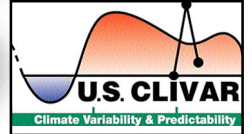


U.S. CLIVAR

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VARIATIONS



The U.S. Atlantic Meridional Overturning Circulation (AMOC) Program

by David M. Legler, Director

Beginning in early 2007 with the publication of the Administration's Ocean Research Priorities Plan, AMOC program began in earnest (supported by the US CLIVAR Office). This program, with its international partners, aims to further develop abilities to observe, understand, and simulate the AMOC as well as characterize its potential impacts on climate (see <http://www.atlanticmoc.org> for program details). It is guided by an Implementation Strategy (see the web page) and implemented by the AMOC Science Team, under the leadership of its current chair, Susan Lozier. AMOC held its first workshop in Annapolis, Maryland on May 4-6, 2009, and welcomed contributions of over 100 U.S. and international participants on topics ranging from the current state of the AMOC, its coherence and connectivity, the influence of AMOC

Continued on Page Two

IN THIS ISSUE

Did Changes in the Subpolar North Atlantic trigger mass loss.....	1
US CLIVAR Summit	4
Effect of AMOC Changes on Tropical Atlantic Climate	5
Deep Limb of the North Atlantic Meridional Overturning Circulations.....	8
Calendar	12

Did changes in the Subpolar North Atlantic trigger the recent mass loss from the Greenland Ice Sheet?

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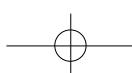
The Greenland Ice Sheet's (GIS) contribution to sea level rise more than doubled in the last seven years due to a surprisingly rapid (and unpredicted) mass loss. The loss was not so much a result of increased surface melt but, rather, of ice loss due to the widespread and nearly-simultaneous acceleration of several outlet glaciers in Greenland's western and southeastern sectors [Rignot and Kanagaratnam, 2006]. Since Greenland's accelerating outlet glaciers terminate at tidewater in deep fjords and their floating ice shelves extend several hundreds of meters below sea-level it has been suggested that the acceleration may have been driven by oceanic changes [Bindschadler, 2006; Holland et al. 2008]. Specifically, increased melting due, for example, to warming ocean waters can speed up ice flow through a reduction of both the basal friction and the frontal buttressing to glacier flow. Indeed Greenland's accelerating glaciers lost their buttressing ice shelves either prior or during the acceleration. The ocean trigger hypothesis is empirically supported by the fact that the accelerating glaciers are located along the margins of the North Atlantic's subpolar gyre whose waters started to warm roughly at the same time as the glaciers began to accelerate [Bersch et al. 2007; Yashayaev et al. 2007]. Yet,

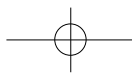
the connection between Greenland's outlet glaciers and the large-scale subpolar ocean is new and far from obvious.

Outlet glaciers in Greenland terminate in deep, long fjords which end at the coast, over Greenland's shallow and broad shelf, a region dominated by cold, fresh waters of Arctic origin (PW), transported around Greenland by the East and West Greenland Currents (Figure 1a). Warm waters of subtropical origin (STW), on the other hand, are found on the continental slope in the core of the Irminger Current, an extension of the North Atlantic Current, or offshore in the gyre's interior. Evidence that STW penetrates inside Greenland's glacial fjords is limited to a handful of summer profiles from Jakobshavn [Holland et al. 2008] and Kangerdlugssuaq Fjords [Azetsu-Scott and Tan, 1997] making it impossible to assess if these waters are present year round, if they are present in other fjords and, in general, what their residence time is. More importantly, the rate of submarine melting depends on the heat transport to the glacier's terminus. Glacier acceleration could thus have been triggered by changes in the volume, properties and/or the circulation of STW in the fjords. Furthermore, several investigators have suggested that positive feedbacks associated with a classic estuarine-type circulation

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Continued from Page One

on climate and related impacts, and AMOC observing system requirements. A summary of the Workshop appeared in a recent (August 4, 2009) issue of EOS. Many of the oral presentations are also available on the AMOC website. The articles in this issue of Variations are a sampling of the results presented at the Workshop.

The AMOC Science Team, now numbering nearly two dozen, continues to address the priorities laid out in its plans. Smaller AMOC Task Teams are forming to better coordinate current and future activities (particularly with our partners in Europe and South America) and catalyze further actions that will address AMOC observational priorities, improve ocean analyses and understanding of relevant mechanisms, and characterize the impacts of AMOC (including predictability).

Look for further advances and results from the AMOC Science Team on their web site and in future issues of Variations.

(increased melting driven by a warming ocean increases the estuarine circulation in the fjord which, in turn, draws more water in) may have played a role in amplifying the glaciers' response [Holland et al. 2008; Hanna et al. 2009]. Yet, there is presently no evidence that an estuarine-type circulation dominates in Greenland's glacial fjords. Identifying the processes that drive STW inside the fjords, and control their variability, is key to understanding the role of the ocean in triggering the ice sheet changes.

A recent study has provided evidence that very warm STW are not only present in large volumes in a major East Greenland glacial fjord but, also, that they are continuously replenished via rapid exchange with the shelf region [Straneo et al. 2009]. The study is based on observations collected in Sermilik Fjord where Helheim Glacier terminates (Figure 1a and b). Helheim Glacier is one of Greenland's largest outlet glaciers and has recently almost doubled its flow speed making it one of Greenland's fastest changing glaciers and a major contributor to sea-level rise [Howat et al. 2005; Stearns and Hamilton, 2007]. Large volumes of STW were observed inside the fjord and on the shelf, both in July and September 2008, Figure 2. Changes in water properties from July to September, velocity measurements and data from two moorings, deployed mid-fjord for the period in-between the surveys, allowed Straneo and colleagues to conclude that Sermilik Fjord is continuously and rapidly exchanging waters with the shelf. The exchange is driven by northeasterly wind events which 'pile up' water at the mouth of the fjord and result in large, strongly-sheared flows inside the fjord. This circulation, which is typical of narrow fjords, tends to be an order of magnitude larger than the classic estuarine circulation and, as such, is much more effective in transporting heat into the fjord [Klinck et al. 1981; Stigebrandt 1990]. Given the temperature of the waters inside Sermilik and their rapid renewal, combined with the fact that Helheim's terminus extends 500-700 m below sea-level, Straneo and colleagues conclude that, at present,

ocean waters are driving substantial submarine melting of Helheim. Furthermore, since the conditions that allow STW to penetrate in Sermilik – its presence on the shelf and along-shore winds – are typical of both E. and W. Greenland, Straneo et al. speculate that ocean waters are likely driving substantial melting at the termini of other outlet glaciers along southeastern and western Greenland.

These findings are supportive of the ocean trigger hypothesis but not conclusive until it is shown that conditions were different prior to the last decade such that submarine melting was greatly reduced. Lack of historical data from Sermilik and other glacial fjords, however, makes it difficult to determine what conditions were like in the past. Some clues of what may have changed, at the same time, are provided by the findings of this new study. First, it seems unlikely that the warming of the STW alone (~ 1 °C; Thierry et al., 2008) may have been responsible for the change since it is smaller than the seasonal temperature change observed by Straneo and colleagues in the fjord or on the shelf. Second, along-shore winds are typical along Greenland coasts [Moore and Renfrew, 2005], making it unlikely that the driver for fjord/shelf exchange was absent in the past. It seems more likely, then, that what has changed is that large volumes of warm STW are presently found on southern Greenland's continental shelves. This notion is supported by a number of recent observations (e.g. Sutherland and Pickart, 2008) and by repeat sections collected along the W. Greenland shelf showing that waters there were much colder prior to the mid-1990s [Holland et al. 2008; Hanna et al. 2009]. Also, while the mechanisms which allow STW to 'climb' onto Greenland's shelves are not clear – this idea is also consistent with the warming of the Irminger current and the subpolar gyre's interior [Myers et al. 2008; Yashayaev et al. 2007] and the gyre's slowdown [Häkkinen and Rhines, 2004] observed over the last decade.

This line of thought naturally leads to the question of what is driving the changes in the subpolar North Atlantic?

