Multidecadal Thermohaline Circulation Variability Driven by Atmospheric Surface Flux Forcing

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ABSTRACT

Previous analyses of an extended integration of the Geophysical Fluid Dynamics Laboratory coupled climate model have revealed pronounced multidecadal variations of the thermohaline circulation (THC) in the North Atlantic. The purpose of the current work is to assess whether those fluctuations can be viewed as a coupled air–sea mode (in the sense of ENSO), or as an oceanic response to forcing from the atmosphere model, in which large-scale feedbacks from the ocean to the atmospheric circulation are not critical.

A series of integrations using the ocean component of the coupled model are performed to address the above question. The ocean model is forced by suitably chosen time series of surface fluxes from either the coupled model or a companion integration of an atmosphere-only model run with a prescribed seasonal cycle of SSTs and sea-ice thickness. These experiments reveal that 1) the previously identified multidecadal THC variations can be largely viewed as an oceanic response to surface flux forcing from the atmosphere model, although air–sea coupling through the thermodynamics appears to modify the amplitude of the variability, and 2) variations in heat flux are the dominant term (relative to the freshwater and momentum fluxes) in driving the THC variability. Experiments driving the ocean model using either high- or low-pass-filtered heat fluxes, with a cutoff period of 20 yr, show that the multidecadal THC variability is driven by the low-frequency portion of the spectrum of atmospheric flux forcing. Analyses have also revealed that the multidecadal THC fluctuations are driven by a spatial pattern of surface heat flux variations that bears a strong resemblance to the North Atlantic oscillation. No conclusive evidence is found that the THC variability is part of a dynamically coupled mode of the atmosphere and ocean models.

1. Introduction

The thermohaline circulation (THC) in the North Atlantic Ocean plays an essential role in the maintenance of the current climate. Warm, salty water from tropical and subtropical latitudes is transported northward to relatively high latitudes. The cold near-surface atmosphere at these latitudes is very effective at extracting heat from the water, thereby allowing the water to cool, increase in density, and sink. The water then flows equatorward at depth as North Atlantic Deep Water. This process contributes to the total oceanic poleward heat transport (on the order of 1 PW at 24°N; Hall and Bryden 1982).

Variations in the intensity of the THC are of substantial importance for the climate of the North Atlantic region. Recent studies (Manabe and Stouffer 1994; Haywood et al. 1997; Wood et al. 1999) have suggested that the THC will weaken in response to enhanced precipitation at high latitudes associated with global warming. This weakening might partially offset the warming effects of enhanced greenhouse gases over parts of the North Atlantic region.

There may also be variations of the THC as part of the spectrum of natural climate variability. Modeling studies have suggested (Delworth et al. 1993, hereinafter referred to as DMS93; Delworth et al. 1997; Timmermann et al. 1998; Capotondi and Holland 1998) that there may be variations in the intensity of the THC with a distinct multidecadal timescale. In particular, DMS93 analyzed an extended integration of a coupled model developed at the Geophysical Fluid Dynamics Laboratory (GFDL) and showed the presence of distinct variability in the North Atlantic THC with a timescale of approximately 40–80 yr. This THC variability was related to large-scale anomalies of sea surface temperature (SST), sea surface salinity (SSS), and surface density in the North Atlantic.

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Recent observational studies (Kushnir 1994; Mann and Park 1996; Mann et al. 1998; Tourre et al. 1999; Delworth and Mann 1999) using instrumental and proxy records over the last 340 yr have shown that there exists a distinct oscillatory pattern of variability in the real climate system with a timescale of approximately 50–100 yr. The associated spatial pattern is hemispheric in scale, but with particular emphasis in the Atlantic region. While the mechanism of such variability in the real climate system is not known, it is certainly plausible that variations in oceanic circulation such as those in DMS93 and the current study may play a substantial role.

