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Multidecadal climate variability in the Greenland Sea and surrounding regions: a coupled model simulation

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Abstract. Pronounced oscillations of ocean temperature and salinity occur in the Greenland Sea in a 2000 year integration of a coupled ocean-atmosphere model. The oscillations, involving both the surface and subsurface ocean layers, have a timescale of approximately 40-80 years, and are associated with fluctuations in the intensity of the East Greenland Current. The Greenland Sea temperature and salinity variations are preceded by large-scale changes in near-surface salinity in the Arctic, which appear to propagate out of the Arctic through the East Greenland Current. These anomalies then propagate around the subpolar gyre into the Labrador Sea and the central North Atlantic. These oscillations are coherent with previously identified multi-decadal fluctuations in the intensity of the North Atlantic thermohaline circulation. The oscillations in the Greenland Sea are related to atmospheric variability. Negative (cold) anomalies of surface air temperature are associated with negative (cold) sea surface temperature (SST) anomalies in the Greenland Sea, with amplitudes up to 2°C near Greenland declining to several tenths of a degree C over northwestern Europe. The cold SST anomalies and intensified East Greenland Current are also associated with enhanced northerly winds over the Greenland Sea.

Introduction

The Great Salinity Anomaly (GSA; Dickson et al, 1988) was a spectacular example of decadal scale oceanic variability in the high latitudes of the North Atlantic. Such events are of potentially profound climatic importance because of the central role of the high latitudes of the North Atlantic in the global thermohaline circulation (Walsh and Chapman, 1990).

Aagaard and Carmack (1989) suggest that the GSA originated through an enhancement of the fresh water and sea ice fluxes from the Arctic in the late 1960s. The results of a numerical experiment (Häkkinen, 1993) support this. The fresh water anomaly moved down the East Greenland Current (EGC), followed the subpolar gyre through the Labrador Sea and into the central North Atlantic, eventually returning to the Greenland Sea in the early 1980s. Evidence that a similar event may have occurred in the early part of the 20th century is presented by Dickson et al. (1988; see their Fig. 8).

In this paper we describe fluctuations of surface salinity which resemble the GSA in a 2000 year integration of a coupled ocean-atmosphere model. The salinity fluctuations are associated with substantial multidecadal variations of sea surface temperature (SST) and climate in the Greenland Sea (see Fig. 1) and surrounding regions.

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Model Description and Experimental Design

The coupled ocean-atmosphere model used in this study is identical to that described in detail in Manabe et al. (1991). The model is global in domain, including the Arctic, with realistic geography consistent with resolution. The model is forced with an annual cycle of insolation at the top of the atmosphere. The atmospheric component numerically integrates the primitive equations of motion using a semi-spectral technique in which the variables are represented by spherical harmonics and by corresponding grid points with a spacing of 7.5° longitude and 4.5° latitude. There are 9 unevenly spaced levels in the vertical. The oceanic component of the model uses a finite difference technique with 12 unevenly spaced levels in the vertical, and a horizontal resolution of approximately 3.75° longitude and 3.75° latitude. Sea ice is predicted using a simple model developed by Bryan (1969), which allows sea ice less than 4 m thick to move with the ocean currents. The model atmosphere and ocean interact through fluxes of heat, water, and momentum at the air-sea interface.

The coupled model employed for this study has a relatively low spatial resolution and simplified physical parameterizations. In spite of these simplifications, the model has successfully reproduced many aspects of observed interannual to decadal variability (Manabe and Stouffer, 1996). We feel that important insights can be gained from such models regarding the fundamental workings of the coupled climate system.

In order to reduce climate drift, adjustments to the heat and water fluxes are applied at the air-sea interface over both open and sea-ice covered regions. These flux adjustments are derived from preliminary integrations of the separate atmospheric and oceanic components (see Manabe et al., 1991, for details). The adjustments vary seasonally and spatially but are constant from one year to the next. Since the adjustments were derived prior to the start of the coupled model integration they are not correlated with sea surface temperature and salinity anomalies. They are therefore unlikely to systematically amplify or dampen such anomalies. In addition, the adjustments help to keep the model near a realistic mean state so that various feedback processes, such as ice-albedo feedback, can have a realistic influence on the model variability.

After preliminary integrations to achieve an initial condition in approximate equilibrium, the model was time integrated for a period of 2000 years. The output from this integration forms the dataset for the analyses presented below.

