Reasons for a fresher northern North Atlantic in the late 20th century

Aixue Hu and Gerald A. Meehl

Climate and Global Dynamics Division, National Center for Atmospheric Research, Boulder, Colorado, USA

Received 4 March 2005; revised 4 May 2005; accepted 10 May 2005; published 7 June 2005.

[1] Observational analyses suggest that the northern North Atlantic is fresher in the late 20th century in comparison to the 1950–60s. Here we examine possible contributors to these observed changes by analyzing a four-member ensemble of 20th century simulations from a coupled climate model. Results show that a weaker meridional freshwater divergence related to a weaker thermohaline circulation in the North Atlantic is the primary cause for the freshening in the northern North Atlantic in the model. The increased P-E tends to enforce it, but the reduced sea ice flux into this region tends to weaken it. **Citation:** Hu, A., and G. A. Meehl (2005), Reasons for a fresher northern North Atlantic in the late 20th century, *Geophys. Res. Lett.*, *32*, L11701, doi:10.1029/2005GL022900.

1. Introduction

[2] Recent observational studies indicate that the northern North Atlantic Ocean has been undergoing remarkable changes in the second half of the 20th century – namely a freshening trend of the ocean water column, especially in the Labrador Sea [*Antonov et al.*, 2002; *Dickson et al.*, 2002; *Curry et al.*, 2003]. The possible cause of this freshening has been attributed to a combined effect of freshwater export from the Arctic in the form of ice and melt-water, increased net precipitation, and increased continental runoff [*Abdalati and Steffen*, 1997; *Dickson et al.*, 2000; *Vinje*, 2001; *Peterson et al.*, 2002], and may also be related to the upward trend of the North Atlantic Oscillation (NAO) during the second half of the 20th century [*Dickson et al.*, 1996]. Observed evidence also shows a freshening trend of the Denmark Strait Overflow water (DSOW) and the Faroe Bank overflow water [*Dickson et al.*, 2002]. These overflow waters along with the dense water formed in the Labrador Sea (the Labrador Sea Water) feed into the lower branch of the global scale oceanic circulation – the thermohaline circulation (THC). It is not clear whether this freshening would be an indicator of a weakening of the THC. Since this freshening is a sign of increased freshwater supply to the subpolar ocean and may have resulted in a more stabilized upper ocean stratification, it is speculated that the THC may have weakened or be in the process of weakening.

[3] In this paper, we use the Parallel Climate Model (PCM) to study the cause of the recent observed freshening in the subpolar North Atlantic and the relationship between that freshening and the THC. Our result basically indicates an increase in precipitation less evaporation ($P - E$, hereafter) in the polar-sub-polar North Atlantic, and a decrease in sea ice export from the Arctic to the Greenland-Iceland-Norwegian (GIN) Seas and further into the Labrador Sea. The combined effect of these two fresh water sources is a production of a small increase in net surface freshwater input into the GIN Seas and a small decrease in the Labrador Sea region. On the other hand, the divergence of the meridional freshwater transport between 45° and 65°N is decreased related to a weaker THC, resulting in a net increase in freshwater supply, which plays an important role in the freshening. This result differs from a recent model study by *Wu et al.* [2004] using HadCM3 who successfully simulated the freshening of the Northeast Atlantic deep water (NEADW) without a THC weakening. They concluded that this freshening may not be an indicator of the THC weakening in the late 20th century. Therefore, our study will shed more light on the relationship between the subpolar freshening and the THC.

2. Model and Experiments

[4] The global coupled model used here is the Parallel Climate Model (PCM) [*Washington et al.*, 2000]. It includes an atmospheric model with T42 horizontal resolution and 18 vertical levels (Community Climate Model, CCM3), a version of Parallel Ocean Program (POP) Model with a horizontal resolution of 2/3 degree and 32 levels in the vertical, a land surface model with the same resolution as CCM3, and a sea ice model with both dynamics and thermodynamics. This model has been used extensively in climate change research [e.g., *Santer et al.*, 2003; *Meehl et al.*, 2003].