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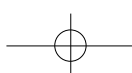
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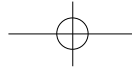
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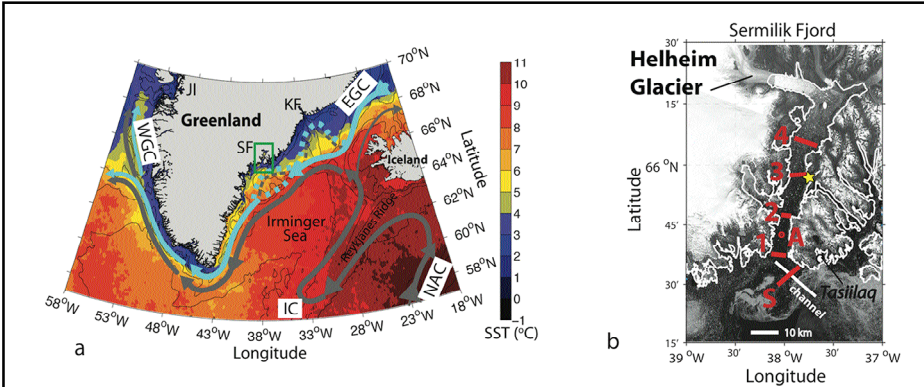


Figure 1. a) Main currents around southern Greenland overlaid on the 2003 mean sea-surface temperature (SST) from the Advanced Very High Resolution Radiometer (filled contours). Bathymetric contours (100, 500, 1000, 2000, 3000 m) are overlaid in black. Cold, polar waters (PW) are found over the shelf, transported by the EGC and WGC (dashed paths indicate multiple branches) and warm, subtropical waters (STW) are transported along the continental slope by the NAC and the IC. The approximate location of Sermilik Fjord (SF and green box), Kangerdlugssuaq Fjord (KF) and Jakobshavn Isbrae (JI) are indicated. b) A Landsat mosaic of Sermilik Fjord. Sections (1 to 4 and S) plus the single station A occupied during the 2008 surveys are indicated in red. The yellow star indicates the moorings location. Figure is from Straneo et al. 2009.

In summary, we speculate that atmosphere/ocean changes since the mid-1990s have resulted in the unprecedented inflow of warm, subtropical waters around the subpolar region and on the Greenland shelves. These changes have been rapidly communicated to the glacial fjords through the wind-driven exchange between the fjord and the shelf and have played a significant role in accelerating outlet glaciers along the southeastern and western sectors. While more measurements at the ice-ocean edge are needed to understand the details of how these changes can effectively trigger an outlet glacier's acceleration, the idea that changes in the poleward heat transport (and the associated overturning circulation) of the North Atlantic can affect the Greenland Ice Sheet on such short time scales is new and has significant implications for our climate system.

Monitoring of the warm inflow into the subpolar region, as well as on the Greenland shelves and inside the glacial fjords, combined with improved modeling of ice-sheet ocean interactions are necessary for us to understand a potentially highly significant and previously overlooked coupling within our climate system.

Acknowledgements

Straneo acknowledges support from WHOI's Ocean and Climate Change Institute and from NSF OCE-0751554,

The fact that the North Atlantic Oscillation (NAO), the dominant mode of variability over this region, switched from a persistent positive phase to a non-persistent phase in the mid-1990s (Figure 3a) has led some investigators to attribute the changes to the NAO alone (e.g. Holland et al. 2008). If this is true then the conclusion is that changes on the margins of the GIS may be driven by the NAO. Yet, there is increasing evidence that the changes in the subpolar region over the last decade are no longer attributable to the NAO alone. A recent study by Häkkinen and Rhines (2009), for example, attributes the anomalous inflow of STW into the subpolar region and Nordic Seas to changes in surface currents driven by shifting wind patterns which are no longer attributable to the NAO alone.

Further evidence of a lessening of the NAO's imprint on the North Atlantic is provided here in terms of the heat content of the North Atlantic. From historical data, we show that, until the mid-1990s, multidecadal fluctuations in heat content of the subpolar and subtropical regions were broadly consistent with shifts in the NAO through its impact on surface heat fluxes and cross-gyre exchanges between the subtropics and subpolar basins (Figure 3; Visbeck et al.

2003). Specifically, periods of negative (positive) NAO gives rise to a warmer (cooler) subpolar and cooler (warmer) subtropical upper ocean and enhanced (reduced) northward flows of warm subtropical waters [Lozier et al. 2008]. This correlation, however, broke down in the mid-1990s and since then both the subtropical and subpolar regions have been gaining heat (Figure 3b) – something which can no longer be explained by the NAO alone.

Summary

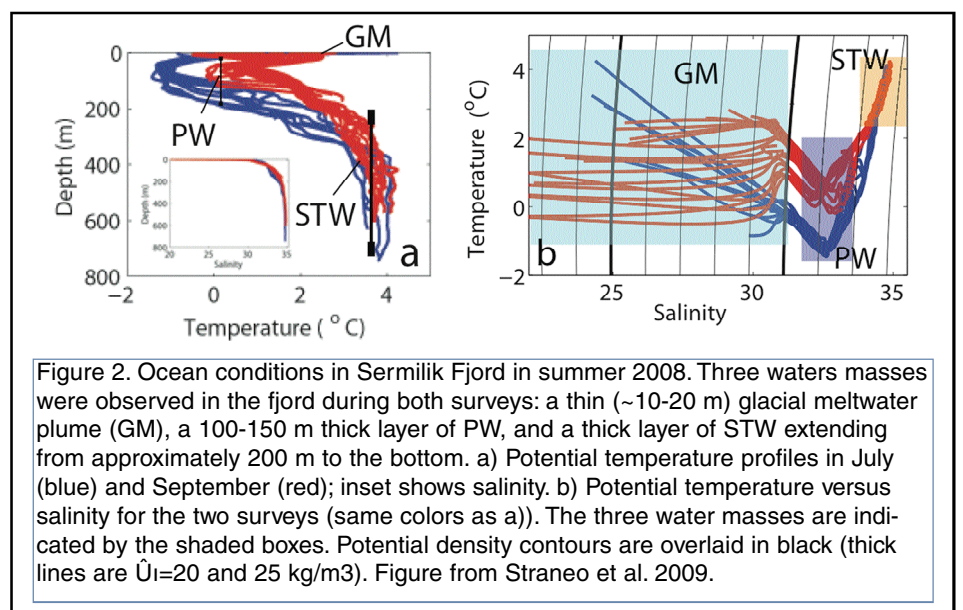
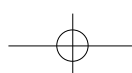
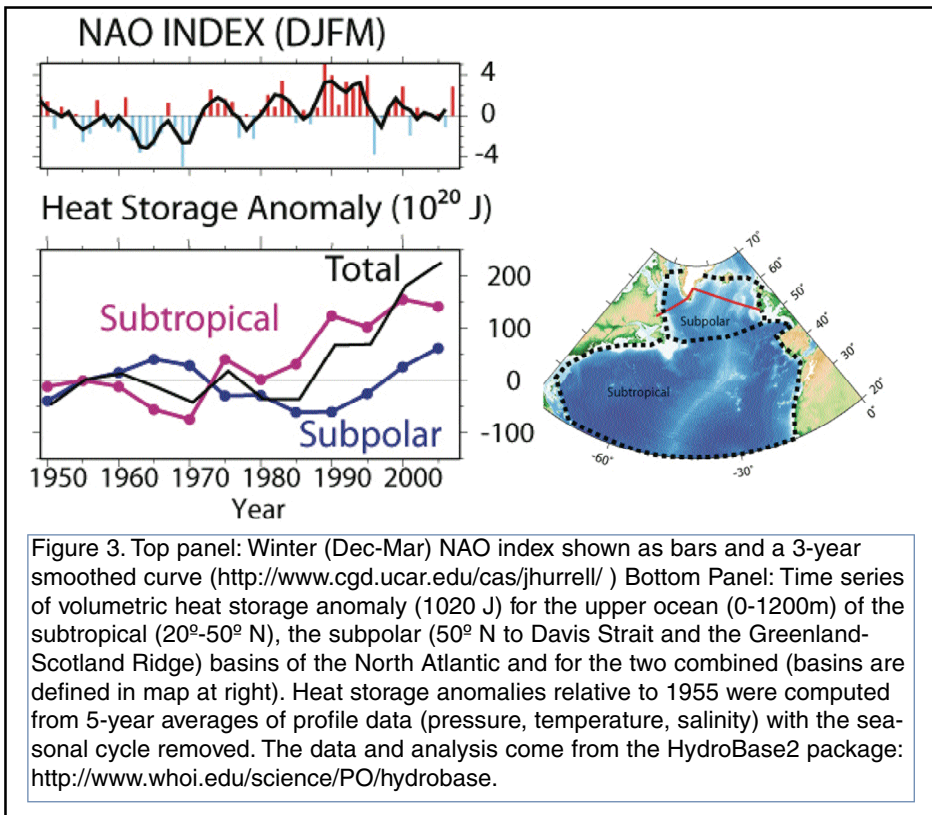


Figure 2. Ocean conditions in Sermilik Fjord in summer 2008. Three water masses were observed in the fjord during both surveys: a thin (~10-20 m) glacial meltwater plume (GM), a 100-150 m thick layer of PW, and a thick layer of STW extending from approximately 200 m to the bottom. a) Potential temperature profiles in July (blue) and September (red); inset shows salinity. b) Potential temperature versus salinity for the two surveys (same colors as a). The three water masses are indicated by the shaded boxes. Potential density contours are overlaid in black (thick lines are $\sigma_t=20$ and 25 kg/m³). Figure from Straneo et al. 2009.