Description of Model Variability

Analyses of the integration described above have revealed multidecadal variations of sea surface salinity (SSS) and SST

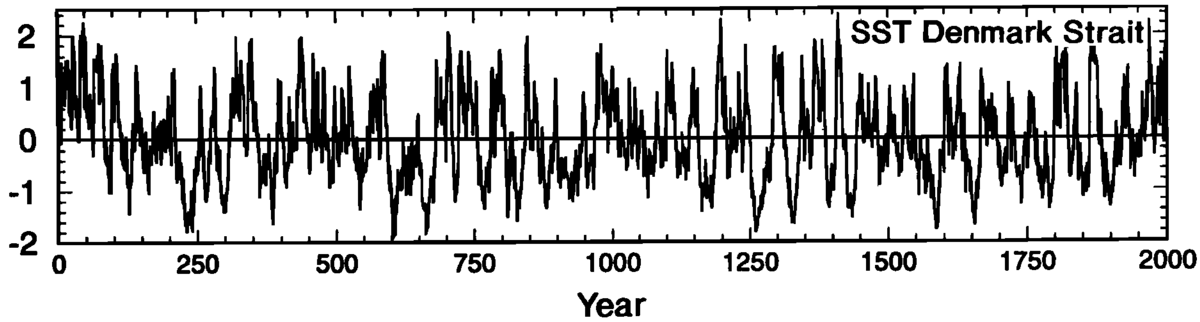

Figure 1. Time series of annual mean model SST in the Denmark Strait (15°W to 26°W at 70°N). Prior to plotting, the time series was filtered such that timescales shorter than 10 years were effectively removed. The values are anomalies from a long term mean of 0.62. Units are °C.

in the Greenland Sea region which are reminiscent of the GSA. Some aspects of this were seen in Manabe and Stouffer (1996), who noted that substantial, low frequency variations of SST and near-surface air temperature occurred in the vicinity of the Greenland Sea (see their Fig. 7b).

The time series of annual mean model SST from a similar region of the current integration (shown in Fig. 1) is characterized by multidecadal variations of temperature, with peak-to-peak differences of more than 3°C. The SST variations are tightly coupled to SSS variations in the same region (linear correlation = 0.92), with typical amplitudes of 0.2-0.3 parts per thousand. The spectrum of SST shown in Fig. 2 reveals enhanced variance at 40-80 years, with a spectral peak at 50-60 years. Visual inspection of Fig. 1 shows that there is a modulation of the amplitude of this 40-80 year variability. Wavelet analysis and singular spectrum analysis were performed on this time series (not shown) and reveal that this modulation has a time scale of several centuries.

In order to describe the space-time structure of this oscillation, linear regressions were computed at various lags between the time series of several variables (ocean temperature, salinity, and currents) at each grid point versus the time series of SST shown in Fig. 1. The regression analyses, computed using annual mean data, reveal the changes in these variables associated with SST anomalies in the Denmark Strait. Figure 3 shows the progression of SSS anomalies from the Arctic to the North Atlantic. Conditions at Lag -15 indicate fresh anomalies dominating the Arctic. At Lag -10, these fresh anomalies still dominate the Arctic, and have extended southward down the EGC and to the region off Newfoundland. The superimposed current anomalies show a stronger than normal EGC enhancing the fresh water transport out of the Arctic. At Lag 0 the freshwater anomalies extend around the subpolar gyre to the central North Atlantic. At this time, positive SSS anomalies are seen to develop in the Arctic, a harbinger of the developing opposite phase of the oscillation. The increase in Arctic SSS is consistent with the anomalously strong transport of fresh water out of the Arctic. At the same time that the surface currents indicate enhanced flow from the Arctic into the Greenland Sea, there is an anomalous flow at depth from the Greenland Sea into the Arctic (not shown). Additional regression analyses (not shown) reveal that positive sea ice anomalies are generally in phase with the negative SSS and SST anomalies.

The spatial pattern of SST anomalies is shown in Fig. 4. Starting from small negative anomalies at Lag -15 (not shown), negative SST anomalies in the Denmark Strait amplify and spread to cover nearly the entire Greenland Sea and portions of the central North Atlantic by Lag 0 (Fig. 4). In addition, an area of positive SST anomalies develops off the North American continent. This pattern appears when the intensity of the model thermohaline circulation is weakest (Delworth et al., 1993; see Fig. 6a), and is reminiscent of the SST anomalies seen in observations (Kushnir, 1994). In addition to advection, the SST and SSS anomalies in the Greenland Sea are strongly influenced by convection. Fresh water anomalies in the near-surface layer can inhibit convection, thereby suppressing the heat and salt exchange with sub-surface layers and amplifying the surface anomalies.