[5] The experiments analyzed here are a four-member ensemble of 20th century simulations with time-evolving concentrations of anthropogenic forcings including greenhouse gases, sulfate aerosols, and ozone. Each of the ensemble members starts from a different state of the control run about 30 years apart after the control run spins up to 1870 conditions (details see *Meehl et al.* [2003]). The solar and volcanic forcings have not been included in these simulations. The simulated global mean temperature variations from these runs are close to the observations, especially for the last 3 decades of the 20th century when anthropogenic forcings were dominant compared to natural forcings [*Meehl et al.*, 2004], but slightly underestimates the warming in parts of the first half of the 20th century when natural forcings played a more important role. In the following analysis, we focus only on climate changes in the latter part of the 20th century, and the linear trend of the control run is removed from all data.

3. Results

[6] The zonal and ensemble averaged salinity difference between 1985–1999 and 1955–1969 is shown in Figure 1a.

0094-8276/05/2005GL022900$05.00

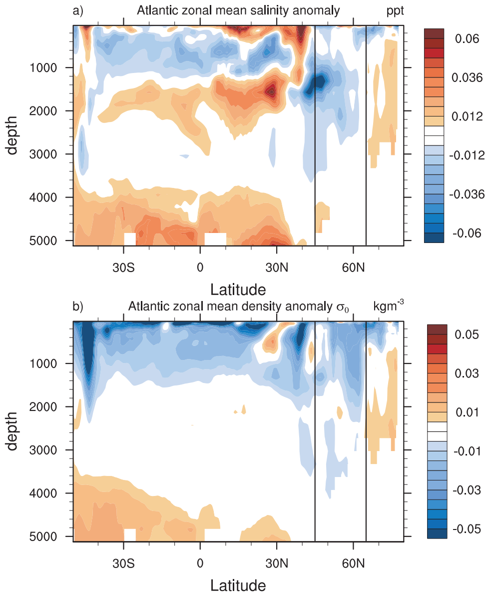

Figure 1. Zonal, ensemble-averaged salinity (a) and density (b) difference between 1955–69 and 1985–99 in the Atlantic sector. Figure 1a is similar to the Figure 2b of *Curry et al.* [2003] who plotted a North-South cross section of the Atlantic. The contour interval is 0.006 ppt for a) and 0.005 kgm^{-3} for b).

The salinity changes are similar to the observations noted by *Curry et al.* [2003] and *Antonov et al.* [2002] with a freshening on both sides of the subpolar Atlantic, and a more saline upper ocean in the subtropics. As reported by *Curry et al.* [2003] for the observations, the strongest freshening in our model is in the deep North Atlantic centered at a depth of 1500 meters. Our model also produces a fresher sub-surface tropics and subtropics, indicating that PCM produces a stronger than observed freshening of the Antarctic intermediate water. Figure 1b shows a density decrease in the model in the upper 1500 meters in most parts of the Atlantic. The density decrease reaches down to more than 3000 meters in the northern North Atlantic, mainly related to the freshening there. In the tropics and subtropics, the density change is induced by both temperature and salinity changes, but is dominated by temperature changes (warming). In this paper, we focus on attributing the causes of the subpolar freshening in North Atlantic between 45° and 65°N (or the northern North Atlantic, a region inside the two black lines in Figure 1) through a freshwater budget analysis.

[7] The freshwater budget in the northern North Atlantic ocean can be affected by the net surface freshwater flux, including the precipitation less evaporation plus river runoff ($P - E$), local sea ice melting and sea ice transported from the Arctic, and can also be affected by oceanic current transport, including the transport of salty subtropical water and fresher polar water into this region by horizontal currents, and by the meridional overturning. Each of these processes will be discussed below.