It is the intent of this paper to serve as a continuation of DMS93 by asking the following questions regarding the nature of the simulated THC variability: 1) Is the multidecadal THC variability reported in DMS93 part of a coupled air–sea mode? In the context of this paper, a coupled air–sea mode refers to a spatial pattern of variability, often associated with a distinct timescale, in which the large-scale state of the ocean (SST) affects the large-scale state of the atmosphere in such a way as to feed coherently back onto the ocean. In such a framework, the quasi-oscillatory behavior of the system cannot exist without the large-scale (two-way) coupling between the ocean and the atmosphere. The El Niño–Southern Oscillation (ENSO) phenomenon is a prominent example of such a coupled air–sea mode. 2) Is the THC variability simply the ocean model's response to atmospheric flux forcing, without any large-scale (two-way) coupling? This possibility could include a damped oceanic mode of variability, either self-sustained or continuously excited by atmospheric forcing (Weaver and Sarachik 1991a; Greatbatch and Zhang 1995). If atmospheric flux forcing is sufficient to generate the variability without large-scale coupling, then what timescales in the atmospheric forcing are important for driving the THC variability? In particular, is the THC variability driven primarily by the low-frequency, interdecadal variability inherent to the atmosphere model, or does the synoptic, high-frequency variability play a role in driving the THC variability? 3) What are the relative roles of the heat, water, and momentum fluxes in driving the THC variability?

To address these questions a number of experiments are conducted with an ocean model extremely similar to the ocean component of the coupled model used in DMS93. The ocean model is forced with time series of annual mean flux anomalies chosen to address the above questions. The results will demonstrate that the THC variability in DMS93 can be largely thought of as the oceanic response to low-frequency surface heat flux forcing from the atmosphere model, modified by local air–sea thermodynamic coupling.

2. Model and experimental design

a. Coupled ocean–atmosphere model

The coupled model used in DMS93 was formulated based on the Bryan–Cox ocean model coupled to an atmospheric general circulation model, and is described in detail by Manabe et al. (1991, 1992). Subsequent to that study an updated coupled model was developed at GFDL that incorporated a version of the Modular Ocean Model (Pacanowski et al. 1991) as its oceanic component. This new coupled model behaves similarly to the older coupled model, although the mean overturning circulation in the North Atlantic in the new model (14 Sv; 1 Sv $\equiv 10^6$ m^3 s^{-1}) is approximately 3 Sv weaker than in the older model. An extended integration of the new model also has multidecadal variations of the THC. This newer coupled model serves as the starting point for the current investigation.

The coupled model is global, with realistic geography consistent with resolution. The model is forced with a seasonal cycle of insolation at the top of the atmosphere. The atmospheric component is an R15 spectral model, with an effective horizontal resolution of approximately 4.5° lat × 7.5° long. There are nine 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 4.5° lat × 3.7° long. Oceanic convection is parameterized as in Cox (1984), with six iterations. In this scheme, if the density in a pair of overlying grid boxes is hydrostatically unstable, the vertical diffusivity is increased to a large value, and the process repeated iteratively. The model atmosphere and ocean interact through fluxes of heat, water, and momentum at the air–sea interface. To reduce climate drift, adjustments to the model-calculated heat and water fluxes are applied at the air–sea interface. These flux adjustments are derived from preliminary integrations of the separate atmospheric and oceanic components [see Manabe et al. (1991) for details].

b. Ocean-only experiments

It is difficult to address the questions posed in the introduction by simply analyzing the output from a coupled model. Since all processes are inherently coupled, the establishment of causality is problematic. Therefore, we make use of additional appropriately designed experiments in which the oceanic component of the coupled model is driven by time series of surface fluxes. These fluxes are derived both from the integration of the coupled model and from an integration of an atmospheric model with a prescribed seasonal cycle of SSTs and sea-ice thickness. By suitably designing the fluxes to be used in each experiment (as discussed below), we can address the questions posed in the introduction.

All model parameters in the ocean-only experiments are identical to those in the coupled model. Sea-ice thickness, however, is restored to climatology in the ocean-only runs with a 50-day restoring timescale. This constraint helps to reduce model drift.

