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 ensemble and a long control simulations using the HadCM3 coupled ocean-atmosphere-sea ice climate model. The 40yr freshening trend during the late half of the 20th century is well 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 100yr 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 1640yr period of the control run, each following a sudden salinity increase. A process analysis has revealed that the salty events in the Labrador Sea are 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 may suggest that external forcings may be needed to trigger 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. Surface ocean heat fluxes over the Labrador Sea and northeastern North Atlantic near the Faroe Bank Channel are positively correlated with the mean radiative forcings at the tropopause associated with solar and volcanic activities.

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. 2004a). 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 global thermohaline circulation (THC) (Broecker et al. 1985, Manabe and Stouffer, 1995 and 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 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 and Curry et al. 2003).

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 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-Shetland channel, the freshening trend can also be traced upstream until the Faroe Bank Channel. Further analysis by Curry et al. (2003) 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.

Although these observed events seem to be largely consistent with climate model projections of global warming, attribution of individual event is difficult due to limited spatial and temporal coverage of observational data, such as the attribution of observed mode water changes in the Indian Ocean (Bryden et al. 2003). Comprehensive coupled climate models can be very helpful in the interpretation of those limited observations. For example, the recent upward trend in global mean near surface temperature can be well reproduced in HadCM3 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. 2004a). 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. 2004b). In a HadCM3 all forcings ensemble simulation, similar freshening trend was found for the same period with similar magnitude, 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. Section 2 gives a brief description of the model and experiments. Section 3 presents simulated freshening in comparison with observations. Section 4 tries to build a statistical significance level of the recent freshening event in comparison 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°x2.5° 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°x1.25°. There are six ocean grid boxes to every atmospheric grid box and the land-sea masks match exactly. 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 3000 years without appreciable drift in the model's climate after the first 400 years. In this study, we take 1640 years of model data excluding the first 400 years.

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 separated forcings. Each ensemble contains four members run with the same external forcing but different initial conditions taking from the control simulation at a 100yr interval. The all forcings ensemble is used as a hindcast of the 20th century climate, while the anthropogenic and natural ensembles are used for attribution purposes. In analyzing the forced experiments, the linear trend for the corresponding period in the control simulation is removed from each individual members first before ensemble mean is produced.

3 Simulated freshening in the deep North Atlantic

The all forcings ensemble provides a hindcast of the 20th century climate. The simulation of global mean surface temperature variations proves very successful in capturing long term trends as well as decaldal to multidecadal variability (Stott et al. 2000). Simulated Arctic sea ice and river flow changes also compares favorably with observations (Gregory et al. 2002, Wu et al. 2004a, b). Stott et al. (2000) have attributed most of the multidecadal variability of surface temperatures to being externally forced due to variations in both natural and anthropogenic factors. The question naturally follows would be that have those forced variability left their fingerprints in the deep climate system 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. Figure 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°x5° 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 mottled salinity are higher than observations. Expanding model data 20 years back to 1929 (see Wu et al. 2004a) confirms the freshening trend starts from 1960, although there are some decadal variability of the maximum salinity for the core NEADW. The freshening trend is consistent in all four members.

Following Dickson et al. (2002), a sequential plot is presented in Fig.2 to trace the freshening trend upstream. Each curve in Fig.2b represents the area-averaged salinity for the given depth in an area indicated in Fig.2a. From top to bottom, there seems to be a freshening event propagating downstream from the Nordic 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 feathers. 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.

4 Forced or internal variability?

The reason for the extensive interest from both the scientific community and the media 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 multidecadal 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). It is very difficult for the attribution of the observed freshening due to insufficient data. It is possible for our model simulations. Although the modeled and observed freshening trends are not identical, the timing and the amplitudes are very similar. An understanding of the modeled event could shed some light for 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?

1640 years of the HadCM3 control integration 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 1640yr control run. Apart from a long term trend, there are 5-6 large amplitude freshening events during the period each following a big salinity increase. Following one particular event, the freshening trend is not very dissimilar to the observed or the modeled freshening event for the late 20th century. Figure 3a shows a typical episode of such events taken from the control run. Following the large salinity increase around model years 40 to 50, the freshening trend from year 60 onwards is very similar to what is observed in both amplitude and length of the period. Figure 3b shows the corresponding maximum winter mixed layer depth. The salty events seem to be closely linked with deep convection and the freshening is accompanied by a quiet period of very weak convective process. A sequential plot following the same path as Fig.2 is presented in Fig.4. Freshening is seen at all locations (even clearer than 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 connected to the recent Arctic sea ice changes that is likely to be anthropogenically forced by global warming.

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, 40yr trends are calculated from the control data for the statistical test. As where to start the 40yr window is arbitrary, the 1640yr timeseries is randomly sampled 10,000 times to generate a probability density function (pdf). The pdf is shown in Fig.3, where the observed freshening is marked with the significance level. There is 7% chance for a 40yr freshening event exceeding 0.05psu. The significance level reduces to 10% if we raise the threshold to 0.04psu. So there is 7-10% chance for the observed freshening trend to be internal variability of the climate system.

