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Deep North Atlantic freshening simulated in a coupled climate model

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Abstract

The observed recent freshening trend in the deep North Atlantic and the Labrador Sea is investigated in three forced ensembles and a long control simulations using the HadCM3 coupled ocean–atmosphere–sea-ice climate model. The 40 yr freshening trend during the late half of the 20th century is captured in the all forcings ensemble that applies all major external (natural and anthropogenic) forcing factors. Each ensemble has four members with different initial conditions taking from the control run at a 100 yr interval. No similar freshening trend is found in each of the four corresponding periods of the control simulation. However, there are five large freshening events in a 1640 yr period of the control run, each following a sudden salinity increase. A process analysis revealed that the increase in salinity in the Labrador Sea is closely linked to deep convections while the following freshening trend is accompanied by a period of very weak convective activities.

The fact that none of the five large freshening events appears in the four corresponding periods following the initial conditions of the four members of the all forcings ensemble suggest that external forcings may have contributed to triggering the events. Further analyses of two other ensemble simulations (natural forcings only and anthropogenic forcings only) have shown that natural rather than anthropogenic factors are responsible. Based on our model results, we can not attribute the simulated freshening to anthropogenic climate change.

1. Introduction

It is well accepted that increasing greenhouse gas emissions to the atmosphere will result in global warming. There may have been enough evidence to show that global warming is already there. Along with global warming, most climate models predict that the hydrological cycle would intensify (IPCC, 2001). This does not only mean an increase in water exchange between the atmosphere and the ocean, but also a possible redistribution of water flux spatially (Wu et al., 2005). Meridionally differential freshwater forcing is regarded as one of the primary factors determining the Atlantic meridional overturning circulation, although it is recognised

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that surface salinity contrast between the Atlantic and Pacific may be important for the global conveyor belt or the thermohaline circulation (THC) (Seidov and Haupt, 2003). Increased rainfall to the northern high latitudes in combination with melting Arctic sea-ice and increased river runoff could provide sufficient freshwater perturbation to seriously weaken or even shut down the THC (Broecker et al., 1985; Manabe and Stouffer, 1995; Rahmstorf, 1995). The THC or the global conveyor belt is believed to form an important branch of the present day climate system. A slowdown of the THC could mean a significant cooling of the northern North Atlantic and Europe due to reduced northward ocean heat transport (e.g. Vellinga and Wood, 2002). The theoretical possibility of multiple equilibria for the Atlantic THC and its possible link with rapid climate change backed by paleo records lead to the fear of catastrophic shift in today's climate (Alley et al., 2003; Weaver and Hillaire-Marcel, 2004). Therefore, detection and monitoring climate change of the Arctic have become a very important and active area of research in recent years (e.g. Rothrock et al., 1999; Hilmer and Lemke, 2000; Hansen et al., 2001; Peterson et al., 2002; Dickson et al., 2002; Curry et al., 2003; Curry and Mauritzen, 2005).

Arctic sea-ice is found to be thinning (Rothrock et al., 1999) and decreasing (Hilmer and Lemke, 2000). River discharges into the Arctic Ocean from the six largest Eurasia rivers are found to be increasing (Peterson et al., 2002). Hansen et al. (2001) have reported decreasing overflows from the Nordic seas into the North Atlantic through the Faroe Bank Channel since the 1950s, which could suggest the THC is already weakening. Recent analysis of historical observations by Dickson et al. (2002) has shown a sustained freshening trend of the deep sub-polar North Atlantic Ocean over the last three to four decades. This freshening is clearly seen from the salinity evolution of the North East Atlantic Deep Water (NEADW) in the Labrador Sea. Since the NEADW is closely related to the dense overflows from the Denmark Strait and the Faroe Bank Channel, the freshening trend can also be traced upstream until the Faroe Bank Channel. Further analysis by Curry et al. (2003) and Curry and Mauritzen (2005) has shown a systematic cooling and freshening of the Atlantic at both polar sides while the tropics and subtropics are warming and salinifying. Combining the Atlantic events with the freshening of intermediate waters in the Pacific and Indian Oceans (Wong et al., 1999; Banks et al., 2000), it is believed that the global hydrological cycle is already speeding up, adding more freshwater to the polar oceans (Boyer et al., 2005).

Although these observed events seem to be largely consistent with climate model projections of global warming, attribution of a individual event is difficult due to limited spatial and temporal coverage of observational data and the complexity of inter connections, such as the attribution of observed mode water changes in the Indian Ocean (Bryden et al., 2003). Comprehensive coupled climate models can be helpful in the interpretation of those limited observations. For example, the recent upward trend in global mean near surface temperature can be well reproduced with only anthropogenic forcings, while the earlier warming trend between 1910 and 1939 can only be reproduced when natural factors are also included (Stott et al., 2000; Meehl et al., 2004). The two warming trends can then be attributed to different causes. The observed trends in Arctic sea-ice are believed to be associated with anthropogenic influence and the decline is predicted to continue (Gregory et al., 2002). The increase in Arctic river runoff is also confirmed in coupled model simulations (Wu et al., 2005). The upward trend is found to be anthropogenically forced and to continue in the 21st century. However, inferring the THC from recently observed freshening trend of the sub-polar North Atlantic was not as many people would have expected (Wu et al., 2004). In a HadCM3 all forcings ensemble simulation, a similar freshening trend of the NEADW was found for the same period with similar magnitude in the Labrador Sea, but the THC was strengthening rather than weakening.

In this paper, the deep North Atlantic freshening trend is further investigated in three different types of forced ensemble simulations in comparison with the long HadCM3 control integration. The main objective is to investigate whether the simulated freshening trend reported in Wu et al. (2004) is linked to anthropogenic global warming. If not, what are the likely causes in the model simulations? Through this, we hope to shed some light on the observed freshening in the recent decades. Section 2 gives a brief description of the model and experiments. Section 3 presents simulated freshening in comparison with observations. Section 4 compares the simulated freshening with internal variability of the coupled climate system. Section 5 presents results from two separate ensemble simulations, one with only natural forcings and the other with only anthropogenic forcings. Conclusions and discussions are presented at the end.

