Impact of freshwater from the Canadian Arctic Archipelago on Labrador Sea Water formation

Paul G. Myers

Department Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta, Canada

Received 24 November 2004; revised 13 January 2005; accepted 13 January 2005; published 19 March 2005.

[1] The transport of freshwater is analyzed in an eddy-permitting regional model of the sub-polar North Atlantic, focusing on the export of freshwater (in liquid form) through Davis Strait. The results show that in the model simulations there is a limited exchange of freshwater between the Labrador shelf and the interior of the Labrador Sea. Very little of the freshwater exported from the Canadian Arctic gets taken up into the model Labrador Sea water (6–8%). Enhancing the freshwater export through Davis Strait by 2/3s has little effect on the freshwater content in the Labrador Sea interior, as well as on Labrador Sea Water formation. **Citation:** Myers, P. G. (2005), Impact of freshwater from the Canadian Arctic Archipelago on Labrador Sea Water formation, *Geophys. Res. Lett.*, *32*, L06605, doi:10.1029/2004GL022082.

1. Introduction

[2] A number of recent studies [*Dickson et al.*, 2002; *Curry et al.*, 2003] have suggested that the high latitudes of the North Atlantic Ocean have been freshening over the last several decades. As the North Atlantic is one of the few regions of the world ocean where deep waters are formed, this freshwater signal is being transferred into the deep oceans [*Dickson et al.*, 2002]. Additionally, as a major source of deep waters for the world ocean and thus, a key player in the global meridional overturning circulation, the high latitude North Atlantic is potentially very sensitive to additions of freshwater (through freshwater's role as a stabilizing element in the buoyancy budget). Sources for the enhanced supply of freshwater to the northern North Atlantic over recent decades includes changes in atmospheric excess precipitation (S. A. Josey and R. Marsh, Surface freshwater flux variability and recent freshening of the North Atlantic in the eastern subpolar gyre, submitted to *Journal of Geophysical Research*, 2004, hereinafter referred to as Josey and Marsh, submitted manuscript, 2004), river runoff, melt from the Greenland ice cap and oceanic transport.

[3] As well as the long term freshening, observations have been made of 2 (or 3) strong low salinity anomalies propagating around the sub-polar gyre [*Dickson et al.*, 1988; *Belkin et al.*, 1998] during the 1970's, 1980's (and possibly 1990's). These events, termed great salinity anomalies (GSAs), were tracked passing from the Nordic Seas, through the Irminger Sea into the Labrador Sea and then back into the eastern part of the gyre. The origin of these anomalies has been suggested to be enhanced export of freshwater/sea ice through Fram Strait [*Dickson et al.*, 1988; *Belkin et al.*, 1998], extreme winters in the Labrador Sea [*Belkin et al.*, 1998], enhanced freshwater outflow from the Canadian Arctic Archipelago [*Belkin et al.*, 1998] or some combination of the above.

[4] The Arctic Ocean is an estuarine basin that exports freshwater to the North Atlantic. It has two main pathways for this export, through Fram Strait to the east of Greenland and through the many small and narrow straits that make up the Canadian Arctic Archipelago, to the west of Greenland. The main pathway for the Arctic export is generally considered to be Fram Strait [*Aagard and Carmack*, 1989]. An estimate of the freshwater transport southward, combining both the liquid and sea ice component is 127 mSv (relative to a reference salinity of 34.8 psu) [*Melling*, 2000]. However their are also significant exports through the Canadian Arctic Archipelago. Estimates of the net freshwater export southward through Davis Strait, again relative to a reference salinity of 34.8 psu, range from 120 mSv [*Loder et al.*, 1998] to 135 mSv [*Melling*, 2004] and 103 mSv [*Cuny and Rhines*, 2005].

[5] The Labrador Sea is a northern arm of the North Atlantic Ocean, shaped as a large bowl open to the south, flanked by continental shelves, narrow along Greenland and wider along the Labrador Coast. Along these shelves and over the shelf breaks flow the West Greenland Current, the Baffin Island Current and the Labrador Current, linking the large scale cyclonic circulation of the region. These boundary currents carry mainly cold and fresh water, isolated from the weakly stratified basin interior by strong fronts [*Lazier and Wright*, 1993].