The North Atlantic oscillation (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. 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 system, although it is not clear what is responsible for the recent upward trend in the NAO (Hurrel 1995, Wu and Gordon 2002, Wu and Rodwell 2004). Moreover, we can not attribute the freshening trend to the upward trend of the NAO, as the model fails to simulate the NAO trend itself.

5 Natural or anthropogenic forcing?

Comparison of observations and the HadCM3 all forcings ensemble with the long control integration points to a strong 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 each of them. This could suggest 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. Figure 4 shows the ensemble mean salinity evolution in the Labrador Sea. The figure was produced in the same way as Fig.1b. Surprisingly, the freshening trend is well reproduced in the ensemble simulation with only natural forcings (see Fig.4a). In the anthropogenic forcings ensemble (Fig.4b), 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 clearly 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 for the natural forcings ensemble, but not for the anthropogenic runs.

Ottera and Drange (2004) have recently shown that both the Arctic sea ice and the Atlantic THC are sensitive to 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 irrediance forcing has the opposite effect leading to negative salinity anomalies and weaker THC. The THC response may also depend where freshwater input actually takes place. Cheng and Rhines (2004) have found that the Atlantic

THC is more sensitive to freshwater influx to the Labrador Sea than the Nordic Seas. They have also found that salinity in much of the Nordic Seas actually increases when the Arctic freshwater source is the strongest there, as a result of enhanced global overturning. This explains what we have found in the all forcings simulation (Wu et al. 2004b). Volcanic eruptions can certainly affect surface heat fluxes. Figure 5 shows the correlation between the mean annual radiative forcing at the tropopause and the ensemble mean surface heat flux (Qs) for the natural forcings simulation. The sub-polar North Atlantic is one of two areas globally that shows high correlation. The other area is in the Southern Ocean upstream of the Drake passage. In Fig.5, the Labrador Sea and northeastern Atlantic near the Faroe Bank Channel are highly sensitive regions to natural radiative forcings, where the correlation coefficients are over 0.4.

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 could 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. Figure 8 shows salinity evolution in the Labrador Sea between 1950 and 2050. The freshening trend during the late half 20th century can be seen although the salinity maximum lays differently to the ensemble mean (see Fig.1) due to different initial conditions. Sharp change occurs from the beginning of the 21st century. Unventilated warm/salty Atlantic water is piling up in the middle layer of the Labrador Sea because of weakening surface 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. The warming/salinifying process can also be seen in other HadCM3 simulations using different SRES scenarios. 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 have been happening already as shown by most up to date observations in the Labrador Sea (Yashayaev et al. 2005). The simulated and predicted changes can all be summarized in Fig.9, which shows the difference in decadal mean T-S diagrams for the water column in the Labrador Sea below 400m. The T-S diagrams include all the individual data points in stead of area-averaged ones used for Fig.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 Labrador Sea.

7 Conclusions and discussion

Three forced ensemble simulations and a long control run using the HadCM3 model are analysed to investigate the mechanisms of deep North Atlantic freshening. The observed 40yr 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 100yr 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 1640yr period of the control run, each following a sudden salinity increase. A process analysis has revealed that the salty events in the Labrador Sea are closely linked to a couple of deep convections while the following freshening trend is accompanied by a period of very weak convective activities. Although there is only a 10% chance statistically, the climate system can have a freshening trend without involving external forcings with similar amplitude and period to the recent observations.

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 may suggest that external forcings may be needed to trigger 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 is no obvious trends in the anthropogenic forcings ensemble. Surface ocean heat fluxes over the Labrador Sea and northeastern North Atlantic near the Faroe Bank Channel are positively correlated with the mean radiative forcings at the tropopause associated with solar and volcanic activities.