[8] The time-evolving $P - E$ from the model between 45° and 65°N from 1890 to 1999 (Figure 2a) shows a 0.0005 Sv/decade (Sv $\equiv$ 10^6 m^3s^{-1}) trend of increased freshwater input in this region from the 1950s to the 1990s, agreeing with the European Centre for Medium-Range Weather Forecasting (ECMWF) 40-year reanalysis (ERA40) data. The mean surface freshwater flux changes from 0.0812 Sv in the period 1955–69 to 0.0826 Sv in the period 1985–99 (Table 1). This change is about 15% of that in ERA40 data. This lower increase in $P - E$ may be related to the model's inability to simulate the upward trend of the NAO in the ensemble mean during the second half of the 20th century since observed studies indicate a positive relation between precipitation and NAO in this region [e.g., *Hurrell*, 1995; *Marshall et al.*, 2001].

[9] We next compare observed precipitation data over land [*Mitchell et al.*, 2004] with the ERA40 precipitation in

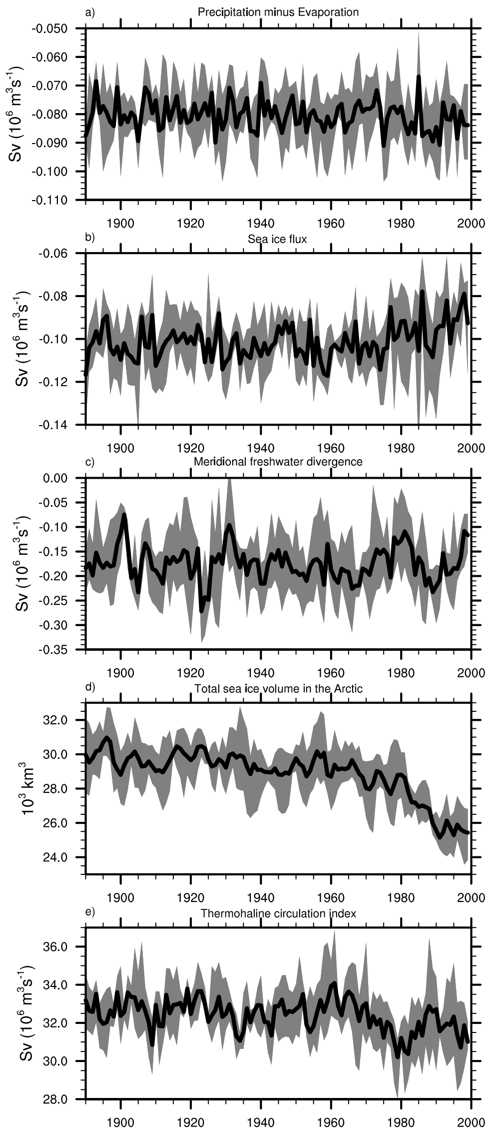

Figure 2. Time evolution of the $P - E$ (a), sea ice flux (b), meridional freshwater divergence (c) between 45 and 65°N from 1890 to 1999. Panel d and e are the time evolution of the total Arctic sea ice volume and the maximum THC index, respectively. The shading indicates the ensemble range and the thick solid lines are the ensemble average. The unit is $10^3 km^3$ for sea ice volume, and Sv (Sv $\equiv$ $10^6 m^3 s^{-1}$) for other panels.

Table 1. Summary of Changes Between 1955–69 and 1985–99[a]

Variables	Units	1955–1969	1985–1999
$P - E$	Sv	0.0812	0.0826
Ice flux in 45–65°N	Sv	0.1055	0.0940
MFWT at 45°N	Sv	0.4737	0.4935
MFWT at 65°N	Sv	0.2920	0.3223
THC	Sv	31.6	30.4
Arctic SSS	ppt	31.81	31.65
Arctic ice volume	10^3km^3	29.31	25.96

[a]Sv $\equiv 10^6 m^3 s^{-1}$. MFWT represents meridional freshwater transport, THC represents thermohaline circulation, and SSS represents sea surface salinity.

the North Atlantic region (Note: the observed data only covers land). The observed data set shows an NAO related change in precipitation pattern, with increased precipitation from northeast America to Iceland and northern Europe, and decreased precipitation along the Canada-southern Greenland coasts, and mid-south Europe between 1985–99 and 1955–69 (figure not shown). By assuming the precipitation pattern over the northern North Atlantic ocean is the same as that in North America and Europe, we find that the ERA40 data possibly overestimates the increase of precipitation in the northern North Atlantic Ocean region. Thus, the underestimation of the $P - E$ change in PCM may not be as large as we have shown above.