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References

- Azetsu-Scott, K. & Tan, F. C. (1997): Oxygen isotope studies from Iceland to an East Greenland Fjord: behaviour of glacial meltwater plume. *Marine Chem.* 56, 239-251.
- Bersch, M., Yashayaev, I. and Koltermann, K. P. (2007) Recent changes of the thermohaline circulation in the Subpolar North Atlantic. *Ocean Dyn.* 57, 223-235.
- Bindschadler, R. (2006): Hitting the Ice Sheet where it hurts, *Science* 311 1720-1721.
- Häkkinen, S. & Rhines, P. B. (2004): Decline of Subpolar North Atlantic Circulation during the 1990s. *Science* 304, 555-559.
- Häkkinen, S. & Rhines, P. B. (2009): Shifting surface currents in the northern North Atlantic Ocean *J. Geophys. Res.* 114, doi:10.1029/2008JC004883.
- Hanna, E. et al. (2009): Hydrologic Response of the Greenland ice sheet: the role of oceanographic warming *Hydrol. Process.* 23, 7-30.
- Holland, D. M., Thomas, R. H., De Young, B., Ribergaard, M. H. & Lyberth, B. (2008): Acceleration of Jakobshavn Isbræ triggered by warm subsurface ocean waters. *Nature Geosci.* 1, 659-664.
- Howat, I.M, Joughin, I., Tulaczyk, S. & S. Gogineni (2005) Rapid retreat and acceleration of Helheim Glacier, east Greenland. *Geophys. Res. Lett.* 32, L22502, doi:10.1029/2005GL024737.
- Klinck, J. M., O'Brien, J. J. & Svendsen, H. (1981): A simple model of Fjord and coastal circulation interaction. *J. Phys. Ocean.* 11, 1612-1626.
- Lozier, M.S., Leadbetter, S., Williams, R. G., Roussenov, V., Reed, M.S.C. and Moore, N.J. (2008): The spatial pattern and mechanisms of heat-content change in the North Atlantic. *Science*, 309, 800-803.
- Moore, G. W. K. & Renfrew, I. A. (2005): Tip Jets and Barrier Winds: A QuickSCAT Climatology of High Wind Speed Events around Greenland. *J. Climate* 18, 3713-3725.
- Myers, P. G., Kulan, N. & Ribergaard, M. H. (2007): Irminger Water variability in the West Greenland Current. *Geophys. Res. Lett.* 34, L17601, doi:10.1029/2007GL030419.
- Rignot, E. and Kanagaratnam, P. (2006), Changes in the velocity structure of the Greenland Ice Sheet. *Science* 311, 986-990.
- Stearns, L. A. and Hamilton, G. S., 2007: Rapid volume loss from two East Greenland outlet glaciers quantified using repeat stereo satellite imagery. *Geophys. Res. Lett.* 34, L05503, doi:10.1029/2006GL028982.
- Stigebrandt, A. (1990): On the response of the horizontal mean vertical density distribution in a fjord to low-frequency density fluctuations in the coastal water. *Tellus* 42A

605-614.

Straneo, F., G.S. Hamilton, D.A. Sutherland, L.A. Stearns, F. Davidson, M.O. Hammill, G. B. Stenson and A. Rosing-Asvid (2009): Rapid Circulation of warm Subtropical Waters in a major, East Greenland Glacial Fjord, *Nature Geoscience*, (under revision).

Sutherland, D. A. & Pickart, R. S. (2008): The East Greenland Coastal Current: Structure, variability, and forcing. *Prog. Oceanogr.* 78, 58-77.

Thierry, V., de Boissésion, E. & Mercier, H. (2008): Interannual variability of the Subpolar Mode Water properties over the Reykjanes Ridge during 1990-2006. *J. Geophys. Res.* 113, C04016, doi:10.1029/2007JC004443.

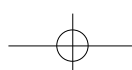
Visbeck, M., E. Chassignet, R. Curry, T. Delworth, R. Dickson, and G. Krahnmann, 2003. *The Ocean's Response to North Atlantic Oscillation Variability*, in *The North Atlantic Oscillation: Climatic Significance and Environmental Impact* (J. Hurrell, Y. Kushnir, G. Ottersen, M. Visbeck, eds.) AGU, Washington, D.C. pp 113-146.

Yashayaev, I. (2007), *Hydrographic changes in the Labrador Sea, 1960-2005*. *Prog. Oceanogr.*, 73, 242-276.

U.S. CLIVAR Summit Summary

U.S. CLIVAR held its annual Summit during the second week of July 2009 in Annapolis, Maryland (USA). During the Summit the three Panels of U.S. CLIVAR met to discuss program progress as well as strategize future activities. Because of the effectiveness and synergy generated in response to current US CLIVAR "Themes" (i.e., "Drought" and "Decadal Predictability/Variability"), U.S. CLIVAR wishes to identify a few additional Themes, or scientific challenges for which U.S. CLIVAR should be encouraging activities for the next 3-5 years. Two candidate themes were selected: extremes (which would likely replace Drought as a Theme) and high-latitude climate changes. Additionally, there was a strong push for U.S. CLIVAR to develop Themes addressing climate changes and carbon cycle, climate and ecosystems, and coastal climate changes. Some of these new themes may be the focus of other programs (e.g. within WCRP); however, Summit discussions suggested that there is an opportunity and need for CLIVAR to more urgently and concretely develop partnership with other programs, to address important challenges that transcend disciplinary boundaries.

For more information:
<http://www.usclivar.org/Summit2009.php>





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Effect of Atlantic Meridional Overturning Circulation Changes on Tropical Atlantic Climate

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The Atlantic Meridional Overturning Circulation (AMOC) is responsible for the northward heat transport at all latitudes within the Atlantic Ocean. Changes in this circulation can have significant influence on the climate system. Both paleo proxy records and water-hosing experiments reveal some robust responses of tropical Atlantic to a weakened AMOC, which include a dipole like SST pattern with cooler (warmer) temperature over the north (south) tropical Atlantic and a southward shift of the Intertropical Convergence Zone (ITCZ) (e.g. Wang et al.2004; Stouffer et al. 2006; Timmermann et al. 2007). It is important to understand why there is such a tight linkage between AMOC changes and tropical Atlantic climate, as this issue may help us to understand and predict potential abrupt climate change.

The hypotheses about the mechanisms through which the AMOC affects tropical Atlantic can be largely divided into two categories. The first category focuses on the role of oceanic dynamics. A frequently invoked mechanism is that a change of the AMOC can affect the interhemispheric SST gradient by modulating cross-equatorial heat transport through planetary wave adjustment (Yang, 1999; Johnson and Marshall, 2002). Recently, Chang et al. (2008) proposed another possible mechanism. He conjectured that the interaction between the AMOC and wind-driven Subtropical Cells (STCs) play an important role in inducing equatorial Atlantic SST response. Based on a coupled general circulation models (CGCM) water-hosing experiment, Chang et al. (2008) hypothesized that the weakened AMOC

causes the North Brazil Current (NBC) to reverse direction and carry warm northern subtropical gyre water to the equatorial region, giving rise to the surface warming in south equatorial Atlantic. This mechanism (hereafter referred as oceanic mechanism) builds on the finding of earlier modeling studies that the pathway of the northern STC to the equatorial zone is blocked by the AMOC return flow along the western boundary under the present climate condition (e.g. Fratantoni et al.2000). The second category focuses more on the role of atmospheric processes. Using an atmospheric general coupled model (AGCM) coupled to a slab ocean, Chiang and Bitz (2005) demonstrated that cooling in high latitudes can be readily transmitted to the tropics through intensifying northeasterly trade winds and its thermodynamic interactions with the oceanic mixed layer. Hereafter, we will refer this teleconnection as the atmospheric mechanism.