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 later may have more to do anthropogenically forced climate change (Gregory et al. 2003, Wu et al. 2004a). The expected weakening of the THC accompanying the freshening is not found in the same set of ensemble simulation (Wu et al. 2004b). 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 et al. 2005). 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. 2004a). 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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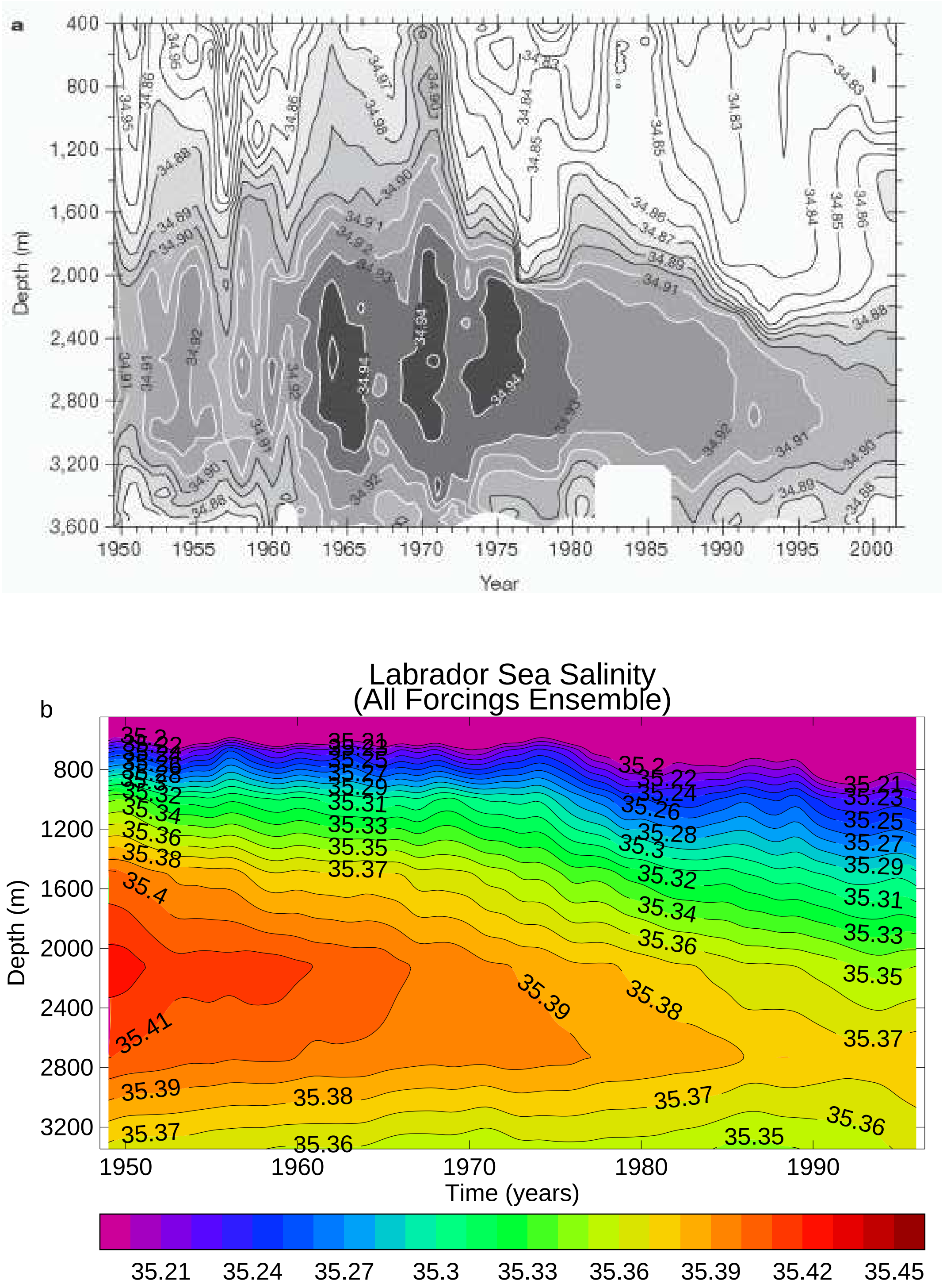

Figure 1: Evolution of Labrador Sea salinity in the HadCM3 all forcings ensemble simulation (a) in comparison with observations for the same period (b) from Dickson et al. (2002) showing the freshening trend of the NEADW form the 1960s.

