods Hole, Massachusetts (Figure 1). Line W is named in memory of Val Worthington, a physical oceanographer at WHOI who devoted a considerable part of his career to measuring and understanding the properties and flows in the Gulf Stream and DWBC. Our research goals include characterizing the nature of the anomalies of water property transport seen at Line W and relating them to fluctuations at other latitudes and ultimately, to variations in air-sea exchange at latitudes where the deep waters are exposed to the atmosphere. We hope that greater accuracy of climate models and improved understanding of the physical processes responsible for MOC variability and its impact on Earth's climate system will result.

Operationally, we are observing the DWBC and Gulf Stream at Line W by utilizing a combination of moored instrumentation and periodic shipboard sampling. Building on a significant archive of historical observations from the region, the modern measurement program was initiated in 2001 with seed funding from The G. Unger Vetlesen Foundation. That support allowed

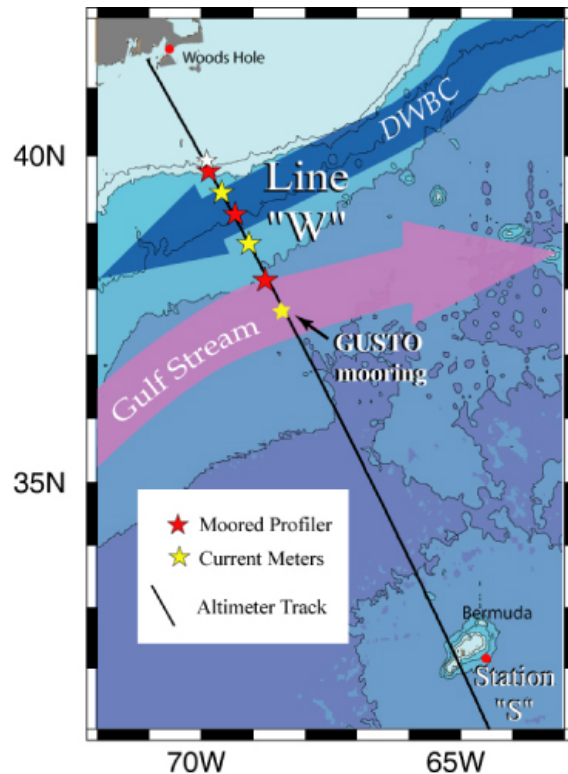


Figure 1: Line W is an array of moorings that monitor changes in the Deep Western Boundary Current (DWBC) and the Gulf Stream. Sensors on the Line W moorings take measurements of water salinity, temperature and velocity along both currents.



us to deploy one mooring for two sequential one-year periods (2001-2002 and 2003-2004) and conduct some shipboard sampling of the DWBC water properties.

In turn, we were able to parlay that seed money into two substantial grants from the National Science Foundation (NSF). The first of these supported an initial four-year sampling effort (Spring 2004-Spring 2008); the second is providing partial funding for six more years of measurements. In these times of tight science funding, we were required to significantly trim our initial funding request to NSF in Principal Investigator (PI) time to analyze the acquired data. Therefore, we are very grateful that the Comer Science and Education Foundation, through WHOI's Ocean and Climate Change Institute, has provided supplemental support for the Line W science team. With this funding, the Line W scientists will be able to oversee the collection, processing and distribution of the basic observations, as well as perform scientific analysis of those data over the next few years.