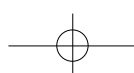
Although these mechanisms have shed some light on the underlying dynamics linking changes in high latitudes to changes in tropical Atlantic, more details need to be examined and explored. For example, Chang et al.'s hypothesis was based on a CGCM simulation where both the atmospheric processes and oceanic processes are included. It is thus difficult to isolate oceanic influence from air-sea interaction processes and identify areas that are most vulnerable to oceanic processes. In Chiang and Bitz's study, the importance of the atmospheric processes might be overestimated as the role of ocean circulation is excluded in their model configuration.

In this study, we investigate the impact of AMOC on the tropical Atlantic

climate and study in detail the relevant oceanic and atmospheric teleconnection mechanisms using a newly developed regional coupled model. The coupled model consists of an AGCM coupled to a 2-1/2-layer reduced gravity ocean model (RGO) over the tropical Atlantic basin. The AGCM is the NCAR CCM3 described in Hurrell et al. (1998) and runs here at its standard resolution T42. The RGO model consists of two active layers that represent surface mixed layer and seasonal thermocline layer (Wen et al., 2009). This coupled model is not only capable of capturing major features of Tropical Atlantic Variability (TAV), but also includes a number of novel features that are well suited for our purpose. For example, the return limb of the AMOC can be controlled directly by varying the imposed mass transport at the open boundaries of the ocean model. The use of regional coupled strategy also allows for an effective separation of AMOC's influence on TAV from other remote influences, such as ENSO and NAO. This model can be run as ocean-alone or fully coupled mode. The ocean model alone allows us to explore whether and to what extent the oceanic processes are responsible to the SST response pattern as suggested in CGCMs. When fully coupled, the model can be used to study the relative importance of the atmospheric processes versus the oceanic processes in AMOC-induced TAV.

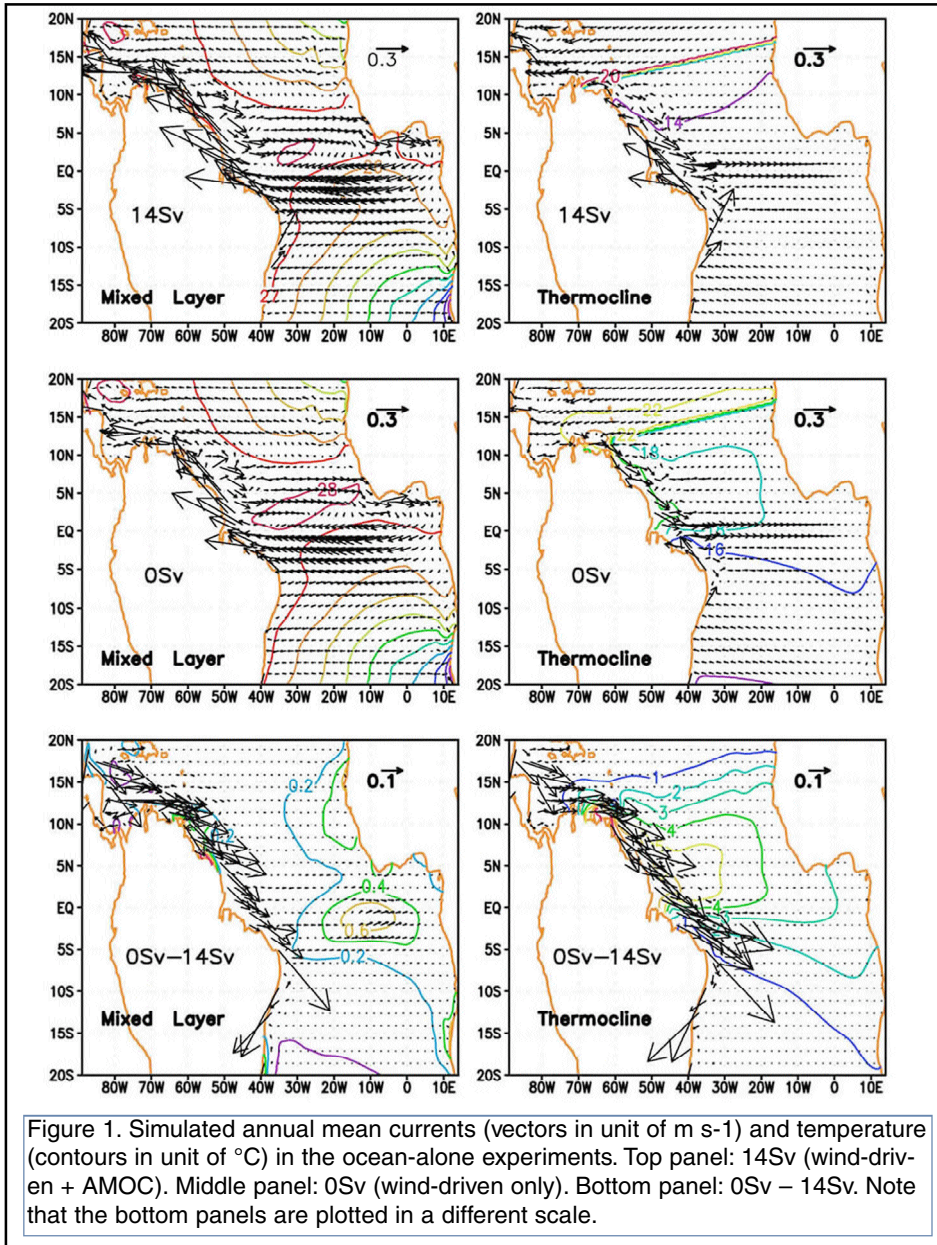
Sensitivity of SST response to changes in AMOC

In this section, we assess the oceanic mechanism, i.e. whether changes in AMOC strength can affect tropical Atlantic SST response by reorganizing the pathway of the STCs. We first use the





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ocean-alone model in two experiments. In the first experiment, a 14Sv northward mass transport is imposed at the open boundaries (Exp. 14Sv). This experiment, which is forced by 'realistic' combination of wind stresses and AMOC, represents the 'current climate state'. In the second experiment, northward mass transport is set to zero at the open boundaries (Exp. 0Sv). The comparisons of these two experiments should allow us assess the extent to which tropical Atlantic SST and ocean circulation system are affected by the shutdown of AMOC.

Figure 1 compares annual mean cur-

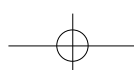
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rent and temperature of the Exp. 0Sv and Exp. 14Sv. In the presence of a full strength AMOC, the return branch of the northern STC is invisible in the thermocline layer and the Atlantic STCs are highly asymmetric about the equator with water mass supplying the EUC mainly from the Southern Hemisphere (right top panel). When the AMOC is shutdown, the northern STC is no longer suppressed. The southward western boundary current just north of the equator is intensified substantially (right middle panel), giving rise to a more symmetric structure of STCs about the equator. This result is consistent with the findings by Fratantoni et al. (2000) and Jochum and Malanotte-

Rizzoli (2001). The dominant feature of the difference is a narrow and continuous southward-western boundary current that is associated with the upper return flow of AMOC.

The AMOC-induced current changes give rise to significant temperature response in the upper ocean. The shutdown of AMOC causes the western boundary current along the northeastern coast of South America to reverse its direction from poleward to equatorward. This circulation changes leads to a rapid increase in thermocline temperature near the strong temperature gradient front. The warm anomaly is then carried equatorward along the western boundary. A portion of the warm water is advected by the North Equatorial Undercurrent, while the other portion enters the equatorial zone and then is carried to the eastern equatorial Atlantic by the Equatorial Undercurrent. As shown in Figure 1 (right bottom panel), there is widespread warming in the deep tropics in the thermocline layer. The subsurface warming leads to substantial surface warming, with the largest warming on the equator and in the eastern side of the basin along the upwelling zones (left bottom panel).