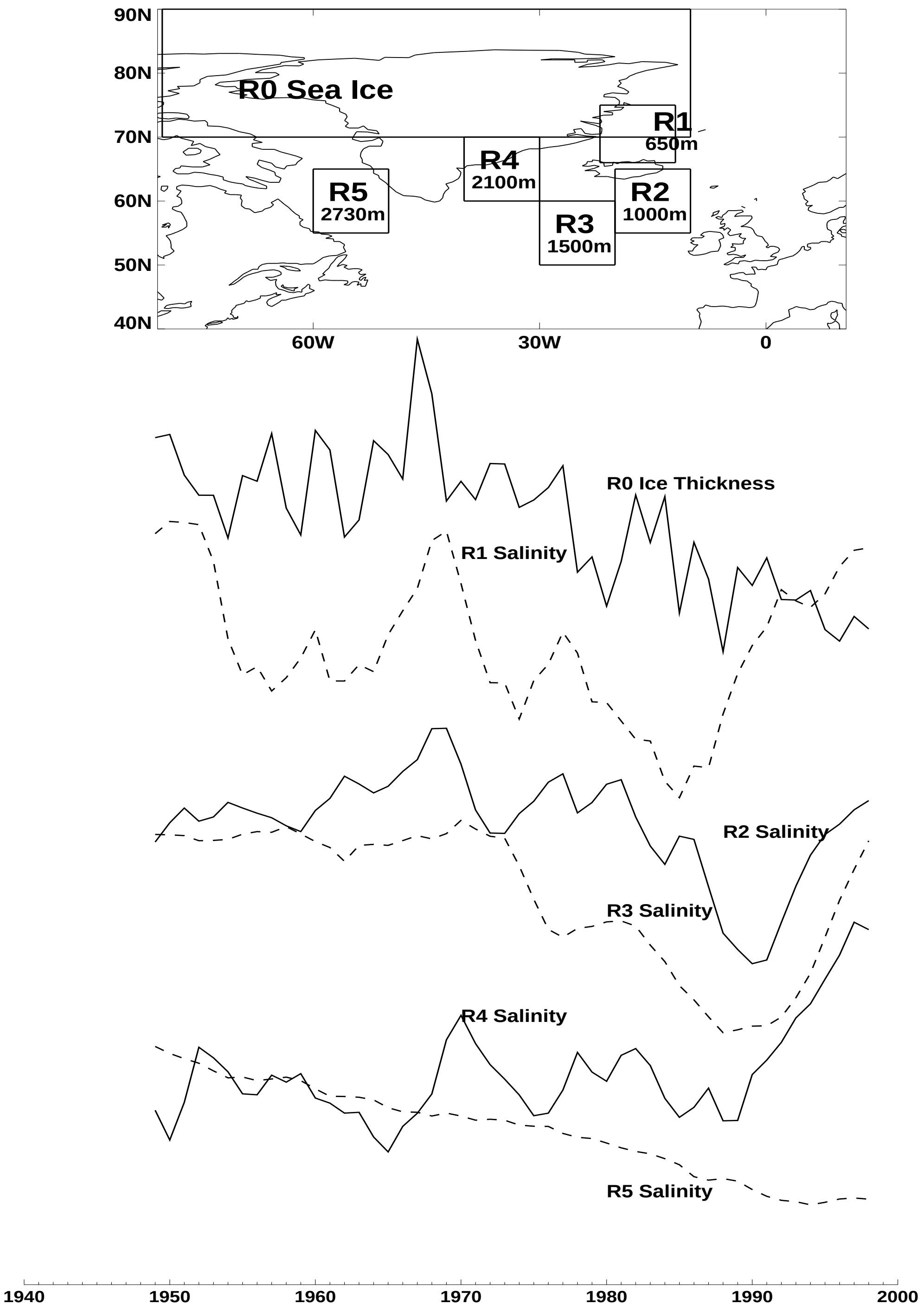

Figure 2: Salinity evolution along the NEADW path upstream of the Labrador Sea. The map indicates the region and depth for each corresponding curve shown in the plot. Each curve represents the area averaged ensemble mean salinity for the given region and depth. Horizontal axis indicates years.