[6] In a coarse resolution ocean model, *Weaver et al.* [1994] applied an additional freshwater source to the Labrador Sea to represent a crude parameterization of the freshwater transport through the Canadian Arctic Archipelago and found that it acted to cap convection and suppress internal oceanic variability. This study was limited however by the coarseness of its resolution (3° by 3°) and the corresponding crudeness of its Labrador Sea circulation. One of the key limitations in the above study, as in any coarse resolution climate model, is the inability to properly represent the sharp front separating the boundary currents from the interior, and thus the exchange into the interior, which is mainly governed by instability and eddy processes [*Lilly et al.*, 2003]. Thus, this study re-examines this question in a much higher resolution eddy-permitting regional ocean model that accurately reproduces the major features of the Labrador Sea circulation and hydrography. A control experiment will examine the behavior of the water exported through Davis Strait (as a proxy for the Archipelago throughflow) in the model. Additional sensitivity experiments will consider

0094-8276/05/2004GL022082

modifications to this transport, such as from increased arctic ice melt associated with warmer temperature from interdecadal climate variability and/or long term warming due to climate change. The end result will be a detailed picture of the importance of this linkage between the Arctic and the North Atlantic.

2. Model

[7] SPOM (Sub-Polar Ocean Model) is a regional configuration set up specifically for process and sensitivity studies of ocean variability questions in the sub-polar North Atlantic. The model, with a horizontal resolution of 1/3 degree and 36 vertical levels (and using a partial cell formulation) employs a scheme with a variable eddy transfer coefficient that is allowed to vary within the 0.5×10^6 to 10^7 cm^2 s^{-1} range. A low background lateral diffusion is obtained by using a biharmonic diffusion coefficient of 7.5×10^{14} cm^4 s^{-1}. The impact of the eddy formulation and parameter choice is examined in detail by *Deacu and Myers* [2005a].

[8] The southern boundary is open (38N) while restoring buffer zones are included along the model's closed northern boundaries (including Hudson's Strait and Baffin Bay). The purpose of these buffer zones is to guarantee the waters transported into the Labrador Sea have appropriate properties. At the surface the forcing is monthly (repeating each year), for both the tracers (using monthly relaxation) and the winds. Other details on the model are described in more detail by *Myers* [2002].

3. Base Experiment

[9] The starting point for our baseline CONTROL experiment was the end of the 80 year simulation performed by *Deacu and Myers* [2005b], which was an extended version of *Deacu and Myers* [2005a] to consider the long term stability of the model formulation. At this point, because the volume and freshwater transports out of the model buffer zones differed from the observations, the winds over these regions (Hudson's Strait, lower Baffin Bay) were modified to provide for more realistic transports. A further 40 year integration was then performed to ensure that the volume and freshwater transports exported from Baffin Bay (in the Baffin Island Current) (Table 1) were within the range of the observations. To enable following the dispersal of 'Arctic' water in the model, an idealized tracer was then initialized in Baffin Bay with a constant value of 1 (through the entire depth of the water column). The model was then integrated for a further 10 years, with the results from this last period of integration being considered our CONTROL experiment.

[10] The model Baffin Island Current, with a volume transport of 2.0 Sv and a freshwater transport of 112 mSv, falls within the range of the observations [*Cuny and Rhines*, 2005]. Annually averaged concentrations of the Baffin Bay tracer from the last year of integration are shown in Figure 1a. The water that is exported through Davis Strait is transported south by the shelf and slope branches of the Labrador Current. The tracer concentration drops along the water's southward path as it is mixed with waters of other sources (West Greenland Current, Hudson Strait, the surface forcing). A key point is that the tracer is basically confined to the shelf and slope, with very little exchange into the interior of the Labrador Sea, especially north of Hamilton Bank. What exchange there is occurs along the broader Newfoundland shelf north of the Grand Banks, where the Labrador Current interacts with the North Atlantic Current. As some of the tracer does reach the interior of the Labrador Sea, some is taken up in the Labrador Sea Water (LSW) formed in wintertime in the model. Concentrations remain low (6–8%), even after 20 years, at depth (Figure 1b). Thus, the Baffin Bay water has small (but not negligible) impact on the LSW.