[10] On the other hand, the modeled sea ice flux from the Arctic to this region exhibits a decreasing trend since the 1950s (Figure 2b), associated with global warming. The total sea ice flux from the Arctic through east Greenland and from Baffin Bay to this region reduces from 0.1055 Sv in 1955–69 to 0.0940 Sv in 1985–99, a 10% decrease, with a trend of 0.0038 Sv/decade. Thus, the total surface freshwater input, $P - E$ plus sea ice flux, shows a net reduction of about 0.0101 Sv, or 5%.

[11] The meridional freshwater transport divergence, including both wind driven gyre and density driven THC, shows a weakening trend of 0.0055 Sv/decade since 1950s (Figure 2c). The southward meridional freshwater flux increases from 0.4737 Sv in 1955–69 period to 0.4935 Sv in 1985–99 period at 45°N, and from 0.2920 Sv to 0.3223 Sv at 65°N. The greater increase of the meridional freshwater transport at 65°N compared to 45°N is mainly due to an 11% reduction of Arctic sea ice volume from 1955–69 to 1985–99, with a trend of 0.94×10^3km^3/decade (Figure 2d). This decrease in sea ice volume results in a 50% increase of the freshwater into the Arctic and leads to a decrease of the Arctic sea surface salinity by 0.16 ppt. When this freshwater anomaly is exported out of the Denmark Strait, the meridional freshwater transport increases there. Because of this higher increase of the meridional freshwater transport at 65°N, the resulting freshwater divergence is decreased by about 0.0105 Sv. Taking into account the freshwater deficit at surface, the net gain of the freshwater in this region is 0.0004 Sv. Therefore, the freshening in the North Atlantic between 45° and 65°N is mainly caused by the decreased meridional freshwater divergence in our model.

[12] This decreased meridional freshwater divergence is related to a weaker THC measured by the maximum strength of the meridional overturning stream function in the Atlantic. This maximum is located at 35°N and at a depth of about 1400 meters. Figure 2e shows a weaker THC with a trend of 0.33 Sv/decade since 1950s. It is weakened by about 1.2 Sv in period 1985–99 compared to the earlier period, about a 4% decrease relative to the mean THC. A lag correlation calculation shows the THC leads meridional freshwater divergence in northern North Atlantic by one year, with a lag -1 correlation coefficient of 0.4 for the whole time series. As the THC weakens, the THC's ability to transport the freshwater anomaly from the northern North Atlantic is reduced.

[13] The weakening of the THC is mainly caused by the surface warming in the northern North Atlantic induced by the increased atmospheric CO_2 concentration [*Stott et al.*, 2000; *Meehl et al.*, 2003; *Broccoli et al.*, 2003]. This surface warming, combined with the freshwater anomaly exported from the Arctic due to increased ice-melting, causes a decrease in surface density, and suppresses deep convection. The mean deep convection between 45° and 65°N decreases by about 0.7 Sv at a depth of 1400 meters where the maximum of the Atlantic meridional stream function is located. We also examine the inter-basin sea surface salinity contrast between North Atlantic and North Pacific as suggested by *Seidov and Haupt* [2003]. This inter-basin salinity contrast increases by about 0.057 ppt, which should contribute to a stronger THC. But the local density changes associated with the CO_2 induced warming in the northern North Atlantic dominate this increased inter-basin salinity contrast, producing a weaker THC in our model.