2. Model and experiments

HadCM3 is the third generation of the Hadley Centre's coupled atmosphere–ocean–sea-ice general circulation model (Gordon et al., 2000). The atmospheric model has a horizontal grid spacing of $3.75° \times 2.5°$ and 19 vertical levels with detailed parameterisations of physical processes. A full description of the atmospheric model can be found in Pope et al. (2000). The ocean component has 20 levels with a horizontal grid spacing of $1.25° \times 1.25°$. There are six ocean grid boxes to every atmospheric grid box and the land–sea masks match exactly between the atmosphere and the ocean. Vertical levels are distributed to enhance resolution near the ocean surface. The model runs without flux correction. The control simulation using pre-industrial atmospheric trace gas concentrations has run over 2000 yr without appreciable drift in the model's climate after the first 400 yr. In this study, we take 1640 yr of model data excluding the first 400 yr. The model produces quite realistic simulations of mean sea surface temperatures, sea-ice extents and ocean heat transports (Gordon et al., 2000). The simulated hydrological cycle takes about 400 model years to come into near balance between surface freshwater flux and meridional ocean transports (Pardaens et al., 2003). The surface layer of the ocean is generally fresher while the deep ocean is more saline compared with observations. A full analysis of freshwater budgets in the HadCM3 control simulation is reported by Pardaens et al. (2003). Interested readers are referred to it for more details. The model also produces realistic Gulf stream variability, air–sea interaction and the North Atlantic oscillation (NAO) as well as decadal and multi-decadal climate variability (see e.g. Cooper and Gordon, 2002; Wu and Gordon, 2002; Wu and Rodwell, 2004; Vellinga and Wu, 2004).

Three ensemble simulations using the same model with different external forcings are analysed to investigate water mass changes in the sub-polar North Atlantic Ocean. Historical forcings from 1859 to 2001 are applied. The external forcings include natural (solar irradiance and volcanic aerosol changes) and anthropogenic (greenhouse gases, sulphate aerosol and ozone changes) factors. The all forcings ensemble includes both natural and anthropogenic factors while the anthropogenic and natural ensembles use only the separate forcings. Each ensemble contains four members run with the same external forcing but different initial conditions taking from the control simulation at a 100 yr interval. The all forcings ensemble is used as a simulation of the 20th century climate, while the anthropogenic and natural ensembles are used for attribution purposes. In analysing the forced experiments, the linear trend for the corresponding period in the control simulation is removed from each individual members before ensemble mean is produced.

3. Simulated freshening in the deep North Atlantic

The all forcings ensemble provides a simulation of the 20th century climate. The simulation of global mean surface temperature variations proves very successful in capturing long term trends as well as decadal to multidecadal variability (Stott et al., 2000). Simulated Arctic sea ice and river flow changes also compare favourably with observations (Gregory et al., 2002; Wu et al., 2004, 2005). Stott et al. (2000) have attributed most of the multi-decadal variability of surface temperature to being externally forced due to variations in both natural and anthropogenic factors. The question that naturally follows would be: can the forced variability be traced down to the deep ocean away from the surface? The observed freshening trends in the deep northern North Atlantic reported by Dickson et al. (2002) and Curry et al. (2003) have certainly suggested such a possibility. Fig. 1 shows the ensemble mean simulation of salinity changes in the Labrador Sea for the period 1949–1999 in comparison with observations. The model grids cover a $5° \times 5°$ area: (50–55°W, 55–60°N). The linear trend in the control run for the corresponding period is subtracted at each grid-point for each member before the ensemble mean and area-average are carried out. Comparing Fig. 1a (Dickson et al., 2002) with Fig. 1b, we find both the timing and amplitude of the freshening are similar between the simulated and the observed, although the absolute values of the modelled salinity are higher than observations. Extending model data 20 yr back to 1929 (see Wu et al., 2004) confirms that the freshening trend starts from the 1960s, although there are some decadal variability of the maximum salinity for the core NEADW. The freshening trend is consistent in all four members, each showing a decreasing trend for the same period. No plots of NEADW evolution for individual members are shown in this paper. Interested readers can refer to Fig. 3a in Wu et al. (2004).

Following Dickson et al. (2002), a sequential plot is presented in Fig. 2 to trace the freshening trend upstream. From top to bottom, there seems to be a freshening event propagating downstream from the Nordic

