The role of Atlantic-Arctic exchange in North Atlantic multidecadal climate variability

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[1] It has recently been suggested that multidecadal variability in North Atlantic sea surface temperature occurs with two dominant periods. In this paper we investigate the origin of these two time scales in a 500 year control run of the GFDL CM2.1 model. We focus on the exchange between the Atlantic and Arctic oceans and study spectra of temperature, salinity and meridional overturning circulation and the correlations between these quantities. The analysis shows that (i) the shorter period variability originates in the North Atlantic and (ii) the exchange between the Atlantic and Arctic can explain the longer period of multidecadal variability in the North Atlantic.
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1. Introduction

[2] Multidecadal variability of ocean temperatures in the North Atlantic has become a much studied yet still relatively poorly understood phenomenon. Both the dominant period in observations and the physical mechanism have been up for debate. From observations the time scale can be roughly divided into the long period (50–70 years [*Schlesinger and Ramankutty*, 1994; *Kushnir*, 1994]) and the shorter period (20–30 years [*Frankcombe et al.*, 2008; *Frankcombe and Dijkstra*, 2009; *Chylek et al.*, 2011]). The same dominant periods are found in models, the GFDL CM2.1 model shows a 20–30 year period [*Zhang*, 2008] while HadCM3 has both a 25 year [*Dong and Sutton*, 2005] and 100 year period [*Vellinga and Wu*, 2004] and ECHAM5-OM1 shows predominantly 70–80 years [*Jungclaus et al.*, 2006], with a different simulation using the same model showing 20–40 year variability [*van Oldenborgh et al.*, 2009]. Multidecadal variability has also been observed in the Arctic [*Venegas and Mysak*, 2000], particularly in the variability of sea-ice extent in marginal seas [*Polyakov et al.*, 2003] as well as variability of the temperature of the Atlantic water in the Arctic ocean [*Polyakov et al.*, 2004].

[3] Several different mechanisms have arisen to describe the physics of the multidecadal temperature changes through examination of the control runs of various coupled climate models. These mechanisms variously describe the variability as an ocean response to low-frequency atmospheric variability [*Delworth and Greatbatch*, 2000], a delayed advective oscillation of the Atlantic Meridional Overturning Circulation (AMOC) [*Lee and Wang*, 2010], a coupled ocean-atmosphere mode [*Timmermann et al.*, 1998] in which the North Pacific may play a role [*Dima and Lohmann*, 2007], a connection between the tropical and North Atlantic [*Vellinga and Wu*, 2004; *Knight et al.*, 2005] or a connection between the North Atlantic and Arctic [*Jungclaus et al.*, 2005].

[4] An alternative approach is to model the climate variability using the simplest possible set up. An internal ocean mode is found to be crucial for the existence of multidecadal variability [*Huck et al.*, 1999; *te Raa and Dijkstra*, 2002] and has been called a 'thermal Rossby mode' because the temperature anomaly propagates across the background temperature gradient, analogous to the way 'normal' Rossby waves propagate across the background potential vorticity gradient. The pattern and period of this thermal Rossby mode are consistent with observations of westward propagating temperature anomalies in the North Atlantic [*Frankcombe et al.*, 2008] and sea level variations along the European and North American coastlines [*Frankcombe and Dijkstra*, 2009], both of which occur on the shorter 20–30 year period. *Frankcombe et al.* [2010] investigated the origin of the two periods of North Atlantic variability in the GFDL CM2.1 climate model, showing that the shorter period is more prominent in temperatures in the North Atlantic while the longer period variability is most prominent in Arctic Ocean salinity. Thus it was hypothesized that the shorter period is due to the thermal Rossby mode mechanism in the North Atlantic while the longer period is related to salinity variability in the Arctic caused by internal saline Rossby modes. The existence of these saline Rossby modes has been demonstrated in highly idealized cases [*Frankcombe and Dijkstra*, 2010].

[5] If the shorter period originates in North Atlantic temperature and the longer period in Arctic salinity then this should be visible in the exchange between the two oceans. Hence in this paper we focus on the different time scales of temperature and salinity variability in the North Atlantic and Arctic and on the exchange between the two oceans. To do this we consider the same 500 year GFDL CM2.1 model control run [*Delworth et al.*, 2006] as was examined by *Frankcombe et al.* [2010].