Table 1. Freshwater Exported From Baffin Bay Through Davis Strait in the Baffin Island Current for the Experiments Discussed in This Paper[a]

Experiment	Freshwater Transport
Control	112 mSv
INC13	155 mSv
INC23	183 mSv

[a]The values given are annually averaged over the last year of integration.

[11] Instead, the Labrador Sea interior in the model is fed from the West Greenland/Irminger Current system. To visualize this, the water flowing through the 12 grid points (4 degrees longitude) directly south of Cape Farewell was tagged with another idealized tracer (with its value again set to 1 through the entire depth of the water column). Concentrations of this tracer after 1 year of integration are shown for the Labrador Sea in (Figure 1c). The fact that there is a stronger transport through this area results in a larger impact on the central Labrador Sea, in addition to the fact that it is also more directly entrained in the interior. High concentrations in the offshore branch of the Labrador Current are consistent with 'weak' mixing across the Labrador shelf-break front. A plot of this tracer on the LSW surface (not shown) shows high concentrations, indicating that the main component of the model LSW (mixed with waters from the surface forcing) has its origins with these waters. These results are consistent with both observational [*Frantantoni*, 2001] and modelling [*Eden and Boning*, 2002] studies suggesting high eddy kinetic energies and strong exchange with the boundary currents and interior along the west coast of Greenland.

4. Enhanced Fluxes

[12] Increasing temperatures and an enhancement of the global hydrological cycle as part of global warming may lead to enhanced freshwater export from the Arctic Ocean, and specifically through the Canadian Arctic Archipelago, into the Labrador Sea. Enhanced freshwater export through Davis Strait has also been suggested to have played a role in enhancing the 1980s GSA [*Belkin et al.*, 1998]. Here changes to the freshwater export through Davis Strait are mimicked by locally modifying the strength of the model winds in Baffin Bay to produce a larger export from this region. We then focus on the impact these modified fluxes have on water formation in the Labrador Sea. We focus on two sensitivity experiments, where we aimed, by modifying the wind forcing, to increase the freshwater transport in the Baffin Island Current by approximately 33% (experiment INC13) and 67% (experiment INC23) respectively (Table 1).