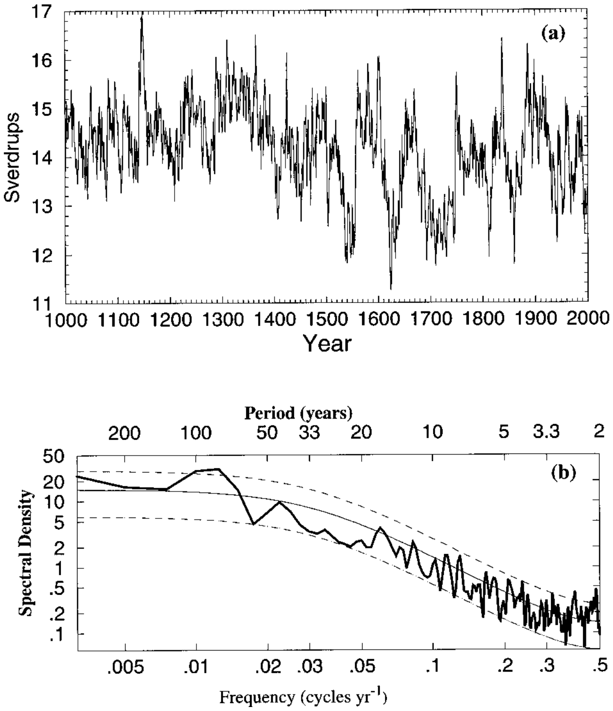

FIG. 1. (a) Time series of the intensity of the THC in the model North Atlantic (referred to as the THC index). The intensity is defined for each year as the maximum of the meridional overturning streamfunction between 20° and 90°N. Units are Sverdrups (Sv). The streamfunction field is computed each year from annual mean meridional velocities zonally averaged over the Atlantic basin. (b) Fourier spectrum of the time series in (a). The spectrum was computed by taking the Fourier transform of the lagged autocovariance function, using a Tukey window and a maximum of 200 lags. The heavy, solid line denotes the spectrum; the thin, solid line denotes a fit of a red noise (first-order Markov) process to that spectrum; the dashed lines denote the 95% confidence interval about the red noise spectrum.

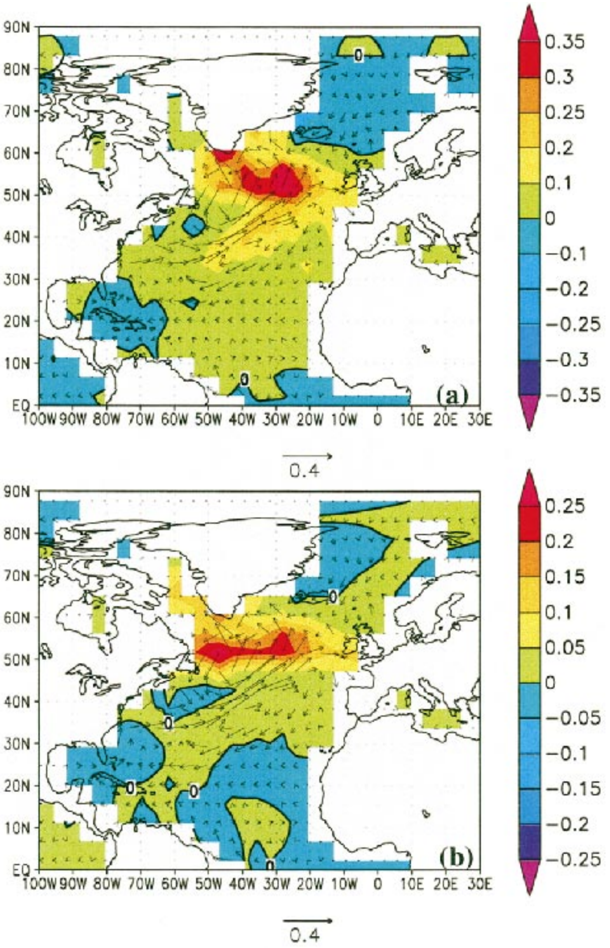

FIG. 2. Linear regression coefficients between various fields and the time series of the THC. These maps may be interpreted as anomalous conditions associated with a 1 Sv increase in the THC intensity. (a) Regressions between SST (color shading), currents at 85-m depth (vectors), and the THC. Units are °C Sv^{-1} for SST and cm s^{-1} Sv^{-1} for currents. (b) Same as (a) but using SSS instead of SST. Units are PSU Sv^{-1} for SSS and cm s^{-1} Sv^{-1} for currents.