4. Summary and Discussion

[14] In this paper, we discuss the possible reasons for the observed freshening of the subpolar North Atlantic using a global coupled model, the Parallel Climate Model (PCM). The model realistically simulates the pattern of observed freshening in the subpolar North Atlantic between 45° and 65°N in the late 20th century. The changes of $P - E$ between 1955–65 and 1985–99 indicate an increase in freshwater input in this region, but the reduced sea ice fluxes from Arctic and Baffin Bay into this region change the $P - E$ induced freshwater surplus to a deficit. On the other hand, the meridional freshwater divergence in this region is reduced in the late 20th century, inducing a freshwater gain. This freshwater gain not only compensates for the deficit of the surface freshwater input, but also leads to a net freshwater gain in this region, which is responsible for the simulated freshening. This reduction of the meridional freshwater divergence is caused by a weaker THC. The weakening of the THC is primarily related to global warming induced changes associated with increased atmospheric greenhouse gas concentrations. The changes include a warmer sea surface temperature in the northern North Atlantic region, increased freshwater supply in the GIN Seas and the Arctic due to enhanced $P - E$ and the reduction of Arctic sea ice volume. The combined effect of these changes is a surface density decrease, a more stable vertical stratification, a weaker deep convection, and a weaker THC.

[15] In this model, the simulated sea ice coverage is greater than observed, especially in the GIN Seas. Although observations suggest that about 20% of the sea ice exported to the GIN Seas from Arctic exits at Denmark Strait [e.g.,

Aagaard and Carmack, 1989], in our model, about 70% of that sea ice is exported into the Labrador Sea and south of the Denmark Strait region. The underestimation of the $P - E$ increase in the northern North Atlantic may be related to the failure of the PCM in simulating the upward trend of the NAO in the second half of the 20th century. Therefore, the model overestimates the changes in sea ice flux and underestimates the changes in $P - E$ in the northern North Atlantic region. In reality, the overall surface freshwater flux in this region, including both $P - E$ and sea ice flux, may have increased, such as in the ERA-40 reanalysis data. This increased surface freshwater supply would have contributed to a more stable vertical stratification. Observations also show that the Arctic sea ice decreases in both ice covered area and thickness, possibly due to global warming [e.g., *Parkinson et al.*, 1999; *Rothrock et al.*, 1999]. The exported melt water from the Arctic to the GIN Seas and the northern North Atlantic, plus the surface warming, stabilizes the upper ocean by decreasing the upper ocean density, suppressing the deep convection there, and inducing a weaker THC. Therefore, although the relative contribution of each of the freshwater suppliers to the late 20th century freshening in northern North Atlantic may be different in reality and in our model, the decrease of the ocean's ability to transport the freshwater anomaly out of the northern North Atlantic caused by a weaker THC is likely to be a major contributor to the freshening in this region in both observations and our model.

[16] Note that the THC (about 32 Sv) in PCM is stronger than observed estimates (about 14 to 20 Sv [e.g., *Roemmich and Wunsch*, 1985]). Previous model studies show a wide range of the simulated THC, however, such coupled models have been proved to be useful tools in learning about processes related to THC in a coupled climate system (e.g., R. J. Stouffer et al., Investigating the causes of the response of the thermohaline circulation to past and future climate changes, submitted to *Journal of Climate*, 2005.). Thus the relative strength of the mean THC may affect the absolute magnitude of the anomalies, but would not alter the conclusions regarding the relative roles of the physical processes we describe.

[17] **Acknowledgments.** The authors thank Drs. Kevin Trenberth and Aiguo Dai for comments on the comparison of observed and ERA40 precipitation data sets, Dr. Marika Holland and Dr. Ruth Curry for their comments. The authors also thank Dr. Dan Seidov and another anonymous reviewer for reviewing this manuscript. A portion of this study was supported by the Office of Biological and Environmental Research, U.S. Department of Energy, as part of its Climate Change Prediction Program. The National Center for Atmospheric Research is sponsored by the National Science Foundation.