Next, we explore the sensitivity of the tropical Atlantic SST to changes in AMOC by decreasing imposed northward mass transport at the open boundaries systematically from 14Sv to 0Sv. To gauge the SST response sensitivity, we define two indices: T1a is the SSTA averaged over an equatorial box of $20^{\circ}W$ - $5^{\circ}W$ and $3^{\circ}S$ - $3^{\circ}N$; T2a is the same as T1a except that it is from the thermocline layer. Figure 2 shows these two indices in response to different strengths of AMOC. An intriguing observation is that the SST response behaves nonlinearly to AMOC changes. The sensitivity of the temperature response increases drastically when the AMOC strength is decreased below a threshold value of about 8Sv. We find that the NBC in the thermocline layer starts to reverse its direction from northward to southward when AMOC is weakened below 8Sv (Fig. 2c). As illustrated in Fig. 1, the AMOC return branch interacts with wind-driven circulation mainly via western boundary current. It





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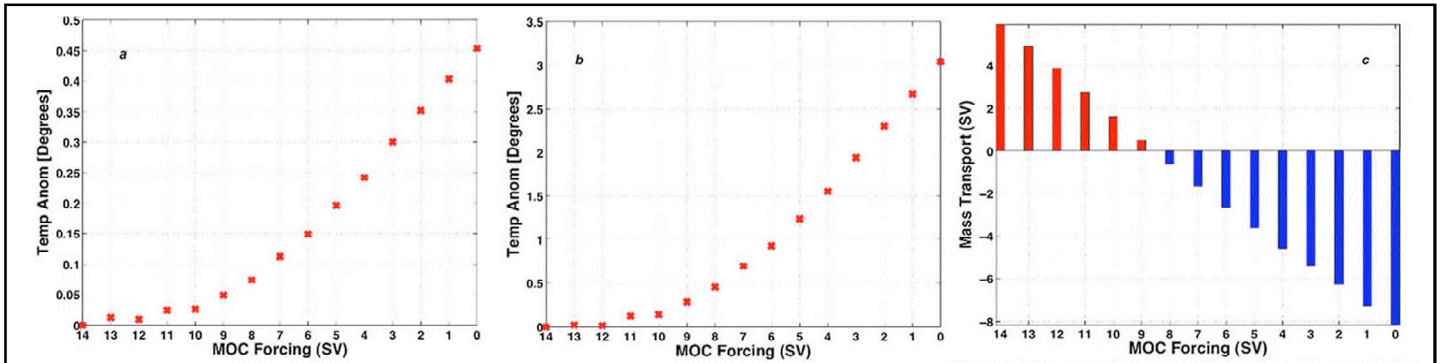


Figure 2. Changes in (a) SST index T1a, (b) thermocline temperature index T2a, (c) the western boundary current transport across 5°N in the thermocline layer as a function of AMOC strength. T1a and T2a are defined as SST anomaly and thermocline temperature anomaly averaged over 20°W-5°W, 3°S-3°N, respectively.

suggests that the nonlinear temperature response is associated with the interplay between the wind-driven northern STC and the AMOC.

Our ocean-only experiments show that the NBC reverses its direction in response to a shutdown of AMOC. Such circulation change causes a pronounced surface warming, leading to warm SST anomalies in the Gulf of Guinea and along the African coast. These findings are in favor of Chang et al. (2008)'s hypothesis. In contrast to the water-hos-

ing experiments carried out by CGCMs, the strong surface cooling in the northern tropical Atlantic is absent in our stand-alone ocean model. It indicates that the ocean dynamics alone cannot explain the dipole-like SST pattern associated with AMOC changes, and the atmospheric mechanism might be responsible for the surface cooling in the Northern Hemisphere.

Impact of AMOC change on TAV

In the light of the ocean-alone experiments, we hypothesized that both the

oceanic and the atmospheric mechanisms contribute to the AMOC-induced TAV change. In this section, we assess the relative importance of atmospheric processes. Three sets of experiments are conducted. In the first, the northward mass transport at the open boundaries of the oceanic component is set to zero. This experiment allows us to examine the extent to which the oceanic mechanism contributes to TAV response to a shutdown of the AMOC (referred to the OME run). The second set is forced by

an anomalous heat flux anomaly in the extratropical North Atlantic. The intent is to test the effect of AMOC-induced cooling in the North Atlantic on TAV via the atmospheric mechanism (referred to the AME run). In the third set of experiment, the model is forced by both the anomalous surface heat flux in the North Atlantic and zero mass transport at open boundaries. This experiment allows us to assess the combined effect of oceanic and atmospheric mechanisms (referred to the OAME run).

Figure 3 shows the Atlantic responses for the three sets of experiments. In the OAME experiment, an interhemispheric seesaw pattern in the SST response emerges with a strong cooling in the North Atlantic and a warming along the equator

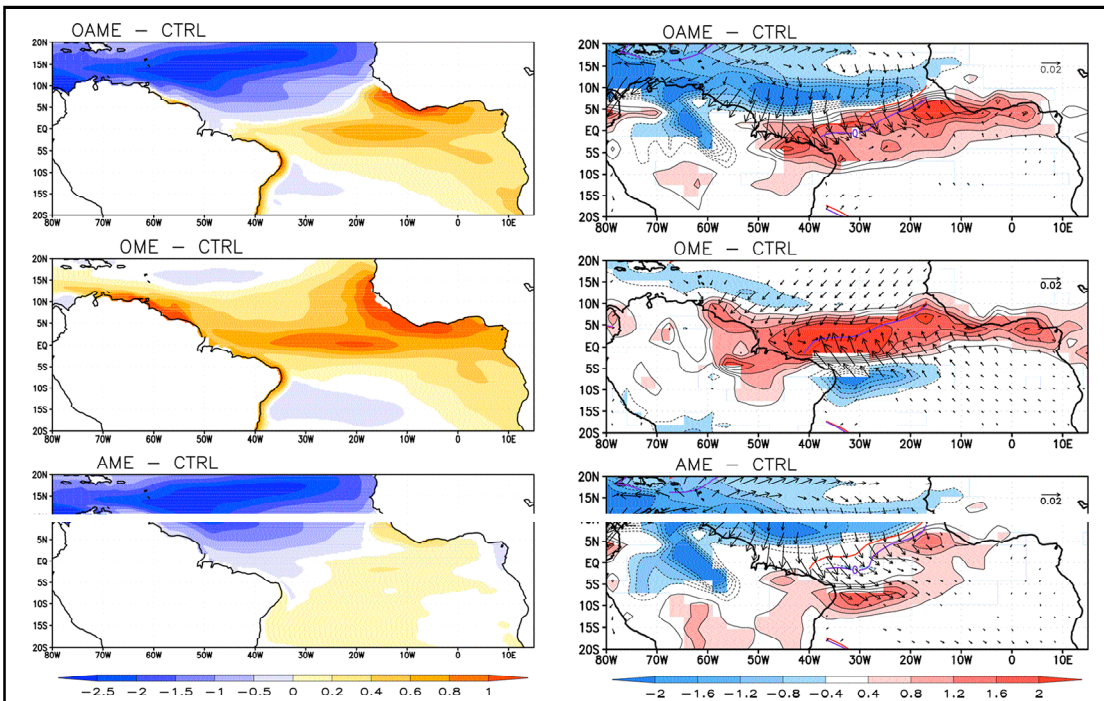
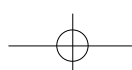
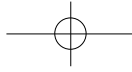


Figure 3. The annual mean SST anomaly (color in °C, left panels), precipitation (contour in mm/day, right panels) and wind stress anomalies (vector in N m⁻², right panels) in the OAME run (upper panels), the OME run (middle panels) and the AME run (bottom panels). The red and purple lines represent the annual mean $\bar{U}_y=0$ lines in the CTRL run and experiment, respectively. Plotted values are significant at the 95% statistical significance level using t-test.





U.S. CLIVAR

and along the upwelling zones of the southeastern tropical Atlantic. Accompanied with the SST change, the ITCZ shifted southward. The results are consistent with CGCM water hosing experiments, suggesting that the oceanic and the atmospheric mechanisms are two essential teleconnections linking AMOC changes to tropical Atlantic. From Figure 3, one can identify that the oceanic mechanism is the primary factor contributing to the warming near and to the south of equator. On the other hand, the atmospheric mechanism is largely responsible for establishing the surface cooling in the tropical north Atlantic and the southward displacement of ITCZ, lending support to Chiang and Bitz's hypothesis.