3. Synopsis of THC multidecadal variability in the fully coupled model

Before presenting results from the ocean-only experiments, we briefly summarize the characteristics of the multidecadal THC variability present in the fully coupled model. The time series of the THC (defined as the maximum value of the annual mean streamfunction in the North Atlantic between 20° and 90°N) is shown in Fig. 1a over years 1001–2000 of an extended control integration of the coupled model. There are substantial variations of the THC around the long-term mean of approximately 14 Sv. The characteristics of the time series are seen to vary. After approximately year 1300 there are substantial multidecadal THC variations, while prior to year 1300 the THC variations have a somewhat shorter timescale. A Fourier spectrum analysis of this time series (shown in Fig. 1b) shows a broad peak at a timescale of approximately 70–100 yr, generally consistent with the results of DMS93, although the spectral peak is shifted to slightly longer timescales. It is important to note, however, that the amplitude and frequency of this variability are modulated on very long timescales. Indeed, there are multicentury periods where this variability is very weak. Such multicentury modulation of decadal and multidecadal variability is a crucial aspect to consider in the interpretation of any climate-related time series.

To define the spatial patterns of various quantities related to the THC fluctuations, linear regressions are computed at each grid point between the time series of various quantities and the THC time series. These regressions are of the form $y = ax + b$, where "x" is the THC time series, and "y" can be SST, SSS, or near-surface currents. Shown in Fig. 2a are the simultaneous regression coefficients of SST and near-surface currents versus the time series of the THC. The plotted quantities are the slopes of the regression lines ("a" in the terminology above), and may be interpreted as the anomalous conditions at a time when the THC is 1 Sv larger than its climatological mean. The pattern resembles that in Figs. 6 and 18 of DMS93, and shows the large-scale anomalous SST and near-surface current structure associated with the THC variations. There is a broad warming in the North Atlantic associated with the enhanced North Atlantic Drift. The SST anomaly pattern bears a distinct resemblance to observational analyses [see Fig. 5 of Kushnir (1994)]. The regressions for SSS and surface currents are shown in Fig. 2b. Positive salinity anomalies cover a large region of the midlatitudes of the North Atlantic, and contribute to positive near-surface density anomalies (not shown; see Fig. 12 of DMS93) in the deep water formation regions of the North Atlantic (approximately 50°–70°N). These positive near-surface density anomalies contribute to the generation of an enhanced THC.

Recently, multidecadal THC variability in the North Atlantic has been reported in multicentury integrations of two other coupled ocean–atmosphere models. Timmermann et al. (1998) show distinct multidecadal THC variations in a version of the coupled model in use at the Max Planck Institute. The variations in their model have a somewhat shorter timescale (30–35 yr) than those in the GFDL model, but the spatial structure is very similar. In addition, Capotondi and Holland (1998) have suggested that the Climate System Model has distinct multidecadal variations of the THC in an extended control integration. The existence of similar THC variability in other models suggests that this type of variability is not particularly sensitive to the model formulation.

4. Is the THC variability in the GFDL model a ‘‘coupled’’ mode?

a. Suitability of ocean-only experiments

It was suggested in DMS93 that the multidecadal THC fluctuations arose as an oceanic mode of variability stimulated by ‘‘nearly random surface buoyancy forcing of heat and water fluxes.’’ Subsequently, Griffies and Tziperman (1995) used a four-box model of the North Atlantic to demonstrate that THC variability similar to that in the coupled model could be excited by white noise surface heat flux forcing. It is difficult to confirm this speculation within the context of a fully coupled model, however, since all processes are inherently coupled. To evaluate this speculation, we have conducted a suite of experiments using the ocean component of the coupled model driven by suitably chosen time series of surface flux forcing.