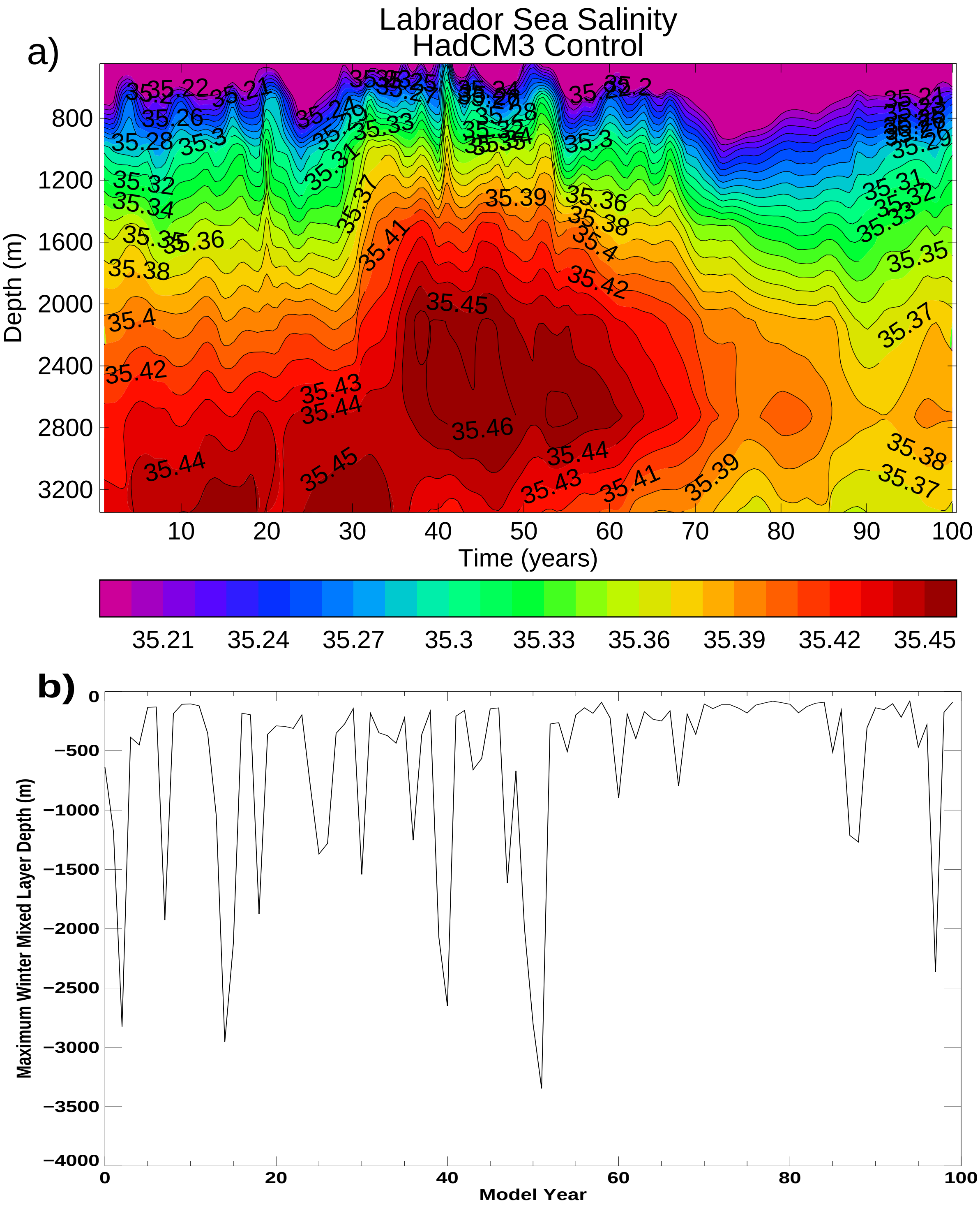

Figure 3: Annual mean salinity evolution in the Labrador Sea (a) and the corresponding maximum winter mixed layer depth (b) from a 100yr period of the long HadCM3 control integration. It shows one of four episodes in 1640 years of the control, which has a freshening trend similar to observations (see Fig.1a).

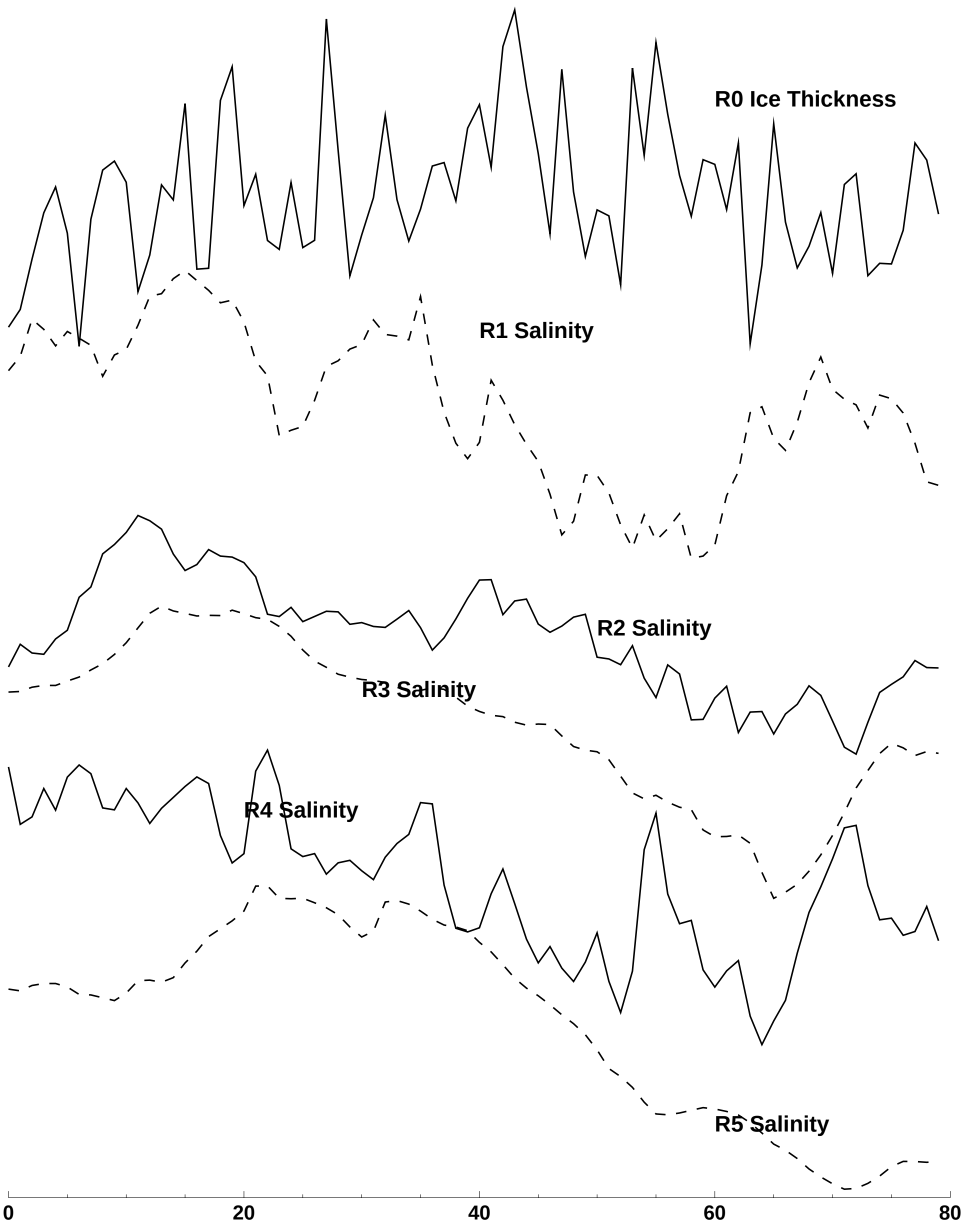

Figure 4: Salinity evolution along the NEADW path upstream of the Labrador Sea. The map indicates the region and depth for each corresponding curve shown in the plot. Each curve represents the area averaged ensemble mean salinity for the given region and depth.