Atmospheric variations are also associated with the SST fluctuations shown in Fig. 1. Surface air temperature anomalies over the Greenland and Norwegian Seas with amplitudes up to 2°C are positively correlated with SST in the Denmark Strait, with anomalies of smaller magnitude extending into northwestern Europe. There are also associated variations in surface pressure, as shown in Fig. 4. The surface pressure anomalies have their largest amplitude approximately 2 years before the largest magnitude of the SST variations. The spatial pattern has a resemblance to the anomalous pressure pat-

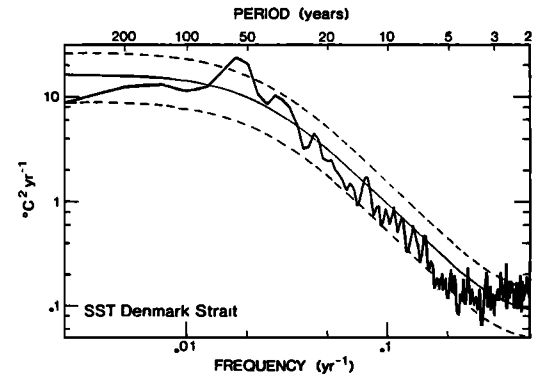

Figure 2. Spectrum of the time series of annual mean model SST in the Denmark Strait (15°W to 26°W at 70°N; this is the time series from Fig. 1 prior to filtering). The logarithm of the spectral estimates (thick, solid line) is plotted versus the logarithm of frequency. The thin, solid line denotes the spectrum of a background first order Markov process, and the dashed lines denote the 95% confidence interval about that background spectrum. The spectrum was estimated by taking the Fourier transform of the autocovariance function using a Tukey window with a maximum lag of 200.

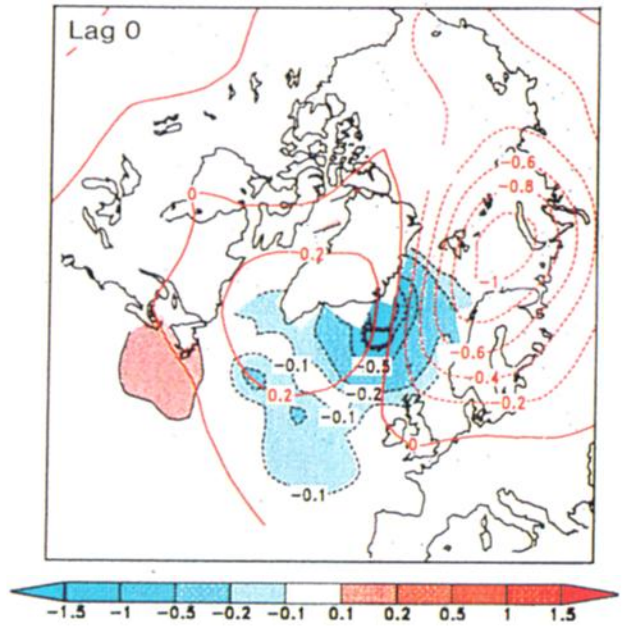

Figure 4. Same as Fig. 3 using the regressions of SST at each grid point versus the time series of annual mean SST in the Denmark Strait (15°W to 26°W at 70°N). The regression coefficients of SST are indicated by the color shading. Superimposed using red contour lines are the regressions of surface pressure (mb per -2°C SST anomaly). Results are shown for Lag 0 for SST, and Lag -2 for surface pressure (i.e., surface pressure leading SST by 2 years).

tern preceding the GSA (Walsh and Chapman,1990), although smaller in magnitude. The associated circulation indicates a weakening of the mean southerly winds over the Nordic Seas when SSTs are negative, coincident with an enhanced EGC. This association suggests the possibility of active atmospheric participation in this model oscillation. A similar possibility was suggested by Wohlleben and Weaver (1995).

Discussion

Previous analyses (Delworth et al., 1993) of this model have revealed multidecadal variations of the THC in the North Atlantic with a time scale of 40-80 years, generally similar to the timescale of the variability described above. In order to investigate the relationship between these THC variations and the Greenland Sea SSS and SST oscillations, the squared coherency was computed between a time series of the THC intensity and the SST time series in Fig. 1. The squared coherency reaches a maximum of 0.50 at a period of approxi-