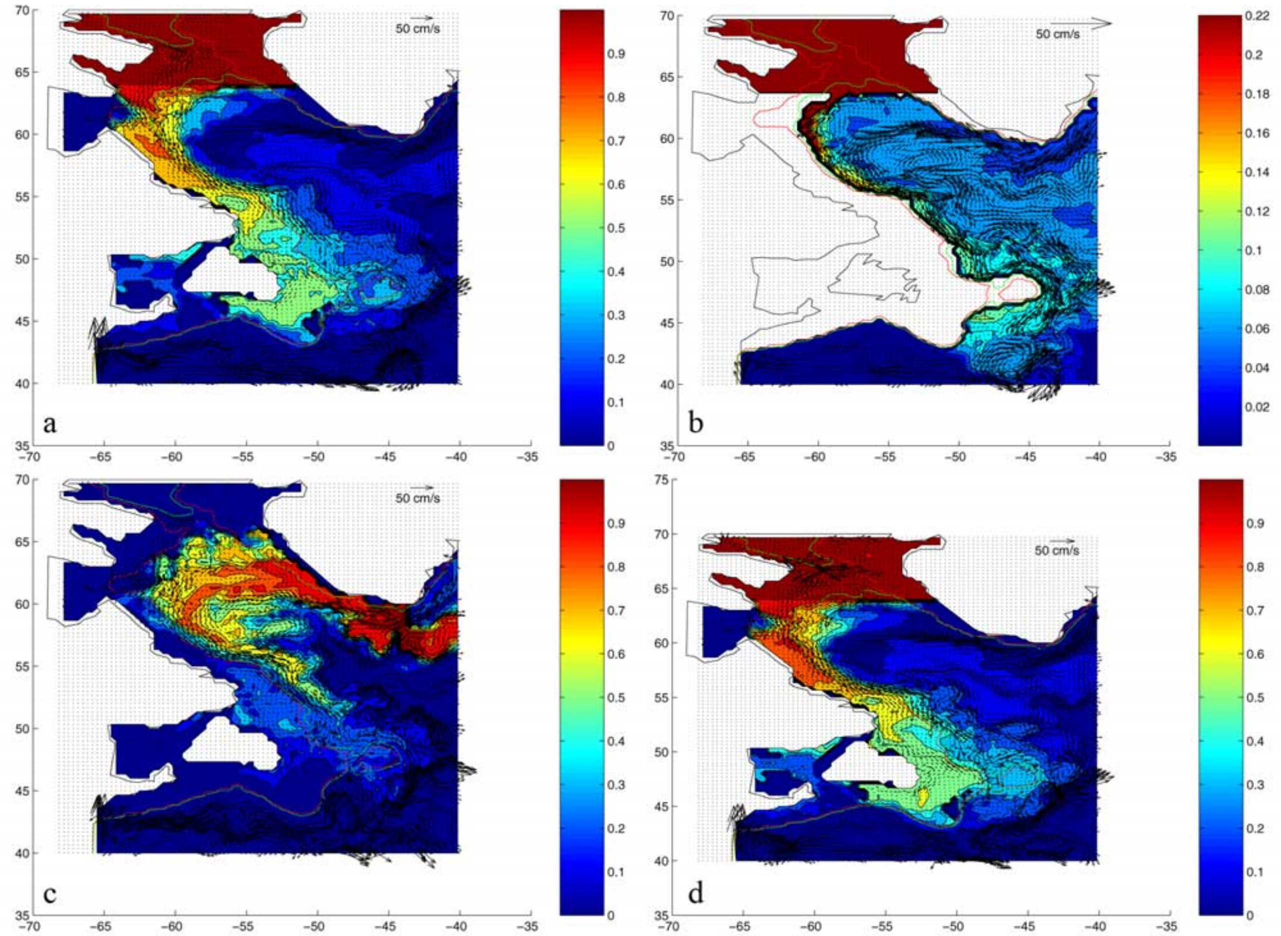

Figure 1. a) Annually averaged (from the last year of integration) concentrations of the idealized Baffin Bay tracer on the third model level (52.6 m) from the CONTROL experiment; b) annually averaged (from the last year of integration) concentrations of the idealized Baffin Bay tracer on the twentieth model level (1517.5 m) (note that choosing another depth surface or projecting the results onto an appropriate isopyncal surface does not qualitatively change the results); c) instantaneous concentration of an idealized tracer tagged to water parcels passing within 4 degrees south of Cape Farewell, after 1 year of integration; d) annually averaged (from the last year of integration) concentrations of the idealized Baffin Bay tracer on the third model level (52.6 m) of the INC23 experiment. In all four figures, the red and green lines are the 500 m and 1000 m isobaths respectively. Current fields (arrows) are superimposed on each figure.

Each of these additional experiments are integrated for 30 years.

[13] Figure 1d shows the annually averaged concentration of the idealized Baffin Bay tracer from the last year of the INC23 experiment. Compared to the CONTROL experiment (Figure 1a), there is little change in the Baffin Bay tracer concentration in the interior of the Labrador Sea, even after 30 years with significantly enhanced export through Davis Strait. Freshwater content in the interior of the Labrador Sea was found to differ by less than 1% between all 3 experiments with variable Davis Strait outflow. An analysis of the volume of Labrador Sea Water formed with density between 27.74 and 27.80 showed that variations between experiments was less than 1% (much smaller than the interannual variability within each experiment). Instead the differences between the experiments were concentrated along the Labrador shelf and slope. Comparing the CONTROL and INC23 wind experiments (Figures 1a and 1d) shows enhanced values of the Baffin Bay tracer all along the Labrador and Newfoundland shelves, from Cape Chidley to the Grand Banks.