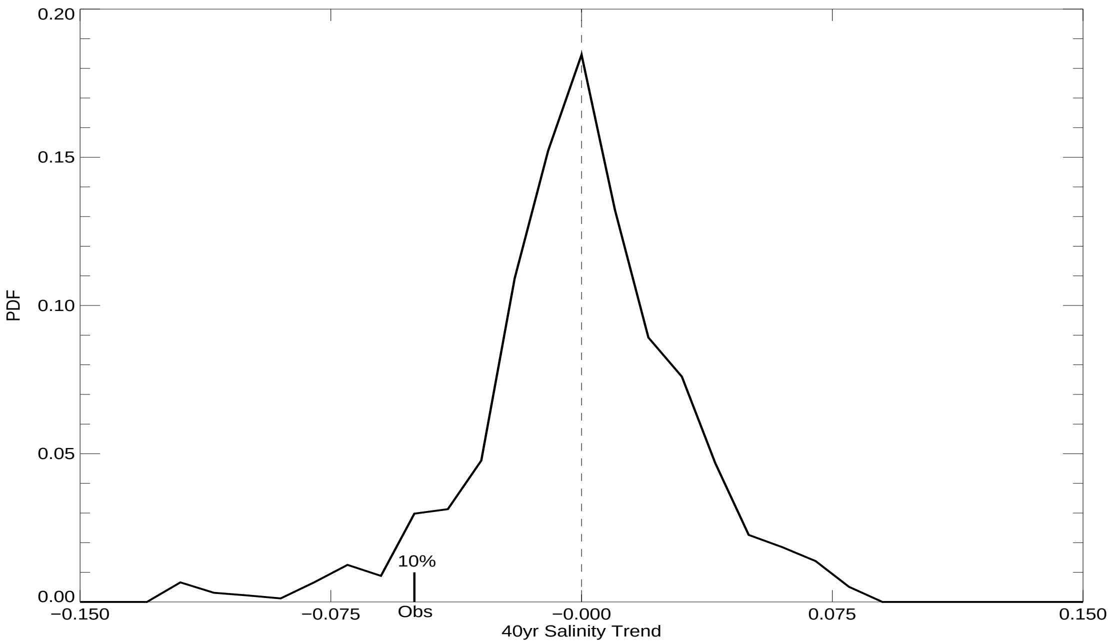

Figure 5: The pdf distribution of 40yr salinity trends calculated from 1640 years of HadCM3 control simulation. The pdf is produced from 10,000 samples of 40yr-time-window randomly taken from the control series. The observed freshening trend is marked to indicate the statistical significance. There is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