References

Aagaard, 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.

Abdalati, W., and K. Steffen (1997), Snowmelt on the Greenland ice sheet as derived from passive microwave satellite data, *J. Clim.*, *10*, 165–175.

Antonov, J. I., S. Levitus, and T. P. Boyer (2002), Steric sea level variations during 1957–1994: Importance of salinity, *J. Geophys. Res.*, *107*(C12), 8013, doi:10.1029/2001JC000964.

Broccoli, A. J., et al. (2003), Twentieth-century temperature and precipitation trends in ensemble climate simulations including natural and anthropogenic forcing, *J. Geophys. Res.*, *108*(D24), 4798, doi:10.1029/2003JD003812.

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.

Dickson, R. R., et al. (1996), Longterm coordinated changes in the convective activity of the North Atlantic, *Prog. Oceanogr.*, *38*, 241–295.

Dickson, R. R., et al. (2000), The Arctic Ocean response to the North Atlantic Oscillation, *J. Clim.*, *13*, 2671–2696.

Dickson, B., et al. (2002), Rapid freshening of the deep North Atlantic ocean over the past four decades, *Nature*, *416*, 832–837.

Hurrell, J. W. (1995), Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation, *Science*, *269*, 676–679.

Marshall, J., et al. (2001), North Atlantic climate variability: Phenomena, impacts and mechanisms, *Int. J. Climatol.*, *21*, 1863–1898.

Meehl, G. A., et al. (2003), Solar and greenhouse gas forcing and climate response in the twentieth century, *J. Clim.*, *16*, 426–444.

Meehl, G. A., et al. (2004), Combinations of natural and anthropogenic forcings in twentieth-century climate, *J. Clim.*, *17*, 3721–3727.

Mitchell, T. D., T. R. Carter, P. D. Jones, M. Hulme, and M. New (2004), A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: The observed record (1901–2000) and 16 scenarios (2001–2100), *Working Pap. 55*, Tyndall Cent., Norwich, U. K.

Parkinson, C. L., et al. (1999), Arctic sea ice extent, areas, and trends, 1978–1999, *J. Geophys. Res.*, *104*, 20,837–20,856.

Peterson, B. J., et al. (2002), Increasing river discharge to the Arctic Ocean, *Science*, *298*, 2171–2173.

Roemmich, D., and C. Wunsch (1985), Two transatlantic sections: Meridional circulation and heat flux in the subtropical North Atlantic Ocean, *Deep Sea Res., Part A*, *32*, 619–664.

Rothrock, D. A., Y. Yu, and G. A. Maykut (1999), Thinning of the Arctic sea-ice cover, *Geophys. Res. Lett.*, *26*, 3469–3472.

Santer, B. D., et al. (2003), Contributions of anthropogenic and natural forcing to recent to recent tropopause height changes, *Science*, *301*, 479–483.

Seidov, D., and B. J. Haupt (2003), Freshwater teleconnection and ocean thermohaline circulation, *Geophys. Res. Lett.*, *30*(6), 1329, doi:10.1029/2002GL016564.

Stott, P. A., et al. (2000), External control of 20th century temperature by natural and anthropogenic forcings, *Science*, *290*, 2133–2137.

Vinje, T. (2001), Fram Strait ice fluxes and atmospheric circulation, 1950–2000, *J. Clim.*, *14*, 3508–3517.

Washington, W. M., et al. (2000), Parallel climate model (PCM) control and transient simulations, *Clim. Dyn.*, *16*, 755–774.

Wu, P., R. Wood, and P. Stott (2004), Does the recent freshening trend in the North Atlantic indicate a weakening thermohaline circulation?, *Geophys. Res. Lett.*, *31*, L02301, doi:10.1029/2003GL018584.

A. Hu and G. A. Meehl, Climate and Global Dynamics Division, National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307, USA. (ahu@ucar.edu)