2. Results

[6] Figure 1 shows three indices related to the North Atlantic, the Atlantic Multidecadal Oscillation index (AMOI, defined as the ten year running mean of sea surface temperature (SST) averaged between 70°W–10°W, 10°N–60°N), the sea surface salinity index (SSSI, defined as the ten year running mean of sea surface salinity (SSS) averaged

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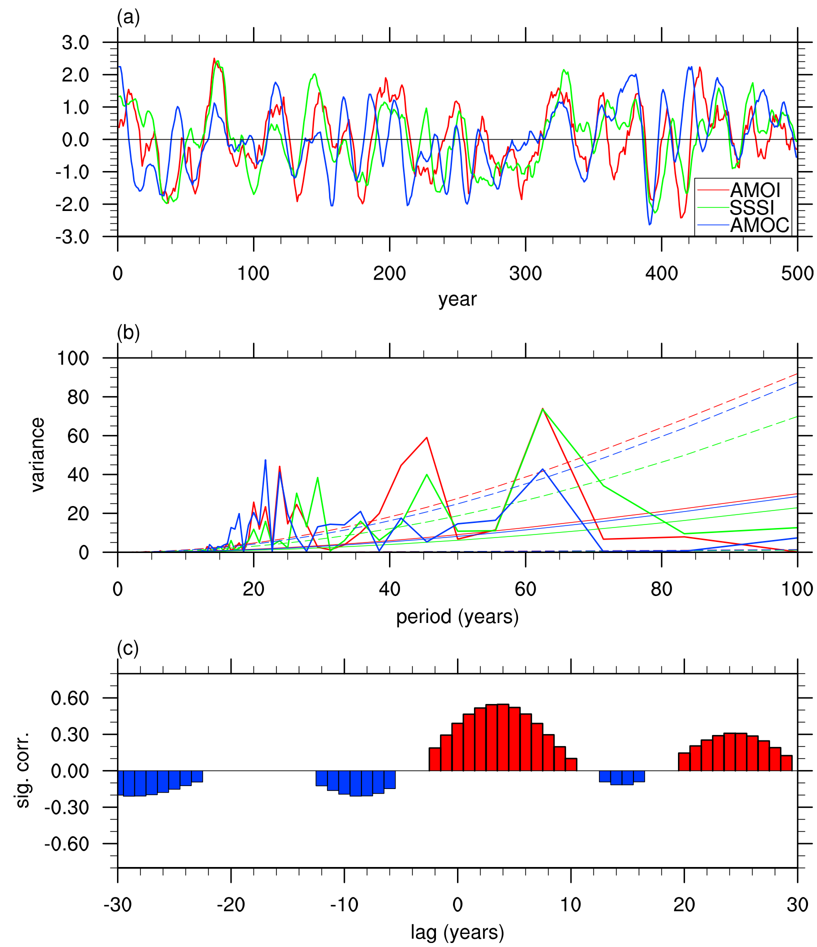

Figure 1. (a) AMOI index (red; °C; ten year running mean of SST averaged between 70°W–10°W, 10°N–60°N), SSS index (SSSI; green; psu; calculated in the same way as AMOI) and AMOC (blue; Sv; at 44°N, 1100 m depth), all three indices have been normalised by their standard deviation, (b) spectra of the three indices (dashed lines indicate the 5 and 95% significance levels) and (c) correlation between AMOC and AMOI (positive lag means that overturning leads).

over the same region as the AMOI), and overturning strength (AMOC, defined at 44°N, 1100 m depth). All three indices display variability on a range of time scales, most notably 20–30, 40–50 and 60–70 years. Correlations between the strength of the AMOC and temperature indicate a dominant oscillation with a period of ~25 years. The AMOC leads temperature by 3–4 years; this is consistent with the thermal Rossby mode mechanism in which a lag of a few years between temperature and AMOC is a characteristic feature [*Huck et al.*, 1999; *te Raa and Dijkstra*, 2002]. It also indicates that the thermal Rossby mode is responsible for the 20–30 year part of the variability in both temperature and AMOC in this model, as suggested by *Frankcombe et al.* [2010] (where overturning data from the CM2.1 model was not analyzed).

[7] Figure 2 shows time series and spectra of the exchange flows between the Atlantic and the Arctic. Transport of salinity from the Arctic to the North Atlantic (red curve) shows significant variability at longer periods than salinity transport in the opposite direction (blue curve), indicating that the longer periods either have their source in the Arctic or are markedly enhanced there. Similarly the shorter period variability is enhanced in the water entering the Arctic from the North Atlantic.