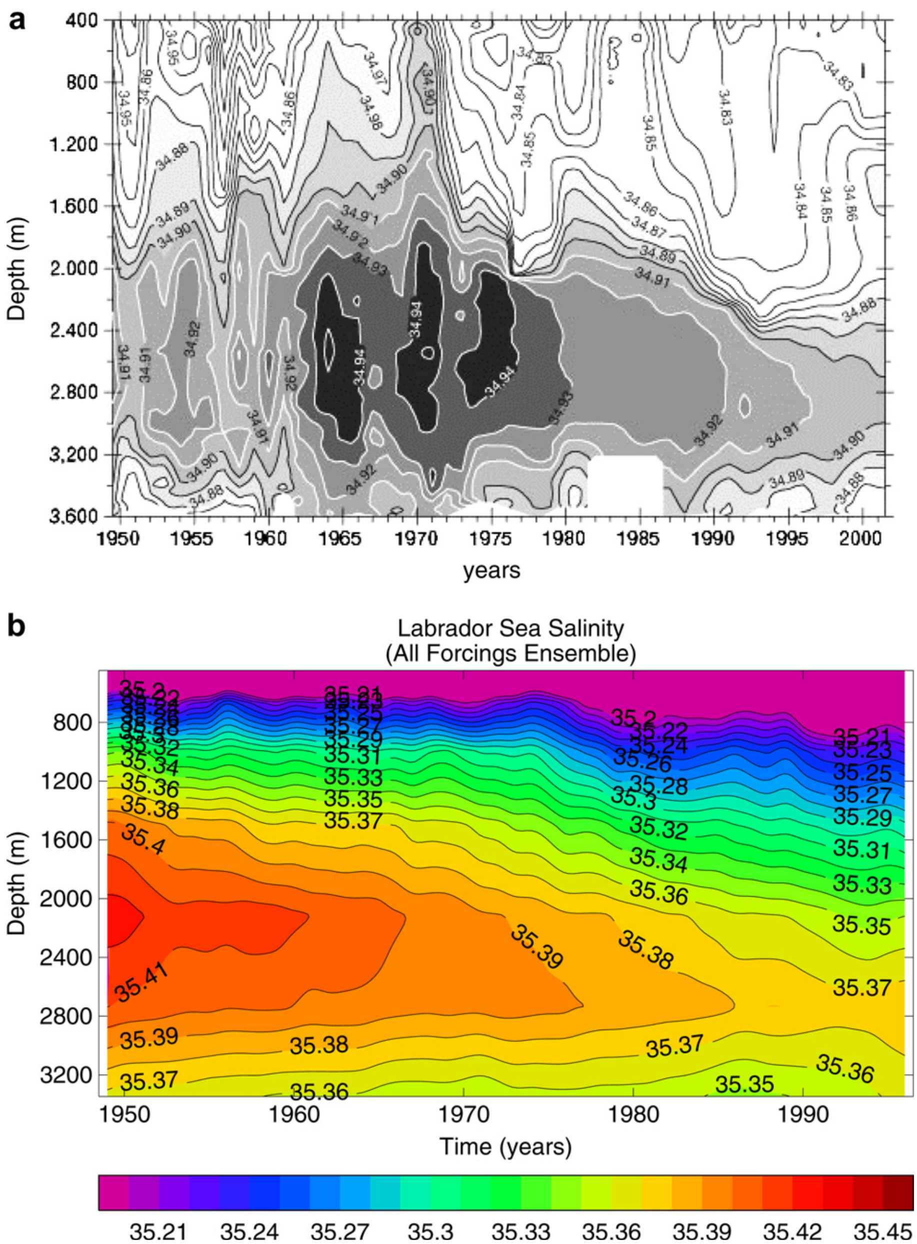

Fig. 1. (a) Evolution of observed Labrador Sea salinity from Dickson et al. (2002) in comparison with (b) the HadCM3 all forcings ensemble simulation for the same period showing the freshening trend of the NEADW from the 1960s.

Seas. However, we fail to find a connection in the Irminger Sea, where there is no obvious trend to link the freshening in the Labrador Sea to the upstream event. But the reverse of the freshening trend from the 1990s is clearly seen in all locations. Comparing our Fig. 2 with the Fig.2 from Dickson et al. (2002), we still find some common features. Both the model and observations show that the freshening starting from the 1970s following a sudden salinity increase. The freshening trend starts to reverse from the 1990s although the decreasing trend in Arctic sea-ice continues, which may suggest different causes for the downward trends. It has also been noted in Curry and Mauritzen (2005) that the decreasing trend in dense overflows through the Faroe Bank Channel reported in Hansen et al. (2001) has reversed in the last 2–3 yr.

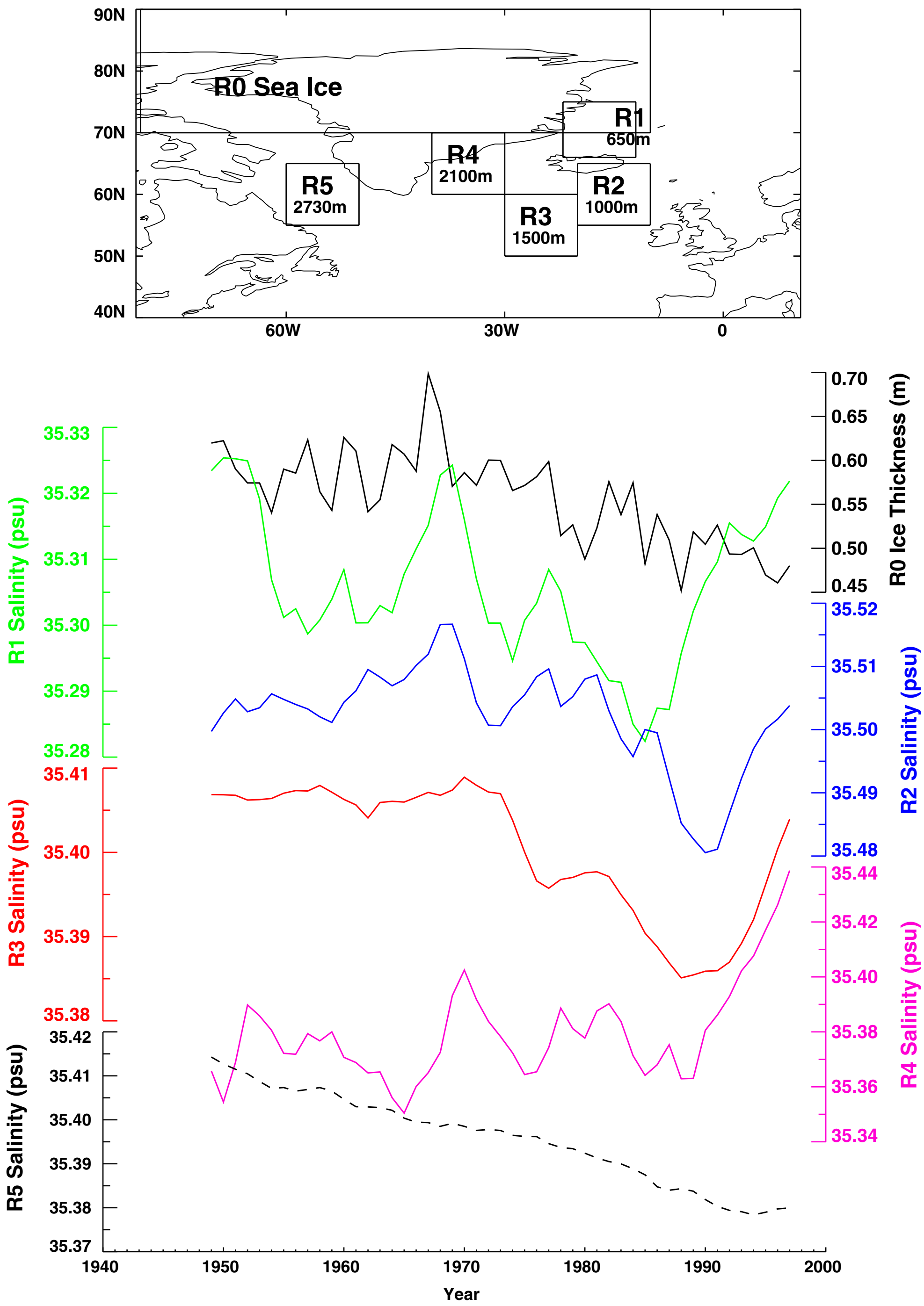

Fig. 2. Salinity evolution along the NEADW path upstream of the Labrador Sea. The map indicates the region and depth for each corresponding curve shown in the plot. Each curve represents the area-averaged ensemble mean salinity for the given region and depth. Horizontal axis indicates years.