References:

- Chang, P., R. Zhang, W. Hazeleger, C. Wen, X. Wan, L. Ji, R. J. Haarsma, W. P. Breugem, and H. Seidel, 2008: Oceanic link between abrupt changes in the North Atlantic Ocean and the African monsoon. *Nature Geoscience*, 1, 444.
- Chiang, J. C. H. and C. M. Bitz, 2005: Influence of high latitude ice cover on the marine Intertropical Convergence Zone. *Climate Dynamics*, 25, 477-496.
- Fratantoni, D. M., W. E. Johns, T. L. Townsend, and H. E. Hurlburt, 2000: Low-Latitude Circulation and Mass Transport Pathways in a Model of the Tropical Atlantic Ocean. *Journal of Physical Oceanography*, 30, 1944-1966.
- Hurrell, J. W., J. J. Hack, B. A. Boville, D. L. Williamson, and J. T. Kiehl, 1998: The dynamical simulation of the NCAR Community Climate Model version 3 (CCM3). *Journal of Climate*, 11.
- Jochum, M. and P. Malanotte-Rizzoli, 2001: Influence of the Meridional Overturning Circulation on Tropical-Subtropical Pathways. *Journal of Physical Oceanography*, 31, 1313-1323.
- Johnson, H. L. and D. P. Marshall, 2002: A Theory for the Surface Atlantic Response to Thermohaline Variability. *Journal of Physical Oceanography*, 32, 1121-1132.
- Stouffer, R. J., J. Yin, J. M. Gregory, K. W. Dixon, M. J. Spelman, W. Hurlin, A. J. Weaver, M. Eby, G. M. Flato, and H. Hasumi, 2006: Investigating the Causes of the Response of the Thermohaline Circulation to Past and Future Climate Changes. *Journal of Climate*, 19, 1365-1387.
- Timmermann, A., H. Goosse, and

Coauthors, 2007: The influence of a weakening of the Atlantic meridional overturning circulation on ENSO. *J. Climate*, 20, 4899-4919.

Wang, X., A. S. Auler, R. L. Edwards, H. Cheng, P. S. Cristalli, P. L. Smart, D. A. Richards, and C. C. Shen, 2004: Wet periods in northeastern Brazil over the past 210 kyr linked to distant climate anomalies. *Nature*, 432, 740-743.

Wen, C., P. Chang, and R. Saravanan, 2009: Effect of Atlantic Meridional Overturning Circulation Changes on Tropical Atlantic Sea-Surface Temperature variability: A 2-1/2 Layer Reduce Gravity Ocean Model Study. *Journal of Climate* (in revise).

Yang, J., 1999: A linkage between decadal climate variations in the Labrador Sea and the tropical Atlantic Ocean. *Geophysical Research Letters*, 26.

Observed and Modeled Pathways of the Deep Limb of the North Atlantic Meridional Overturning Circulation

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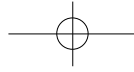
Ever since Henry Stommel and colleagues predicted on theoretical grounds the existence of a deep, western-intensified boundary current transporting cold dense water from the northern North Atlantic and the Antarctic ([Stommel and Arons, 1960b; Stommel and Arons, 1960a]), observational evidence for such a current has steadily increased, especially in the North Atlantic. Water property and tracer studies have consistently shown a narrow vein of North Atlantic Deep Water (including overflow waters from the Nordic Seas and convectively formed Labrador Sea Water) hugging the continental slope of the western North Atlantic from the subpolar region to the equator (e.g., [Talley and McCartney, 1982; Doney and Jenkins, 1994; Smethie Jr. et al., 2000]). Also, current measurements made at numerous locations along the western boundary of the North Atlantic always show a mean equatorward flow over the slope, coincident with the NADW tracer signature (e.g., [Pickart and Watts, 1990; Bryden et al., 2005; Dengler et al., 2006]). From these and other observations developed an understanding of the

North Atlantic Deep Western Boundary Current (DWBC) as the primary conduit for the southward transport of cold water, often referred to as the deep limb of the "great ocean conveyor" ([Broecker, 1991]) that contributes to maintaining Earth's climate system.

It was therefore somewhat surprising when, in the 1990s, two float studies in the western subpolar North Atlantic showed no evidence of a continuous DWBC connecting the subpolar to the subtropical regions of the North Atlantic. Floats drifting at intermediate depths (400-1500 m, the level of Labrador Sea Water) in the DWBC at the exit of the Labrador Sea were all expelled from the DWBC relatively quickly and drifted eastward along the subpolar-subtropical gyre boundary ([Lavender et al., 2000; Fischer and Schott, 2002]).

These results inspired a new float study of the export pathways of Labrador Sea Water from the subpolar North Atlantic ([Bower et al., 2009]). Whereas profiling floats (like Argo floats, which surface periodically to fix their position) were used in the earlier float studies, we used acoustically





VARIATIONS

tracked RAFOS floats to avoid any possible bias in float trajectories caused by repeated trips to the sea surface. Fifty-five RAFOS float trajectories, about half at 700 m and half at 1500 m, were obtained from 13 sequential releases, nominally one release of about six floats every three months, during 2003-2006. Each float obtained position fixes and temperature and pressure measurements once per day for two years before surfacing to transmit its data. The float release sites were distributed across the continental slope at 50°N between the 1400 and 2600-m isobaths.

Figure 1a shows the trajectories of all 55 floats, and Figure 1b shows their two-year displacement vectors plus vectors for four additional floats which were not trackable. Like the profiling floats, a large majority (~71%) of the RAFOS floats peeled away from the western boundary east of the Grand Banks. Some of these drifted into the eastern North Atlantic with the North Atlantic Current, an extension of the Gulf Stream that flows first northward along the eastern flank of the Grand Banks, then eastward and northeastward across the Atlantic. Unlike the profiling floats, some RAFOS floats followed the DWBC pathway around the Grand Banks, but the number, less than 10%, was still small in light of the expectation that the DWBC is the major export pathway for recently ventilated water from the northern North Atlantic. Even more surprising was the southward pathway taken by 10 of the RAFOS floats from the vicinity of the southern tip of the Grand Banks into the subtropical interior. The largest meridional displacements were observed in this group of floats. These observations point to a new pathway for the export of Labrador Sea Water through the interior subtropics, and although the number of floats is admittedly very low, and the sampling period limited in time, suggest that the interior pathway may be at least as important if not dominant compared to the DWBC pathway.

In an attempt to overcome the necessarily limited number of observed float trajectories, we simulated the trajectories

of over 7000 “e-floats” using a high-resolution numerical model that has been shown to reproduce many observed features of the North Atlantic circulation in this area. Specifically, the 1/12° resolution Family of Linked Atlantic Model Experiments (FLAME), based on the Geophysical Fluid Dynamics Laboratory MOM2.1 code and modified as part of the FLAME project at IFM-GEOMAR in Kiel, Germany ([Boening et al., 2006; Getzlaff et al., 2006]) was used to compute the simulated trajectories.

These observations point to a new pathway for the export of Labrador Sea Water through the interior subtropics, and suggest that the interior pathway may be at least as important if not dominant compared to the DWBC pathway.

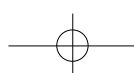
Following a ten year spin-up from rest with climatological forcing, this model was run with interannually varying wind stresses and heat fluxes for the period 1987-2004. Model output consists of three-dimensional snapshots of horizontal velocity, temperature and salinity fields over the domain on a 1/12° resolution Mercator grid. In the vertical, the domain was split into 45 z-coordinate levels. The vertical velocity was computed from the horizontal velocity by requiring that the local divergence of the three-dimensional velocity field be zero throughout the model domain.

Velocity fields from FLAME model years 1994, 1996, and 1998, repeated sequentially, were used to calculate 15-year trajectories. (Note that these years - '94, '96, '98 were the only data available at the time. Recent recalculations using 13 sequential years yielded results very similar to the results presented here.) These years represent a variety of forcing states as indicated by the North Atlantic Oscillation (NAO) index. E-floats were released sequentially over the course of the first three years and

every trajectory was computed for 15 years using 3-day average 3-dimensional model velocity fields. E-float positions are estimated from the 3D model velocity fields, so the virtual floats are displaced both horizontally and vertically to simulate water parcel movement as accurately as possible. Because the RAFOS floats were isobaric (constant pressure) and thus followed only the horizontal component of fluid motion, we calculated and used simulated 3D and 2D model trajectories and found no significant difference in the results discussed below ([Bower et al., 2009]).