[8] Further evidence that the different periods result from processes in different basins can be found by looking at correlations between AMOC and temperature and salinity in the North Atlantic and Arctic. The correlation between AMOC strength and temperature at different depths in the North Atlantic is shown in Figure 3a. The 20–30 year period with the AMOC leading that is visible in the correlation between AMOC and AMOI (Figure 1c) continues down to about 500 m; below that there is no clear pattern of significant correlations. The correlation between AMOC and North Atlantic salinity (not shown) is very similar to the correlation between AMOC and North Atlantic temperature.

[9] Variability on a time scales of both 20–30 years and about 40 years is visible when SST in the Arctic is correlated with salinity at different depths in the North Atlantic (Figure 3b), as well as when SST in the North Atlantic is correlated with temperature at different depths in the Arctic (Figure 3c). This shows both the long and the short period appear in both the North Atlantic and the Arctic.

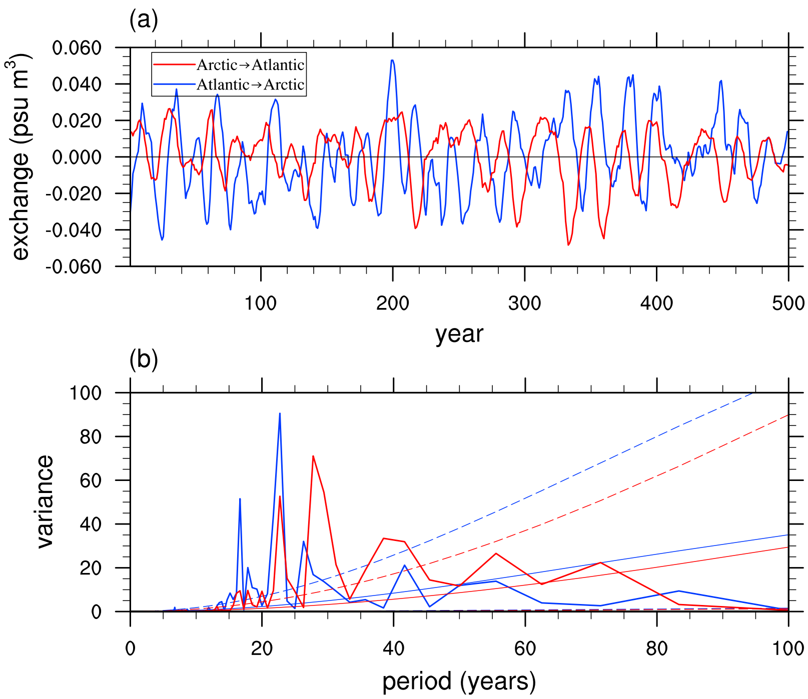

Figure 2. (a) Exchange of salinity (meridional north- and southward salt flux) between the Atlantic and the Arctic (ten year running means) and (b) their spectra (dashed lines indicate the 5% and 95% significance levels). The indices are calculated by multiplying annual salinity by annual velocity and integrating with depth along 70°N. Positive values indicate greater (lesser) transport of salinity into (out of) the Arctic. The results for temperature exchange are the same.

[10] Figure 3d shows the correlation between AMOC and salinity at different depths in the Arctic. Here the highest correlation at the surface shows salinity leading AMOC, while through most of the depth AMOC leads. The period is clearly much longer than in the correlation between AMOC and North Atlantic temperature (Figure 3a). The same long period is seen in the correlation between AMOC and Arctic temperature (not shown).

[11] These results point to the importance of the Atlantic-Arctic exchange in causing the different time scales of variability and suggest the mechanistic framework as illustrated in Figure 4. The 20–30 year variability as observed in North Atlantic temperatures (including westward propagation of temperature anomalies below the surface [*Frankcombe et al.*, 2008], and sea level variations on the European and North American coasts [*Frankcombe and Dijkstra*, 2009]) is all consistent (cf. Figure 3a) with the period and pattern of the thermal Rossby mode in the North Atlantic which is excited by atmospheric noise [*Frankcombe et al.*, 2009]. Many climate models show variability on this time scale, where it is indeed always linked to variability of the AMOC. The variability in temperature is transported northward to the Arctic leading to the shorter period multidecadal variability in the Arctic as observed in the exchange of salinity at 70°N (Figure 2).