5. Discussion and Implications

[14] How do these modelling results fit in with observations of freshwater in the region? *Loder et al.* [1998] found from hydrographic data that the primary source of freshwater to the Labrador Shelf was from the high latitudes. Based on oxygen isotope/salinity data, *Khatiwala et al.* [1999] similarily found that Baffin Bay freshwater is a prime contributor to water masses along the Labrador shelf through to the Scotian shelf. Recently, S. Schmidt and U. Send (Origin and composition of seasonal Labrador Sea freshwater, submitted to *Journal of Physical Oceanography*, 2004) examined the seasonal cycle of Labrador Sea freshening. They suggest that the Labrador Current only supplies freshwater to the interior of the Labrador Sea for a short time during spring and that 60% of the annual

freshwater that reaches the central Labrador Sea originates with the West Greenland Current. Significant interaction between the West Greenland Current and the Labrador Sea through eddy processes is supported by observations of high eddy kinetic energies in this area, as well as through modelling studies [*Eden and Boning*, 2002; *Katsman et al.*, 2004] showing that these eddies play in a key role in restratification after convection in the Labrador Sea.

[15] With the importance of eddy processes in the Labrador Sea, one can ask about the appropriateness of using an eddy-permitting rather than an eddy resolving model in this study. For example, *Chanut et al.* [2003] suggest that 1/15 degree resolution is needed to properly represent the eddies involved with restratification and thus their role in freshwater transport. However, *Eden and Boning* [2002] suggest that while their 1/12 degree experiment was not sufficient for resolving the rim current eddies, they were able to qualitatively represent the patterns of EKE in the West Greenland Current with a 1/3 degree model. Furthermore, *Deacu and Myers* [2005a] found (using the same model as in this study) that, if anything, the model EKE along the West Greenland Current was underestimated. This would suggest, if the WGC eddies are crucial to the provision of freshwater to the Labrador Sea interior, this transport would be underestimated rather than overestimated here. That said, further studies of the small scale eddy processes and their parameterization in the Labrador Sea is needed to ensure that models can properly represent exchange processes in the Labrador Sea.

[16] Studies have suggested the importance of freshwater on water formation in the high latitude North Atlantic (and it has been pointed out that it is the freshwater anomalies that lead the sea ice anomalies in this region [*Mysak et al.*, 1990]). However, these studies have traditionally used coarse resolution models that either applied the added freshwater directly to the entire high latitude gyre region and/or have broad, diffuse boundary currents that easily allow freshwater to be exchanged into the interior. If the additional freshwater source being simulated is related to increased atmospheric precipitation (e.g. Josey and Marsh, submitted manuscript, 2004), then this approach may not be problematic. If instead, a significant component of the additional freshwater is related to glacier or sea ice melt, and/or river runoff, then this freshwater source should realistically be applied along the coasts, and if the exchange with the interior is too easy/large, then one may find such studies overestimating the importance of the freshwater input to the large scale circulation.

[17] *Khatiwala and Visbeck* [2000] suggest that an eddy-induced overturning circulation linked to isopycnal slumping and baroclinic instability leads to surface inflow of freshwater from the boundary currents into the interior of the Labrador Sea, sinking and then outflow at depth towards the boundaries. *Spall* [2004] used an idealized circular ocean basin to examine water mass transformation and thermohaline circulation in a marginal basin. Although providing much insight into understanding processes in the Labrador Sea, both studies considered the Labrador Sea as a symmetric basin with equal exchange from both the WGC and the LC. Yet results like the present ones highlight the fundamental asymmetry of the basin, with significant differences in exchanges between the boundary currents and the interior between 'sides' that needs to be considered in future theoretical studies.

[18] **Acknowledgments.** This work was funded by NSERC and CFCAS grants (GR-019 and the Canadian CLIVAR network) awarded to PGM. We would like to thank Daniel Deacu for his assistance with this work.

References

Aagard, K., and E. C. Carmack (1989), The role of sea ice and other fresh water in the Arctic circulation, *J. Geophys. Res.*, *94*, 14,485–14,498.

Belkin, I. M., S. Levitus, J. Antonov, and S.-A. Malmberg (1998), "Great salinity anomalies" in the North Atlantic, *Prog. Oceanogr.*, *41*, 1–68.

Chanut, J., B. Barnier, L. Debreu, and W. Large (2003), Restratification after deep convection in the Labrador Sea: A high resolution model study, *Geophys. Res. Abstr.*, *5*, Abstract 08741.