An initial comparison of e-float trajectories with the observations indicated that Labrador Sea Water spreading patterns were similar to the observed ones based on the RAFOS floats. The first two years of a random subset of 72 e-floats, initialized at the RAFOS float launch sites, showed that most of the e-floats were expelled from the DWBC east of the Grand Banks, a small fraction followed the DWBC and a somewhat larger fraction took the interior pathway ([Bower et al., 2009]). This encouraging result prompted us to analyze longer e-float trajectories, and to address specifically the question of Labrador Sea Water pathways from the exit of the subpolar region through the subtropics. This is a question that cannot be answered with present day float technology, i.e. limited battery life.

To address this specific question, we analyzed the subset of e-floats that traveled from the launch site at 50°N to 32°N in less than 15 years (the maximum trajectory length). This conditional sampling eliminated about 81% of the e-floats, leaving 1338 e-floats. A two-dimensional histogram of e-float locations is shown in Figure 2a. Some e-floats in this conditionally sampled group peel away from the western boundary before reaching the Tail of the Grand Banks, but they are re-entrained and still reach 32°N within 15 years. Some of these make the entire cyclonic circuit around the subpolar gyre before making it to 32°N. Most e-floats however drifted relatively rapidly southward over the continental slope to the Tail of





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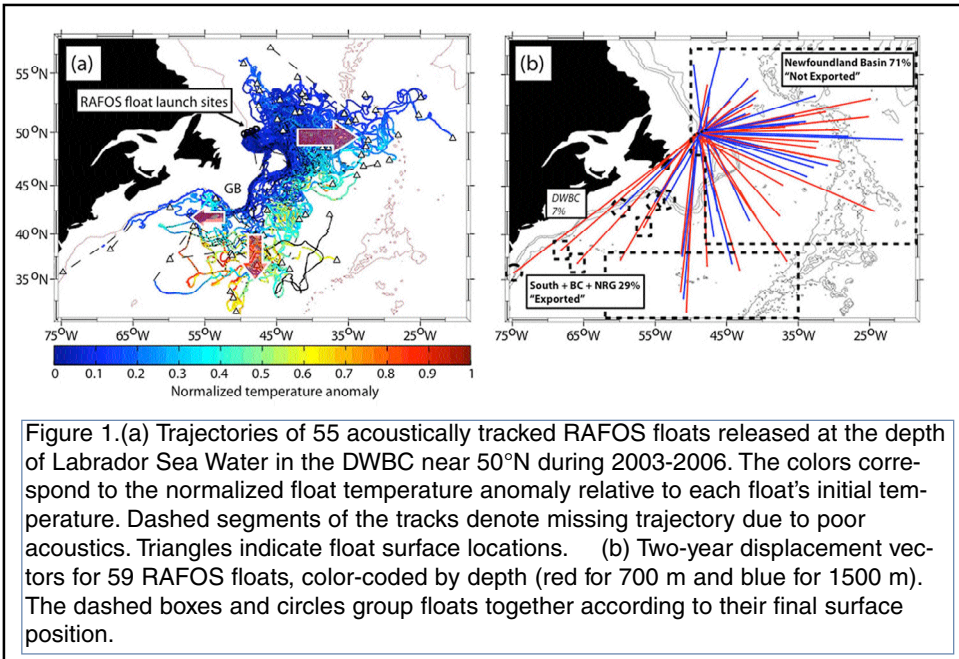


Figure 1. (a) Trajectories of 55 acoustically tracked RAFOS floats released at the depth of Labrador Sea Water in the DWBC near 50°N during 2003-2006. The colors correspond to the normalized float temperature anomaly relative to each float's initial temperature. Dashed segments of the tracks denote missing trajectory due to poor acoustics. Triangles indicate float surface locations. (b) Two-year displacement vectors for 59 RAFOS floats, color-coded by depth (red for 700 m and blue for 1500 m). The dashed boxes and circles group floats together according to their final surface position.

this group “all inshore”. The yellow circles show the same but only for floats which have remained exclusively in the DWBC (“exclusively inshore”), that is, they followed the DWBC path continuously without crossing the 4000-m isobath. The blue lines indicate the longitudinal distribution of volume crossing each latitude in the interior (“all offshore”).

All of the e-floats were initialized inshore of the 4000-m isobath at 50°N. The volume associated with all inshore drops gradually along the eastern flank of the Grand Banks, then precipitously from the eastern to western flanks of the bank. The volume associated with exclusively inshore e-floats drops even more, indicating that there are very few e-floats that follow the DWBC continuously around the Grand Banks.

Continuing westward along the boundary west of 55°W, the all inshore volume grows slightly, an indication that some volume rejoins the DWBC in this area. But near 65°W, only about 24% of the original tagged volume is in the DWBC; the remainder is making its way southward in the interior. South of about 35°N, the volume in the interior turns more westward and rejoins the boundary current by about 30°N. These model results suggest that the interior pathway is more important in terms of volume of Labrador Sea Water tagged at 50°N.

Finally, we note that although the

the Grand Banks, where this one main pathway splits into two: one path continuing along the continental slope and a second southward into the interior then westward back toward the western boundary. The splitting of pathways at the Tail of the Grand Banks is consistent with the RAFOS float trajectories, and the longer e-float trajectories illustrate the longer-term pathways through the subtropics.

Figure 2a is useful for illustrating e-float pathways, but it does not provide any information on which pathway is dominant nor on the associated transit times along each path. Figure 2b ([Bower et al., 2009]), which we call

the Napoleon’s March diagram after a well-known graphic illustrating the decimation of Napoleon’s army during its march across Russia, provides an accounting of the same e-floats used in Figure 2a, but quantifies the importance of the DWBC and interior pathways. More precisely, it tracks the volume associated with each e-float at launch based on the cross-sectional area that the e-float represented and the current speed. The diameters of the red circles are proportional to the volume of tagged water that crosses each latitude inshore of the 4000-m isobath, which we use as the demarcation between the DWBC and the offshore region. We call

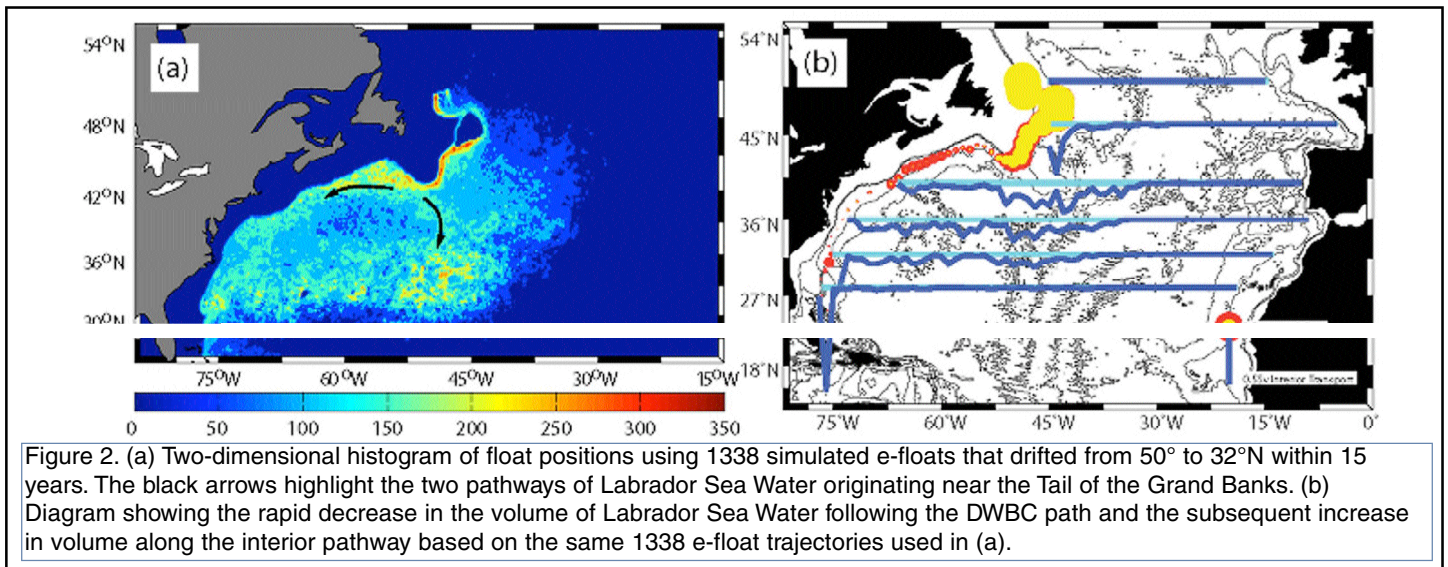
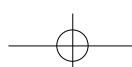


Figure 2. (a) Two-dimensional histogram of float positions using 1338 simulated e-floats that drifted from 50° to 32°N within 15 years. The black arrows highlight the two pathways of Labrador Sea Water originating near the Tail of the Grand Banks. (b) Diagram showing the rapid decrease in the volume of Labrador Sea Water following the DWBC path and the subsequent increase in volume along the interior pathway based on the same 1338 e-float trajectories used in (a).