4. Forced or internal variability?

The reason for the extensive interest from the scientific community in the observed freshening is the possible implication of an already occurring intensified global hydrological cycle. However, it is not certain that is the case. It is well known that the climate system in the North Atlantic sector exhibits significant decadal and multi-decadal variability. Strong low-frequency variability is found in the long HadCM3 control integration involving ocean circulation and water mass changes (Cooper and Gordon, 2002; Wu and Gordon, 2002; Vellinga and Wu, 2004). The modelled and observed freshening trends are not identical, the timing and the amplitudes are similar. An understanding of the modelled event could shed some light on the observed. A trend in a smaller time-window may only be part of low-frequency variability in a bigger time domain. Is such a freshening trend significantly different from internal variability of the climate system?

HadCM3 control integration (1640 yr) is used to test the statistical significance of the observed freshening trend. Depth averaged salinity for the same area as used for Fig. 1 is produced from the 1640 yr control run.

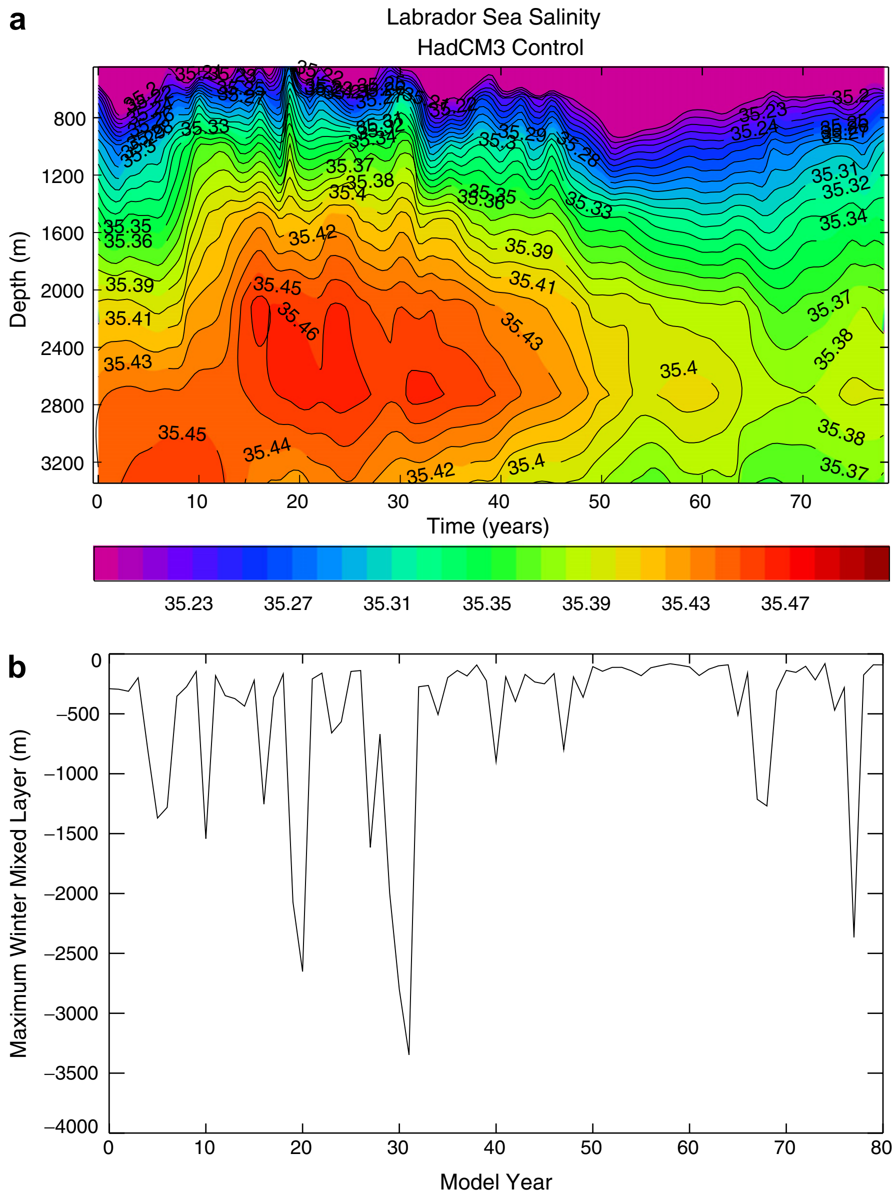

Fig. 3. Annual mean salinity evolution in the Labrador Sea (a) and the corresponding maximum winter mixed-layer depth (b) from a 80 yr period of the long HadCM3 control integration. It shows one of five episodes in 1640 yr of the control, which has a freshening trend similar to observations (see Fig. 1a).

Apart from a long term trend, there are 5–6 large amplitude freshening events during the period, each following a big salinity increase. The freshening trends are similar to the observed and the modelled freshening event for the late 20th century. Fig. 3a shows a typical episode taken from the control run. Following the large salinity increase around model years 10–20, the freshening trend starts in year 30 and lasts for almost 50 yr. Fig. 3b shows the corresponding maximum winter mixed-layer depth in the area. The increase in salinity is closely linked to extended deep convection and the freshening occurs in a quiet period of weak convection. A sequential plot following the same path as in Fig. 2 is presented in Fig. 4. Freshening is seen at all locations (even more clearly than in Fig. 2), but the decreasing trend in Arctic sea-ice is not evident here. There is a possibility that the deep North Atlantic freshening may not necessarily be connected to the recent Arctic sea-ice changes that is likely to be anthropogenically forced by global warming (Gregory et al., 2002). The detailed mechanism of the freshening process requires more work, although the link between mixed-layer depth and the freshening