All experiments use a seasonal cycle of climatological mean surface fluxes and flux adjustments from the coupled model. In addition, most experiments also impose a time series of annual mean surface flux anomalies derived from either the coupled model or an accompanying integration of an atmosphere-only model. The nature of the flux anomaly time series, as discussed below, allows us to evaluate the role of the atmosphere in generating the THC variability. Note that this design excludes forcing variability at timescales less than the seasonal cycle. In all experiments sea-ice thickness is restored to an observed climatology with a timescale of 50 days. This is the only restoring condition in the model.

TABLE 1. List of experiments.

Experiment name	Characteristics
COUPLED	Output from fully coupled ocean–atmosphere model.

The experiments listed below all consist of the ocean component of the coupled model forced at the air–sea interface with a repeating seasonal cycle of surface fluxes (heat, water, and momentum) and flux adjustments (heat and water) produced by the coupled model. Sea ice is restored to an observed seasonal cycle with a 50-day restoring time. In addition, various time series of annual mean surface flux anomalies are applied to the ocean model (except experiment CLIM). The different characteristics of those annual mean flux anomalies differentiate the experiments below, and are chosen to explore the characteristics of the multidecadal variability. The experiment names are designed to reflect the characteristics of the annual mean surface flux anomalies applied in each experiment. All experiments below are 400 yr in length.

Experiment name	Annual mean flux anomalies applied to model:
CLIM	No interannual flux anomalies applied.
TOTAL	Annual mean flux anomalies of heat, water, and momentum from the coupled model are applied in the same time sequence as they occurred in the coupled model.
RANDOM	Same as TOTAL, except that the sequence in which the fluxes are applied to the model is random. For each model year, flux anomalies from a randomly selected year from the coupled model output are applied to the ocean model.
ATMOS	Annual mean flux anomalies of heat, water, and momentum, derived from an extended integration of an atmosphere-only model with a repeating seasonal cycle of prescribed SSTs and sea ice, are applied to the ocean model.
HEAT	Same as TOTAL except that only heat flux anomalies are applied.
WATER	Same as TOTAL except that only water flux anomalies are applied.
MOMENTUM	Same as TOTAL except that only momentum flux (wind stress) anomalies are applied.
HEAT_LP	Same as HEAT except that the time series of annual mean heat flux anomalies is subjected to a low-pass filter (effectively removing timescales shorter than approximately 20 yr) prior to forcing the ocean model.
HEAT_HP	Same as HEAT, except that the time series of annual mean heat flux anomalies is subjected to a high-pass filter (effectively removing timescales longer than approximately 20 yr) prior to forcing the ocean model.

The suite of experiments is listed in Table 1. The names of the experiments are designed to denote the source of the flux anomalies used to force the ocean model. The time series of the surface flux anomalies can come either from the extended control integration of the coupled model or an integration of the same atmospheric model as the coupled model but with a prescribed seasonal cycle of SSTs and sea-ice thickness. All model integrations are started from the oceanic conditions at the end of year 1440 from the control integration. This is near the beginning of a multicentury period (see Fig. 1a) in which the multidecadal THC fluctuations are energetic. The time series of fluxes extracted from the coupled model cover the period from year 1441 to 2000.

It should be noted that in some of our experiments (notably RANDOM and ATMOS) there is no damping of SST anomalies through the surface heat flux term, since the surface heat flux is specified independently of SST. The absence of this damping, however, does not induce a substantial model drift (as shown by the results below, at least over the course of the 400-yr integrations conducted). The restoration of sea-ice thickness to a climatological seasonal cycle provides an effective large-scale damping on the system. Negative (or positive) SST anomalies at higher latitudes will create positive (negative) anomalies of sea-ice thickness. As the sea-ice thickness is restored to climatology, heat is effectively added to (removed from) the system. In addition, explicit diffusion damps small-scale SST anomalies, and the advection of heat by the time-varying three-dimensional oceanic circulation also serves to effectively mix locally generated heat anomalies. Thus, the lack of surface heat flux damping does not hinder the utility of this experimental design in answering the questions posed in the introduction.