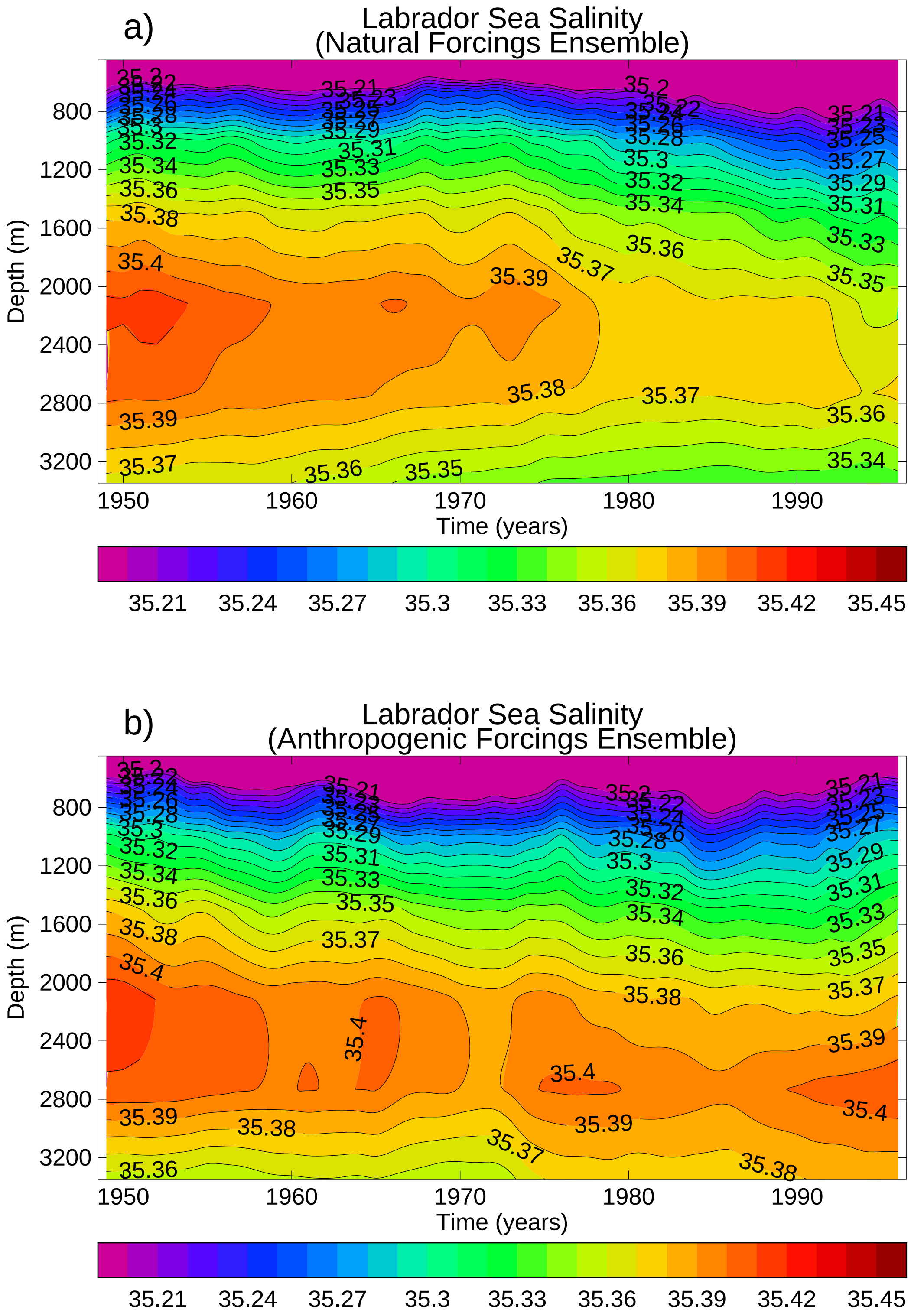

Figure 6: Evolution of Labrador Sea salinity in the HadCM3 natural forcings ensemble simulation (a) in comparison with the same from the anthropogenic forcings ensemble (b).

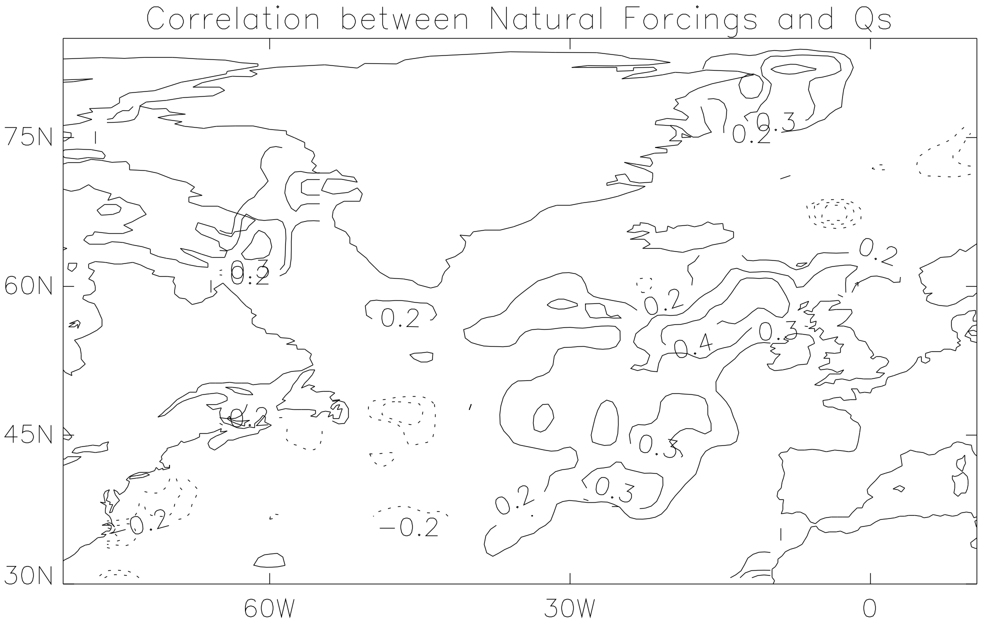

Figure 7: Correlation map showing the spatial structure of the ensemble mean annual ocean surface heat flux response to the zonal symmetric natural forcings. The Labrador Sea and the northeastern North Atlantic near the Faroe Bank Channel are sensitive regions.