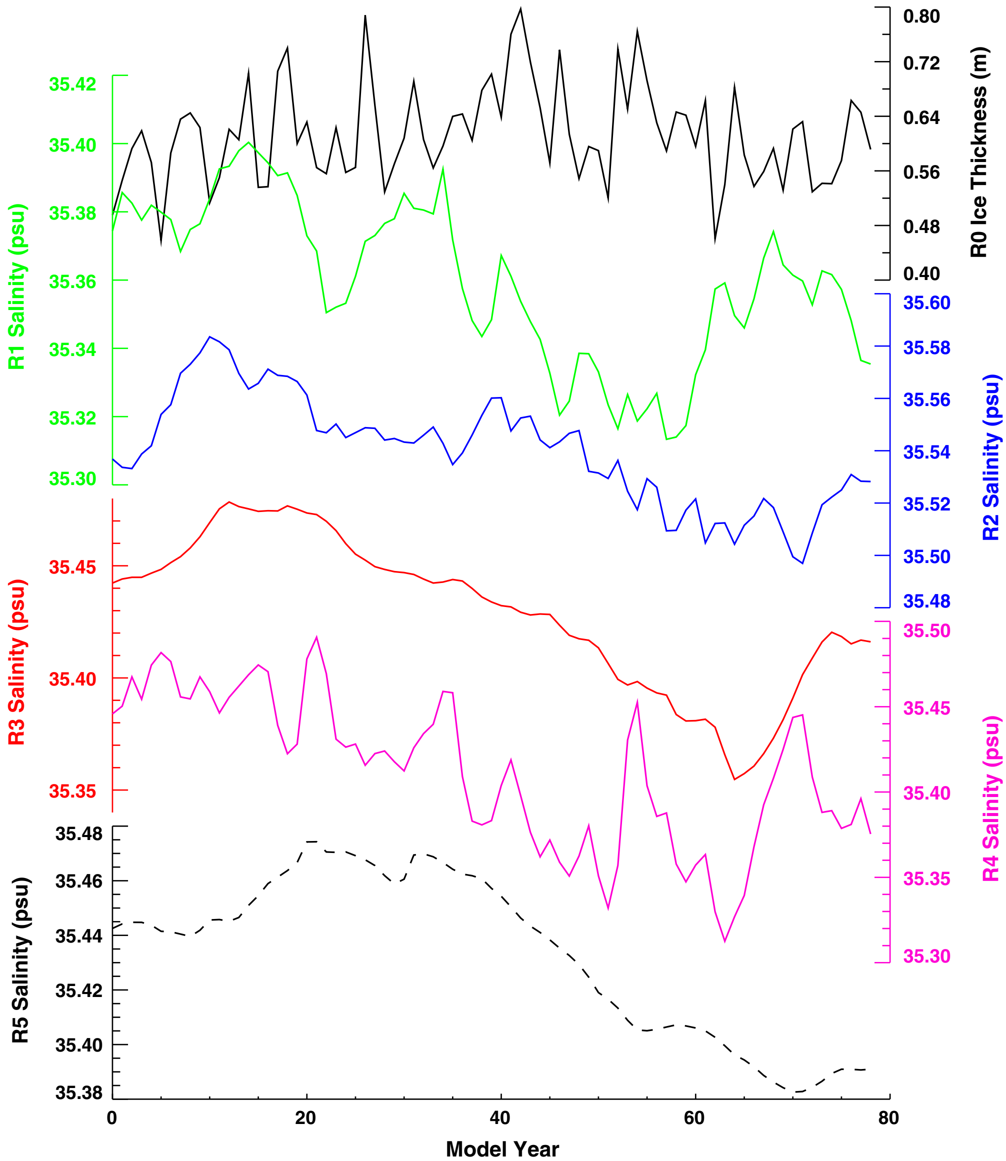

Fig. 4. Salinity evolution along the NEADW path upstream of the Labrador Sea. Each curve represents the area-averaged ensemble mean salinity for the given region and depth.

is suggestive of a possible connection. It is known from Cooper and Gordon (2002) that deep convection in the Labrador Sea can strongly influence the upper ocean circulation of the sub-polar North Atlantic.

To quantify the significance of the freshening events, a statistical algorithm is designed for a test. After removing a quadratic trend from the long timeseries, 40 yr linear trends are calculated from the control data for the statistical test. As where to start the 40 yr window is arbitrary, the 1640 yr timeseries is randomly sampled 10,000 times to generate a probability density function (pdf). The pdf is shown in Fig. 5, where the observed freshening is marked with the significance level. There is a 7% chance for a 40 yr freshening event exceeding 0.05 psu. The significance level increases to 10% if we lower the threshold to 0.04 psu. So there is 7–10% chance for the observed freshening trend to be internal variability of the climate system as the observations show a 0.04–0.05 psu salinity reduction. This corresponds to 5 out of 41, if the 1640 yr timeseries is sequentially cut into 41 independent 40 yr periods. There is also a 10% chance for each of the four members of the all forcings ensemble simulation to show such a freshening trend without the influence of the forcing. However, with external forcing, each of the four members shows a freshening (see Fig.3a in Wu et al., 2004).

The NAO is the dominant mode of climate variability in the North Atlantic sector. It controls air–sea fluxes and coordinates deep ocean convection in the Norwegian and the Labrador Seas (Dickson et al., 1996). A change in the NAO can certainly affect water mass properties in the sub-polar North Atlantic. But the NAO can also be regarded as part of the internal climate variability, although it is not clear what is responsible for the recent upward trend in the NAO (Hurrell, 1995; Wu and Gordon, 2002; Wu and Rodwell, 2004). Moreover, we cannot attribute the freshening trend to the upward trend of the NAO, as the all forcings ensemble does not show an upward trend in the NAO itself.