Cuny, J., and P. B. Rhines (2005), Volume, freshwater and heat transport through Davis Strait, *Deep Sea Res.*, in press.

Curry, R., B. Dickson, and I. Yashayaev (2003), A change in the freshwater balance of the Atlantic Ocean over the past four decades, *Nature*, *426*, 826–829.

Deacu, D., and P. G. Myers (2005a), Effect of a variable eddy transfer coefficient in an eddy-permitting model of the Sub-Polar North Atlantic, *J. Phys. Oceanogr.*, in press.

Deacu, D., and P. G. Myers (2005b), Analysis of an 80-year integration of a 1/3-degree model of the sub-polar North Atlantic, *J. Oceanogr.*, in press.

Dickson, R. R., J. Meincke, S.-A. Malmberg, and A. J. Lee (1988), "The great salinity anomaly" in the northern North Atlantic 1968–1982, *Prog. Oceanogr.*, *20*, 103–151.

Dickson, R. R., T. J. Osborn, J. W. Hurrell, J. Meincke, W. Turrell, S. Dye, and J. Holfort (2002), Rapid freshening of the deep North Atlantic Ocean over the past four decades, *Nature*, *416*, 832–837.

Eden, C., and C. Boning (2002), Sources of eddy kinetic energy in the Labrador Sea, *J. Phys. Oceanogr.*, *32*, 3346–3363.

Frantantoni, D. M. (2001), North Atlantic surface circulation during the 1990's observed with satellite-tracked drifters, *J. Geophys. Res.*, *106*, 22,067–22,093.

Katsman, C., M. A. Spall, and R. S. Pickart (2004), Boundary current eddies and their role in restratification of the Labrador Sea, *J. Phys. Oceanogr.*, *34*, 1967–1983.

Khatiwala, S., and M. Visbeck (2000), An estimate of the eddy-induced circulation in the Labrador Sea, *Geophys. Res. Lett.*, *27*, 2277–2280.

Khatiwala, S. P., R. G. Fairbanks, and R. W. Houghton (1999), Freshwater sources to the coastal ocean off northeastern North America: Evidence from $H_2^{18}O/H_2^{16}O$, *J. Geophys. Res.*, *104*, 18,241–18,255.

Lazier, J. R. N., and D. G. Wright (1993), Annual velocity variations in the Labrador Current, *J. Phys. Oceanogr.*, *23*, 659–678.

Lilly, J. M., P. B. Rhines, F. Schott, K. Lavender, J. Lazier, U. Send, and E. D'Asaro (2003), Observations of the Labrador Sea eddy field, *Prog. Oceanogr.*, *59*, 75–176.

Loder, J. W., B. Petrie, and G. Gawarkiewicz (1998), The coastal ocean off northeastern North America: A large-scale view, in *The Sea*, vol. 11, edited by A. R. Robinson and K. H. Brink, pp. 105–133, John Wiley, Hoboken, N. J.

Melling, H. (2000), Exchanges of freshwater through the shallow straits of the North American Arctic, in *The Freshwater Budget of the Arctic Ocean*, *NATO Sci. Ser. 2*, vol. 70, Springer, New York.

Melling, H. (2004), Fluxes through the northern Canadian Arctic Archipelago, *ASOF Newsl.*, *2*, 3–7.

Myers, P. G. (2002), SPOM: A regional model of the sub-polar North Atlantic, *Atmos. Ocean*, *40*, 445–463.

Mysak, L. A., D. K. Manak, and R. F. Marsden (1990), Sea-ice anomalies in the Greenland and Labrador Seas during 1901–1984 and their relation to an interdecadal climate cycle, *Clim. Dyn.*, *5*, 111–133.

Spall, M. A. (2004), Boundary currents and watermass transformation in marginal seas, *J. Phys. Oceanogr.*, *34*, 1197–1213.

Weaver, A. J., S. M. Aura, and P. G. Myers (1994), Interdecadal variability in an idealized model of the North Atlantic, *J. Geophys. Res.*, *99*, 12,423–12,441.

P. G. Myers, Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB, Canada T6G 2E3. (pmyers@ualberta.ca)