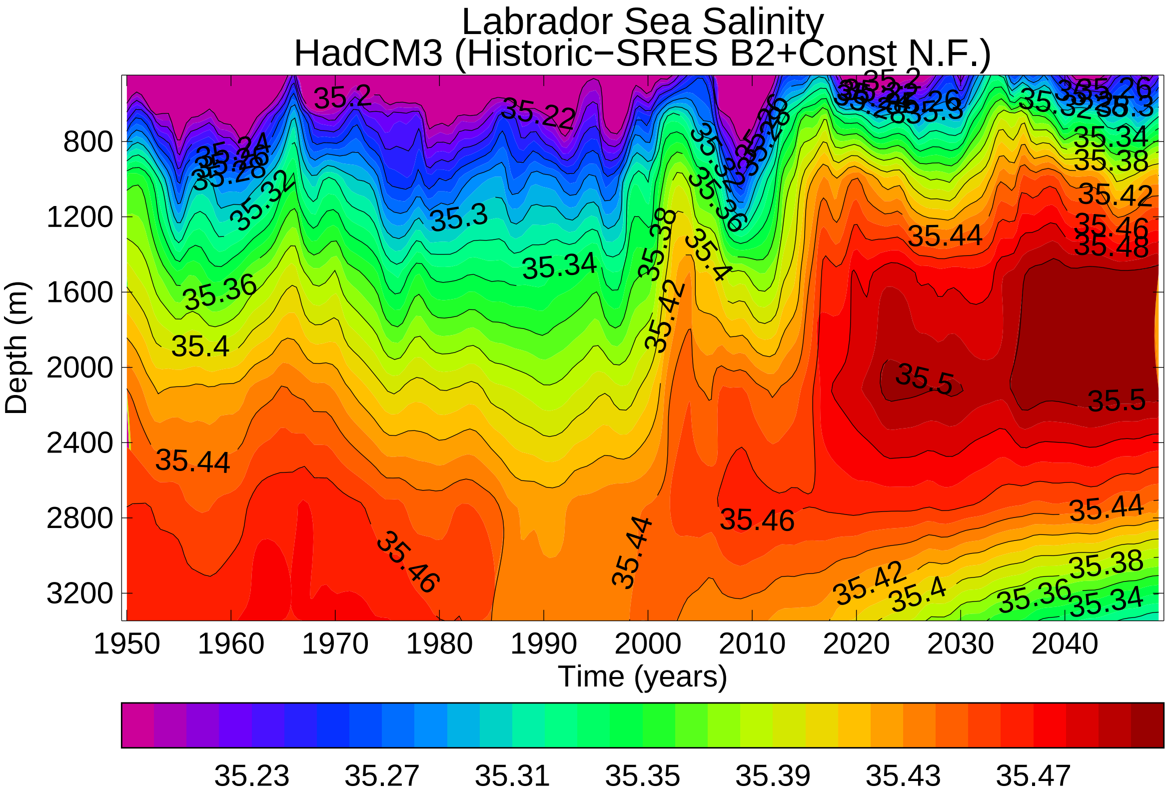

Figure 8: Evolution of Labrador Sea salinity in a HadCM3 simulation. The model is forced with all historic major external (natural and anthropogenic) factors until 1997 when natural forcings are fixed while anthropogenic forcings follow the IPCC SRES B2 scenario. The early part of the run forms a member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

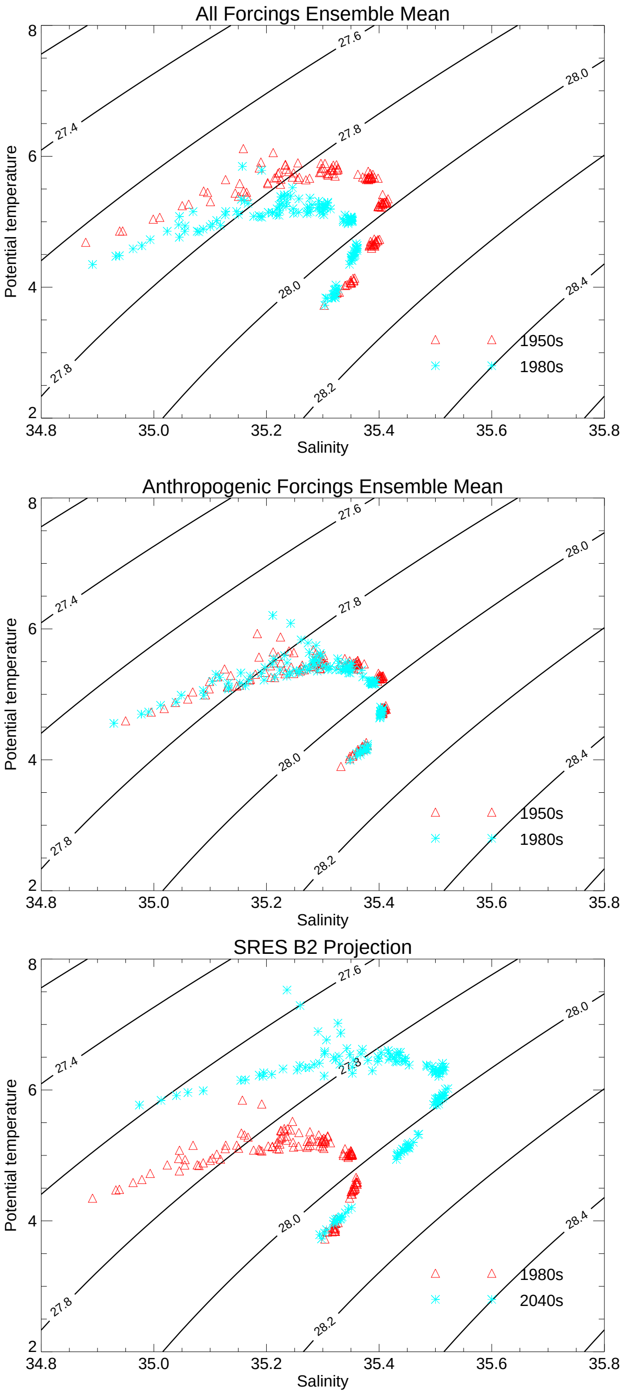

Figure 9: Decadal mean T-S diagrams for the Labrador Sea below 400m in three different simulations. The cooling and freshening can be clearly seen in the all forcings ensemble (top) but not in the anthropogenic forcings ensemble (middle). However, the model predicts warming and salinfying of the Labrador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