5. Natural or anthropogenic forcing?

Comparison of observations and the HadCM3 all forcings ensemble with the long control integration points to a possibility that the freshening trend during the last four decades is externally forced with a statistical 90% significance level. However, there is a 10% chance for the freshening trend simulated in the all forcings ensemble (possibly the observed as well) to be internal variability of the coupled climate system. In the four periods of the control simulation corresponding to the different initial conditions of the four ensemble members, no similar freshening trend is found in any of these. This suggests that the freshening event may be triggered by external forcings. In this section, the freshening event is investigated in two separate ensemble simulations: the natural ensemble and the anthropogenic ensemble. This is to determine which external factors are more likely to be responsible for the freshening trend. Fig. 6 shows the ensemble mean salinity evolution in the Labrador Sea. The figure was produced in the same way as Fig. 1b. The freshening trend is only reproduced in the ensemble simulation with natural forcings (see Fig. 6a). In the anthropogenic forcings ensemble

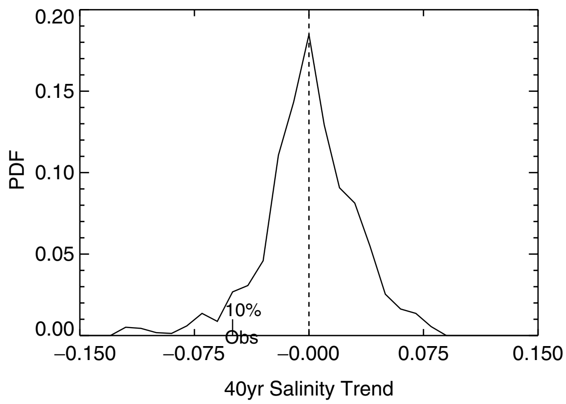

Fig. 5. The pdf distribution of 40 yr salinity trends calculated from 1640 yr of HadCM3 control simulation. The pdf is produced from 10,000 samples of 40 yr-time-window randomly taken from the control series. The observed freshening trend is marked to indicate the statistical significance. There is less than 10% chance for internal variability to reach the observed freshening level.

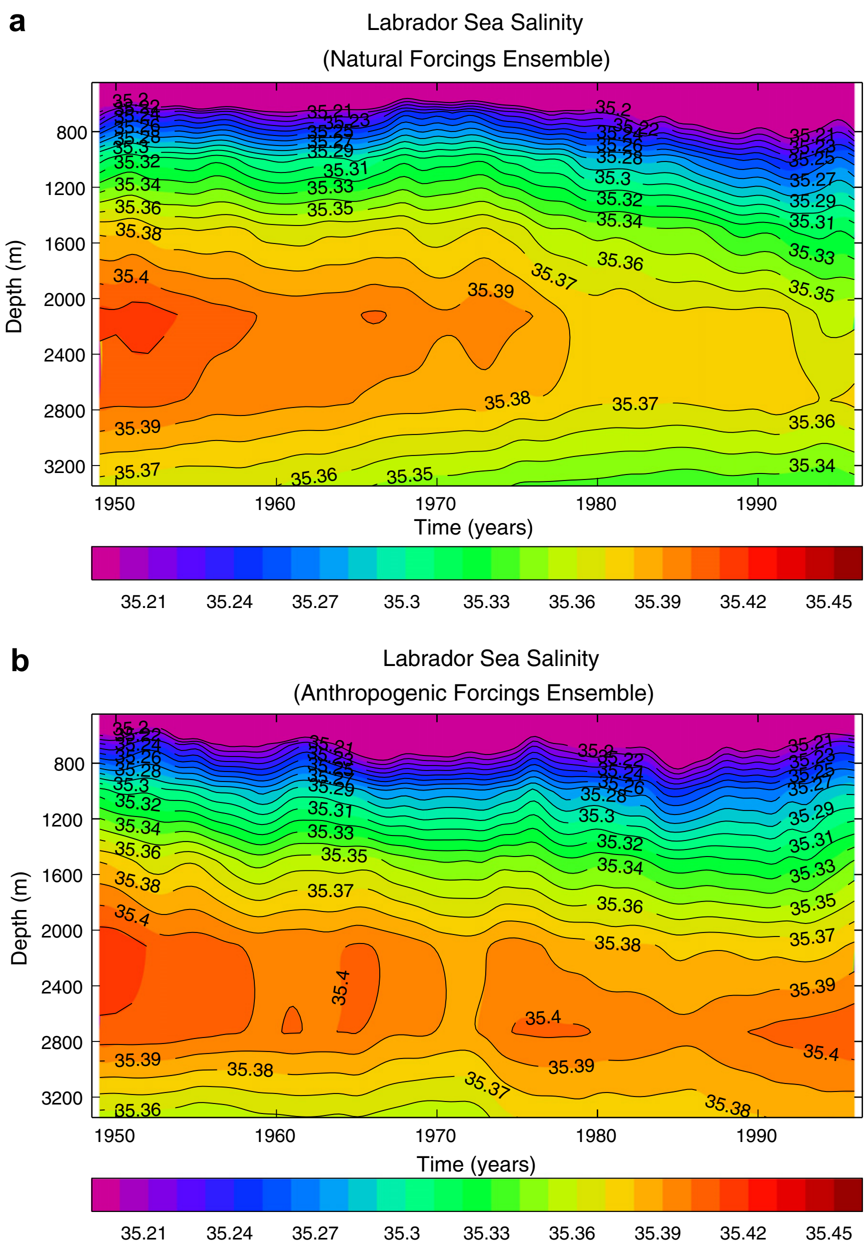

Fig. 6. Evolution of Labrador Sea salinity in the HadCM3 natural forcings ensemble simulation (a) in comparison with the same from the anthropogenic forcings ensemble (b).

(Fig. 6b), there is hardly any noticeable trend for the core NEADW. T–S diagrams (see Fig. 9) which shows all individual points rather than area-averages also reveal the difference between the two ensembles. Comparing sequential plots in the form of Fig. 2, the difference is found to be basin wide. Freshening trends are seen in all locations in the natural forcings ensemble, but not in the anthropogenic runs.