[12] Independently, long time scale (longer than 40 years) variability arises due to internal ocean mechanisms associated with saline Rossby modes in the Arctic (analogous to the thermal Rossby mode in the North Atlantic). *Frankcombe et al.* [2010] found this salinity variability in the Arctic (by analysis of the results of the same GFDL-CM2.1 model simulation as analyzed in this paper) on multidecadal time scales, while *Frankcombe and Dijkstra* [2010] showed in an idealized Arctic model that an internal mode on approximately the right period does exist. The mode is damped in the idealized Arctic models but could be excited by variability in Atlantic inflow as well as atmospheric, sea ice or river runoff variability.

[13] This longer period variability is found in the southward salt exchange at 70°N and consequently propagates into the North Atlantic (Figure 2). There have been various explanations of the effect of Arctic great salinity anomalies (GSAs) on AMOC strength. *Zhang and Vallis* [2006] and *Dima and Lohmann* [2007] argue that GSAs are linked to temperature and circulation changes in the North Atlantic, and also to AMOC strength. On the other hand, *Haak et al.* [2003] found that GSAs had a minimal impact on the AMOC. For the GFDL-CM2.1 model [*Zhang and Vallis*, 2006], it is expected that the AMOC adjusts to salinity changes at high latitudes on the (multidecadal to centennial) overturning time scale which may lead to the longer period in the AMOC and AMOI, as seen in Figure 1 and consistent with the correlations in Figures 3b–3d.

3. Discussion

[14] The aim of this paper was to explain the various peaks in the spectra of AMOI and AMOC as found in a 500 year control simulation of the GFDL-CM2.1 model. The multidecadal time scale range has been roughly divided into variability with a period of 20–30 years, and variability