VARIATIONS

DWBC has been called the “fast track” for the equatorward progression of recently ventilated Labrador Sea Water (e.g., [Molinari et al., 1998]), the simulated float trajectories suggest that the interior pathway through the subtropics can also be relatively rapid. Figure 3 shows trajectories of the 10 e-floats that reached 32°N most quickly (less than about 1.5 years) up to the point where they crossed 32°N. Seven of these “fast trackers” quickly reached 32°N via the interior pathway through the subtropics. The wide range of longitudes where the interior e-floats cross 32°N compared to the narrow band for the DWBC illustrates the more diffuse character of the interior pathway.

In summary, observed and simulated float trajectories reveal the existence of an interior pathway for the southward spreading of Labrador Sea Water through the subtropical North Atlantic. The model results further suggest that the interior pathway may carry more volume compared to the DWBC path. The fastest transit times from 50° to 32°N are similar along the two pathways, although we note that the DWBC path is longer and average speed along that path must therefore be faster. The interior pathway appears to be more diffuse, which will make it more challenging to detect compared to the narrow DWBC pathway.

In closing, we note that while the comparison between observed and modeled trajectories was favorable over the two-year time span of the observations, the results based on the extended integration of the simulated particle trajectories beyond two years needs further corroboration with observations. We also note that this study dealt only with Labrador Sea Water, the lightest and shallowest component of North Atlantic Deep Water. The spreading pathways of the deeper overflow water from the Nordic Seas, which contribute significantly to the global meridional overturning circulation, remain to be explored.

References

Boening, C. W., M. Scheinert, J. Dengg, A. Biastoch, and A. Funk (2006),

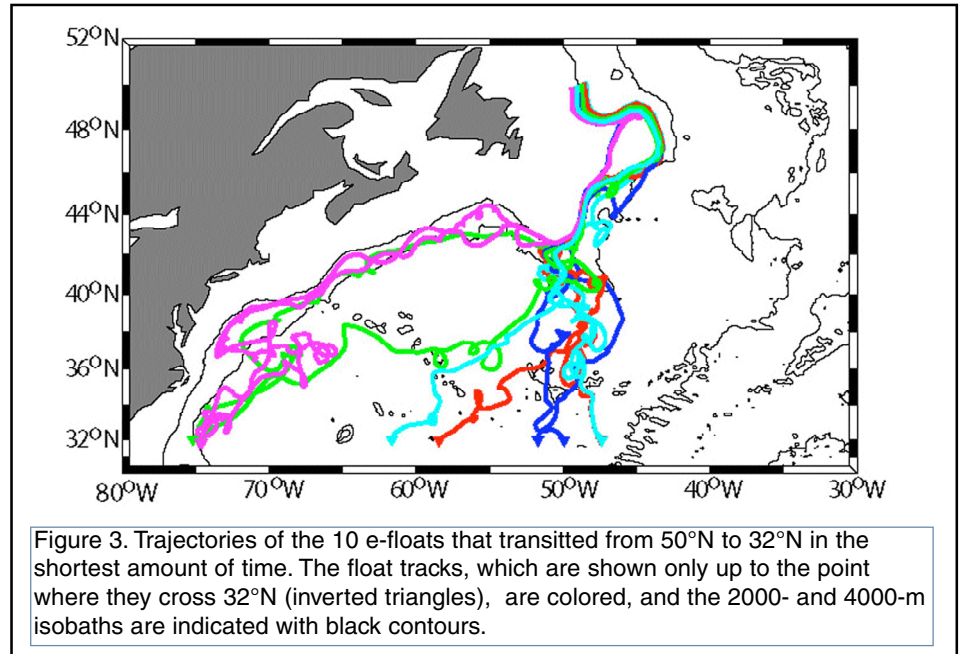


Figure 3. Trajectories of the 10 e-floats that transitted from 50°N to 32°N in the shortest amount of time. The float tracks, which are shown only up to the point where they cross 32°N (inverted triangles), are colored, and the 2000- and 4000-m isobaths are indicated with black contours.

Decadal variability of subpolar gyre transport and its reverberation in the North Atlantic overturning, Geophys. Res. Lett., 33, L21S01, doi: doi: 10.1029/2006GL026906.

Bower, A. S., M. S. Lozier, S. F. Gary, and C. W. Boening (2009), Interior pathways of the North Atlantic meridional overturning circulation, 459(7244), 247.

Broecker, W. S. (1991), The great ocean conveyor, *Oceanography*, 4, 79.

Bryden, H. L., W. E. Johns, and P. M. Saunders (2005), Deep western boundary current east of Abaco: Mean structure and transport, *J.Mar.Res.*, 63, 35.

Dengler, M., J. Fischer, F. A. Schott, and R. Zantopp (2006), Deep Labrador Current and its variability in 1996-2005, *Geophys.Res.Lett.*, 33(21), doi: 10.1029/2006GL026702.

Doney, S. C., and W. J. Jenkins (1994), Ventilation of the Deep Western Boundary Current and Abyssal Western North Atlantic: Estimates from Tritium and 3He Distributions, *Journal of Physical Oceanography*, 24, 638.

Fischer, J., and F. A. Schott (2002), Labrador Sea Water Tracked by Profiling Floats - From the Boundary Current into the Open North Atlantic, *J.Phys.Oceanogr.*, 32(2), 573-584.

Getzlaff, K., C. W. Boening, and J. Dengg (2006), Lagrangian perspectives of deep water export from the subpolar North Atlantic, *Geophys.Res.Lett.*, 33(21), doi: 10.1029/2006GL026470.

Lavender, K. L., R. E. Davis, and W. B. Owens (2000), Mid-depth recirculation observed in the interior Labrador and Irminger seas by direct velocity measure -

ments, *Nature*, 407(6800), 66-69.

Molinari, R. L., R. A. Fine, W. D. Wilson, R. G. Curry, J. Abell, and M. S. McCartney (1998), The arrival of recently formed Labrador Sea water in the Deep Western Boundary Current at 26.5[deg]N, *Geophys.Res.Lett.*, 25(13), 2249-2252.

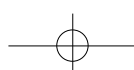
Pickart, R. S., and D. R. Watts (1990), Deep Western Boundary Current variability at Cape Hatteras, *J.Mar.Res.*, 48, 765-791.

Smethie Jr., W. M., R. A. Fine, A. Putzka, and E. P. Jones (2000), Tracing the flow of North Atlantic Deep Water using chlorofluorocarbons, *J. Geophys. Res.*, 105, 14297-14324, doi: DOI: 10.1029/1999JC900274.

Stommel, H., and A. G. Arons (1960a), On the abyssal circulation of the World Ocean--II. An idealized model of the circulation pattern and amplitude in oceanic basins, *Deep-Sea Res.*, 6, 217-233.

Stommel, J., and A. B. Arons (1960b), On the abyssal circulation of the World Ocean--I. Stationary planetary flow patterns on a sphere, *Deep-Sea Res.*, 6, 140-154.

Talley, L. D., and M. S. McCartney (1982), Distribution and circulation of Labrador Sea Water, *J.Phys.Oceanogr.*, 12, 1189-1205.





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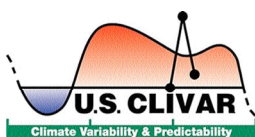
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