How natural forcings affect water mass properties is not clear to us at the present stage. It certainly requires more work into the detailed mechanisms. Ottera and Drange (2004) have recently shown that both the Arctic sea-ice and the Atlantic THC are sensitive to changes in solar irradiance forcing. Low solar irradiance can lead to the expansion of the Arctic sea-ice and positive salinity anomalies and hence stronger THC. High solar irradiance forcing has the opposite effect leading to negative salinity anomalies and weaker THC. Volcanic eruptions can certainly affect surface heat fluxes. The global average surface heat flux into the ocean in the natural forcings ensemble simulation is strongly correlated with the average radiative heat fluxes at the tropopause (correlation coefficient over 0.8, see Fig. 7). Each of the large volcanic eruptions causes a 1–2 W m^{-2} reduction

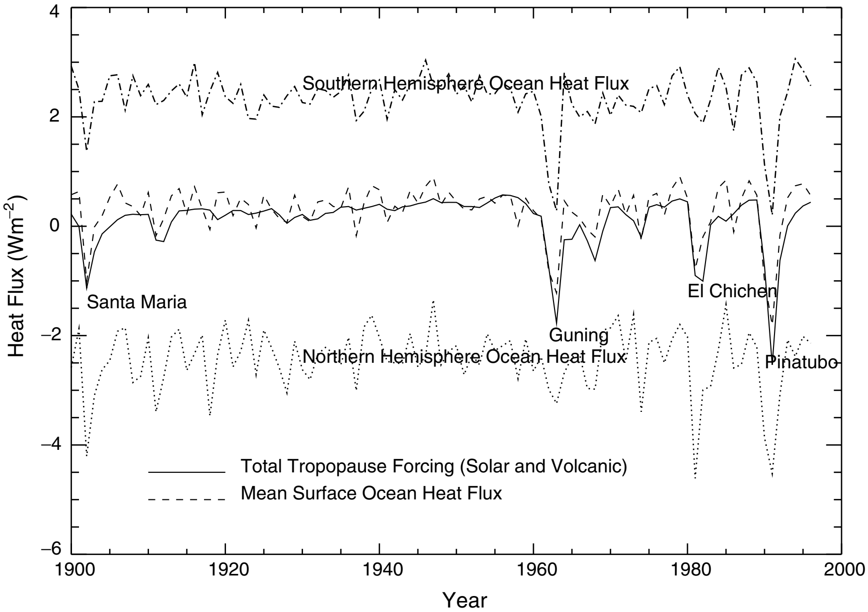

Fig. 7. Total radiative forcing at the tropopause for the 20th century (thick solid line) and the corresponding average ocean surface heat flux (dashed) showing the cooling of global oceans by volcanic eruptions. Some events impact more on the northern oceans while others have more influence on the southern oceans.

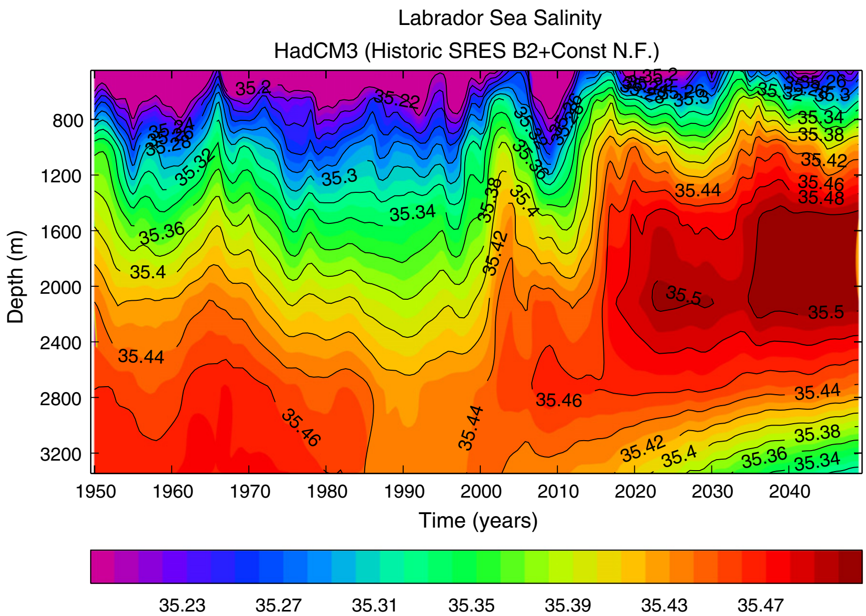

Fig. 8. Evolution of Labrador Sea salinity in a HadCM3 simulation. The model is forced with all historic major external (natural and anthropogenic) factors until 1997 when natural forcings are fixed while anthropogenic forcings follow the IPCC SRES B2 scenario. The early part of the run forms a member of the all forcings ensemble and the later part is a model prediction.

of downward heat flux at the tropopause, leading to a similar amount of reduction in ocean surface heat flux on an annual mean timescale. Namely, each of the four major volcanic eruptions during the 20th century could have caused the world oceans to cool by 1–2 W m^{-2}. Some of the events have more impact on the northern ocean while the others mainly affect the southern oceans. In a particular season and a specific area, the