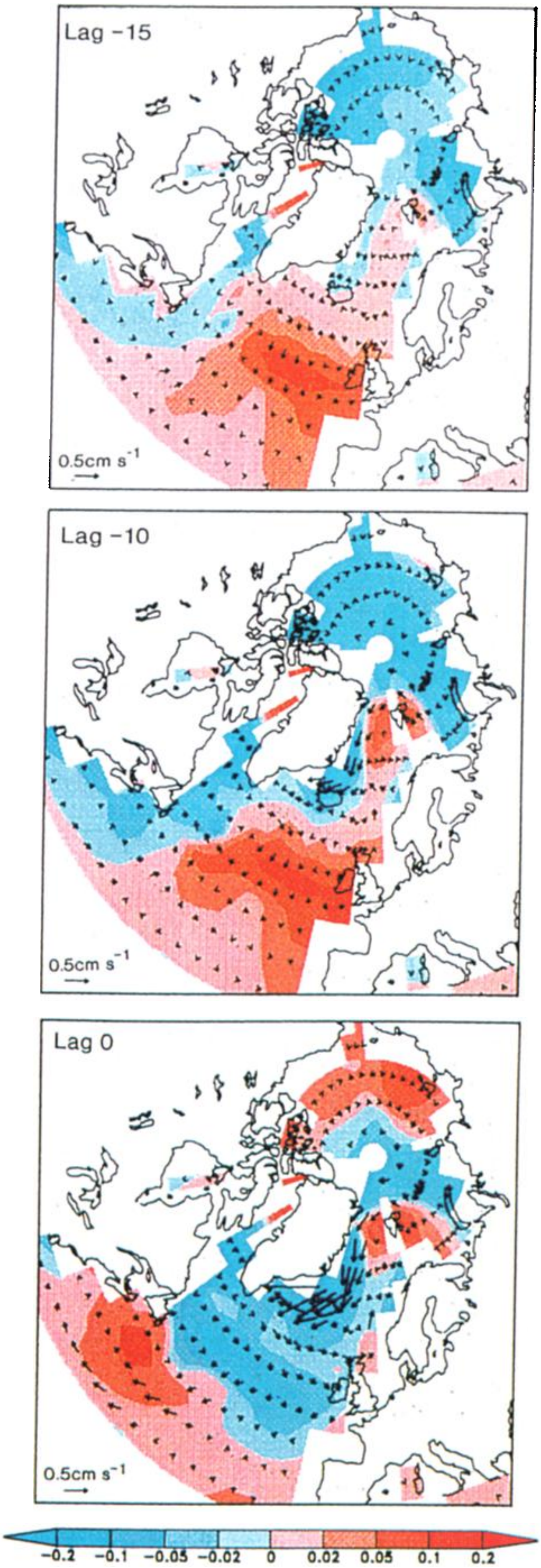

Figure 3. Regressions of annual mean SSS at each grid point versus the time series of annual mean SST in the Denmark Strait (15°W to 26°W at 70°N). The contoured values are the slopes of the regression lines multiplied by -2 (to indicate conditions associated with an SST anomaly of -2°C). The field at Lag -15 indicates conditions 15 years prior to a -2°C SST anomaly in the Denmark Strait. Units are parts per thousand per -2°C SST anomaly. In addition, the regressions of the surface currents are indicated by the vectors. Units are cm s^{-1} per -2°C SST anomaly. For clarity of plotting, not all current vectors are shown at very high latitudes.

mately 57 years, with the THC time series lagging the SST (and SSS) in the Denmark Strait by approximately 10 years. The THC is weakest when SSS over the sinking region of the THC (defined as the area from 50°N to 70°N in the North Atlantic) is at a minimum (see Fig. 9a of Delworth et al., 1993). This relationship leads us to speculate that enhanced transport of relatively fresh water and sea ice from the Arctic, through the East Greenland Current and Denmark Strait, and into the Labrador Sea regions may weaken the THC in the North Atlantic. The increase of relatively fresh, low density water in the near-surface layers of the Labrador Sea and neighboring regions ("fresh water capping") inhibits the convective exchange of heat between the cold near-surface layers and the relatively warmer sub-surface layers (Lazier, 1980, provides observational evidence for this). This reduced supply of heat to the surface layer inhibits air-sea heat exchange by cooling the surface waters, thereby reducing the supply of negative buoyancy to the near-surface layer and weakening the THC.

The above discussion suggests that the Greenland Sea oscillation could have a role in generating the multidecadal variations of the THC through fresh water capping of its sinking region. However, there is also the possibility that the multidecadal variations of the THC may have a role in generating the Greenland Sea oscillation. It is difficult to distinguish between these two possibilities based on one numerical experiment, in which all processes are inherently coupled. Therefore, additional numerical experiments will be required to understand both the interactions between these two oscillations and the factors that determine their time-scales.

One possible mechanism for decadal scale (10-20 year) variability was put forward by Mysak et al. (1990), who suggested that anomalous river runoff into the Arctic created the anomalous fresh water and sea ice pulse known as the GSA. In our model, however, the time series of river runoff into the Arctic has a white spectrum (i.e., approximately uniform variance at all time scales). This suggests that an explicit forcing through anomalous river runoff is not present in this model.

Tree ring records (D'Arrigo, 1995; Briffa et al., 1992) provide substantial evidence of multidecadal variability in the high latitudes of the North Atlantic, with spectral peaks ranging from 30 to 80 years. Analyses of instrumental and proxy data from the last five centuries (Mann et al., 1995) provide evidence for distinct multidecadal variability in the North Atlantic and Arctic. It is certainly plausible that interactions between the Arctic and the North Atlantic may contribute to this variability, particularly by altering the surface fresh water export from the Arctic (as in the model variability described here). A promising path to enhancing our understanding of such variability lies in a combination of observational and proxy data analysis combined with a wide variety of modeling studies.

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