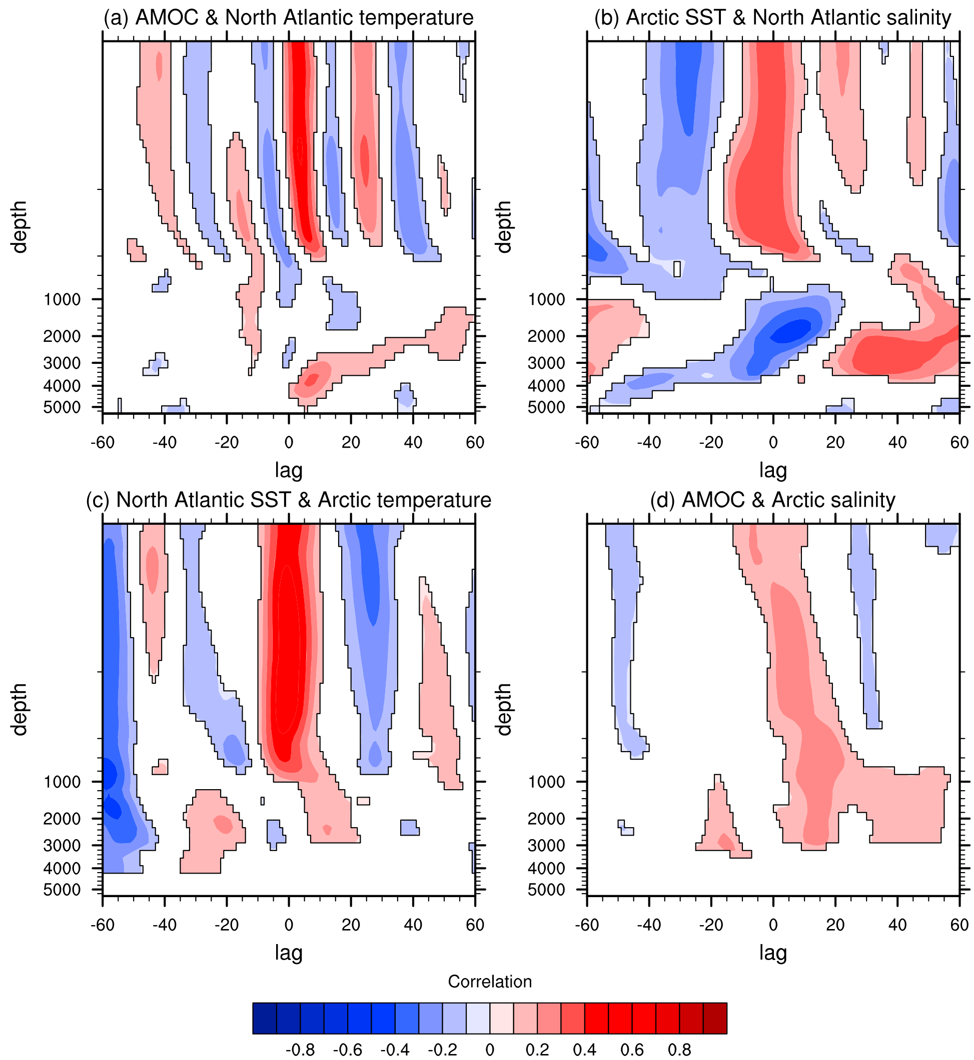

Figure 3. Correlations between (a) AMOC and temperature at each level in the North Atlantic, (b) SST in the Arctic and salinity at each level in the North Atlantic, (c) SST in the North Atlantic and temperature at each level in the Arctic and (d) AMOC and salinity at each level in the Arctic. Note that the depth axis is non linear and white areas indicate that the correlations did not pass a 95% significance test. Temperature and salinity are averaged over the same region as in Figure 1 for in the North Atlantic, and north of 65°N for the Arctic.

with a period of greater than about 40 years. The main new idea is sketched in Figure 4, where the short period is generated in the North Atlantic and propagates into the Arctic while the longer period is generated in the Arctic and propagates into the North Atlantic.

[15] While this view explains the latitudinal variation of the periods found in SST observations by *Frankcombe et al.* [2010], several issues remain unclear in the results of the GFDL-CM2.1 model. First, in this model the longer period Atlantic temperature variability seems to have two main peaks, at 40–50 and 60–70 years. The longer periods are observed more prominently at higher latitudes which points to the Arctic also playing a vital role. Perhaps the time that the anomalies take to propagate around the Arctic and then back into the North Atlantic emphasizes the longer periods. However this does not explain the differences in the variability of temperature and salinity (Figures 1 and 3). Second, the 40–50 and 60–70 year peaks of AMOC are also relatively weak compared to the peaks in AMOI and SSSI (Figure 1). The 60–70 year variability in exchange is weaker than the 20–30 year variability (significant in Arctic to Atlantic flow at the 90% level), which makes it difficult to explain the strong response in the AMOI and SSSI. Resonance of the shorter periods is possible, however then a stronger AMOC response would also be expected. This requires further investigation, in this model as well as in other climate models.

[16] Apart from these problems explaining some of the details of the spectra in AMOC, AMOI and SSSI, the GFDL-CM2.1 results lead to the conclusion that Atlantic-Arctic exchange processes combined with internal variability in both basins may lead to the two different periods of multidecadal variability in the North Atlantic climate system. Observations on the exchange flow are relatively scarce [*de Steur et al.*, 2009], and the results here indicate

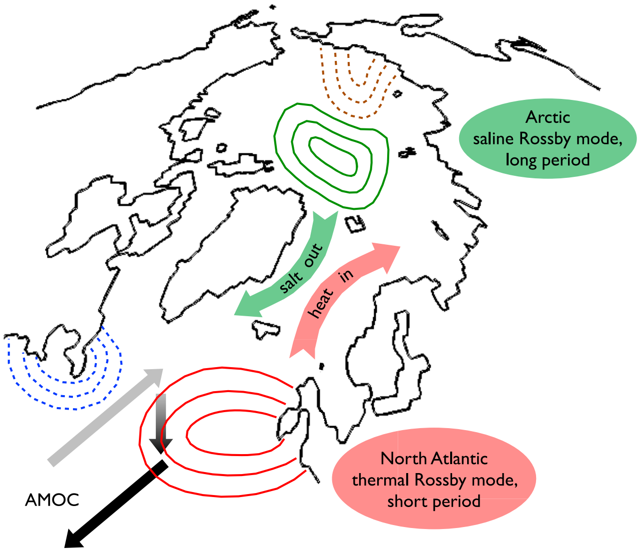

Figure 4. Illustration of the interaction of the two internal modes. The shorter period mode in the North Atlantic appears as a strengthening/weakening of the AMOC associated with the westward propagation of temperature anomalies near the surface. The longer period mode in the Arctic involves salinity anomalies propagating across the pole.

the importance of such measurements for understanding and predicting North Atlantic climate variability.

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