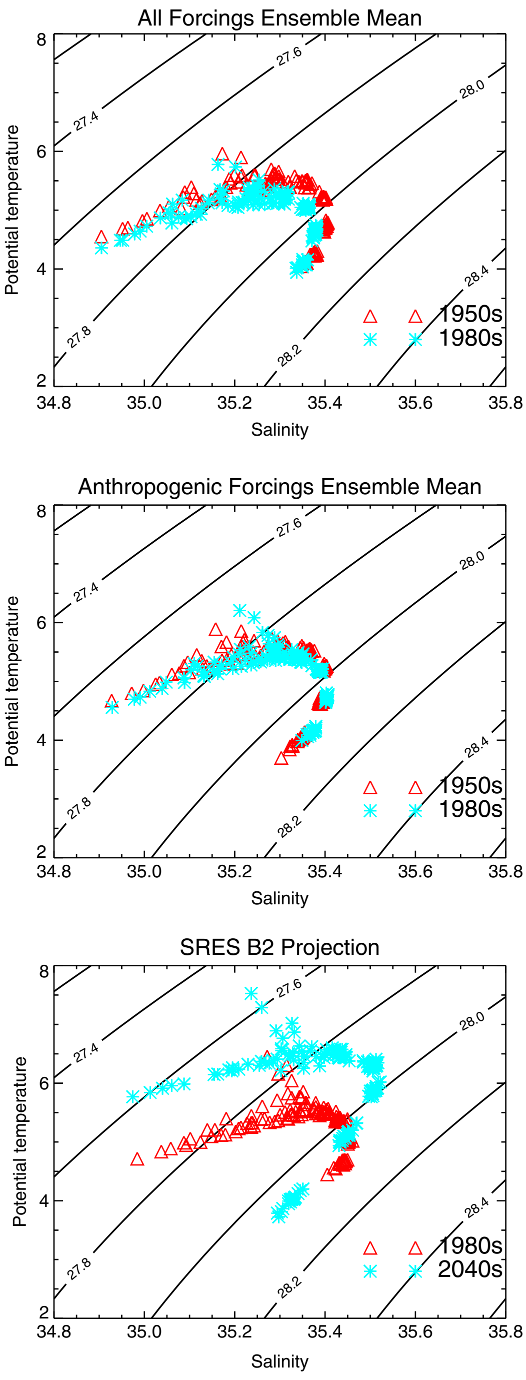

Fig. 9. Decadal mean T–S diagrams for the Labrador Sea below 400 m in three different simulations. The cooling and freshening can be clearly seen in the all forcings ensemble (top) but not in the anthropogenic forcings ensemble (middle). However, the model predicts warming and salinifying of the Labrador Sea during the first half of the 21st century.

cooling rate may be larger than the average. This extra cooling could provide a triggering mechanism for deep convection that affects water mass properties.

6. A possible future trend

It is important to understand what has happened in the past, but the future status may be very different for the Labrador Sea. Wood et al. (1999) have reported that under increasing greenhouse emissions to the atmosphere Labrador Sea convection may completely stop and Denmark Strait overflow diverts to the east. This would imply large changes in water mass structures for the northern North Atlantic and the Labrador Sea. The first member of the all forcings ensemble is extended into the 21st century. After 1997, natural forcings are fixed while anthropogenic forcings follow the IPCC SRES B2 scenario. Fig. 8 shows the salinity evolution in the Labrador Sea between 1950 and 2050. The freshening trend during the late 20th century can be seen although the salinity maximum lies deeper than the ensemble mean (Fig. 1) due to different initial conditions. A sharp change occurs at the beginning of the 21st century. Unventilated warm/salty Atlantic water is piling up in the middle layer of the Labrador Sea because of weakened convection. This warm/salty water takes over the whole layer previously occupied by the Labrador Sea water (LSW) and the NEADW causing a reverse of the freshening trend with massive temperature and salinity increase. In the bottom, one can clearly see the freshening of the Denmark Strait overflow water (DSOW) into the 21st century. This freshening trend persists through the 21st century. Such water mass property changes, including the warming/salinifying above 2.5 km and the cooling/freshening below can also be seen in other HadCM3 simulations using different SRES scenarios. This picture is inconsistent with the observed and simulated freshening trend for the late 20th century.

From the climate monitoring point of view, sub-surface ocean temperature/salinity in the central Labrador Sea could provide a useful cursor for climate change. The termination of the freshening trend and the warming and salinifying predicted by the HadCM3 model may be happening already now as shown by most up-to-date observations in the Labrador Sea (Yashayaev, personal communication). The simulated and predicted changes can all be summarised in Fig. 9, which shows the difference in decadal mean T–S diagrams for the water column in the Labrador Sea below 400 m. The T–S diagrams include all the individual data points in stead of area-averaged ones used for Figs. 1,3,6 and 8. The cooling and freshening between the 1950s and the 1980s are well simulated in the all forcings ensemble (see Fig. 9, top) but not in the anthropogenic forcings ensemble (middle). However, between the 1980s and the 2040s, the model predicts an increase in both temperature and salinity in the middle and upper Labrador Sea while the opposite at the bottom for the DSOW.

7. Conclusions and discussion

Three forced ensemble simulations and a long control run using the HadCM3 model are analysed to investigate the cause of deep North Atlantic freshening. The observed 40 yr freshening trend during the late 20th century reported by Dickson et al. (2002) has been captured in the all forcings ensemble that applies all major external (natural and anthropogenic) factors. Each ensemble has four members with different initial conditions taking from the control run at a 100 yr interval. No similar freshening trend is found in each of the four corresponding periods of the control simulation. However, there are five large freshening events in a 1640 yr period of the control run, each following a sudden salinity increase. A process analysis has revealed that the salinity increase in the Labrador Sea is closely linked to a couple of deep convection events while the following freshening trend is accompanied by a period of very weak convective activities. Although statistically there is only a 10% chance, the climate system can have a freshening trend with similar amplitude and period as in recent observations without involving external forcings.

The fact that none of the five large freshening events appears in the four corresponding periods following the initial conditions of the four members of the all forcings ensemble suggests that external forcings may have contributed to triggering the events. Further analyses of two other ensemble simulations (natural forcings only and anthropogenic forcings only) have shown that natural rather than anthropogenic factors are responsible. There are no obvious freshening trends in the anthropogenic forcings ensemble in the same period, while the timing and amplitude of freshening in the natural forcings ensemble look very similar to the all forcings simulation. Surface ocean heat fluxes are strongly correlated with the mean radiative forcings at the tropopause associated with solar and volcanic activities. If a possible connection exist between natural forcings and deep North Atlantic freshening, the mechanism through what such connection is established remains to be understood.

It is, however, clear that we cannot attribute such freshening trends to anthropogenic climate change based on our model simulations. The recent freshening trends seen in the deep North Atlantic and the Labrador Sea may be different from the change in Arctic sea-ice and freshening of the high latitudes. The latter may have more to do with anthropogenically forced climate change (Gregory et al., 2002; Wu et al., 2005). The expected weakening of the THC accompanying the freshening is not found in the same set of ensemble simulation (Wu et al., 2004). The freshening trend of the NEADW seen in the Labrador Sea from the 1970s may have already ended. A reversed trend predicted by the HadCM3 model may have just started to appear (Yashayaev, personal communication, 2006). Nonetheless, we do expect a cooling and freshening trend of the Denmark Strait overflows during the 21st century under projected climate change. Its effect is expected to appear in the bottom of the Labrador Sea. The hydrological cycle is predicted to intensify (IPCC, 2001) as greenhouse gas concentration in the atmosphere increases and the polar regions are expected to receive more freshwater from both increasing rainfall and increasing river discharges (Wu et al., 2005). The effect of this on the deep North Atlantic Ocean may have yet to come. How the combined freshwater forcing from the intensified hydrological cycle and melting Arctic sea-ice may affect the Atlantic THC and the northern hemisphere climate requires close monitoring and further research.

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