In the first experiment (CLIM) the ocean model is run with only the climatological seasonal cycle of surface fluxes (i.e., no interannual variability). The flux adjustment terms are also included (as is the case for all the experiments). Shown in Fig. 3 is the THC time series from this experiment (thin, solid line) as well as the THC from the coupled model. There is virtually no variability of the THC in experiment CLIM, demonstrating that some atmospheric variability is needed to excite the multidecadal variability in this particular model. CLIM shows that the THC variability in the coupled model is not a self-sustained oscillation under constant surface flux forcing, as in the ocean models of Greatbatch and Zhang (1995) and Chen and Ghil (1995). We have also run an experiment that is the same as CLIM, except that an additional term is added that restores the surface temperature back to the seasonally varying climatological SST of the coupled model. The timescale for the relaxation is 50 days, the same as used in the spinup of the ocean model prior to coupling. The surface boundary condition is then the same as under mixed boundary conditions (Weaver and Sarachik 1991a). Again, no self-sustained variability is found (not shown).

In experiment TOTAL the ocean model is run with the time series of annual mean surface flux anomalies (heat, water, and momentum) from the coupled model from year 1441 to 1840. This experiment reproduces very closely the THC time series from the coupled model (see Fig. 3). This result confirms that the framework of using only the ocean component of the coupled model is appropriate for analyzing the THC fluctuations. The high correlation between the ''COUPLED'' and ''TOTAL'' THC time series in Fig. 3 (0.97) suggests that flux variations on timescales less than 1 yr do not contribute substantially to the generation of the simulated multidecadal THC variability.

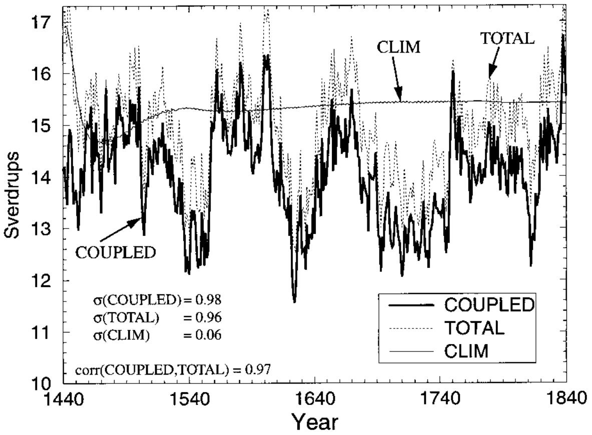

FIG. 3. Time series of annual mean THC index (Sv) from (i) the fully coupled model (thick, solid line, COUPLED), (ii) an independent run of the ocean component of the coupled model forced with the complete time series of annual mean flux anomalies from the coupled model (dashed line, TOTAL), and (iii) an additional run of the ocean component of the coupled model with no interannual variation of surface flux anomalies (thin, solid line, CLIM). See Table 1 for a more complete description of each of the experiments.

It should be noted that the time series of annual mean flux anomalies imposed in experiment TOTAL (and other experiments listed in Table 1) is discontinuous from one year to the next. The imposed flux anomaly is constant from 1 January to 31 December, after which it is changed to a new value for the next year. The fact that experiment TOTAL reproduces so well the behavior of experiment COUPLED suggests that the discontinuity from one year to the next in the flux anomalies does not detract from the experiments.

There is an initial jump in the THC after the start of the experiment. This jump is related to the imposition of the restoring conditions on sea-ice thickness. At this time in the fully coupled model integration the simulated sea ice was greater than observed in the northwest Atlantic. The restoration condition removed this sea ice, effectively removing freshwater from the system. As additional heat is removed from the ocean, sea-ice is formed, and upper-ocean salinity is increased through brine rejection. Any ice formed greater than observed is removed, but the increased salinity from brine rejection remains behind. This process effectively increases the density of the near-surface water, thereby enhancing the THC. This transient increase in the THC, however, lasts for only one decade. It is indeed somewhat re-

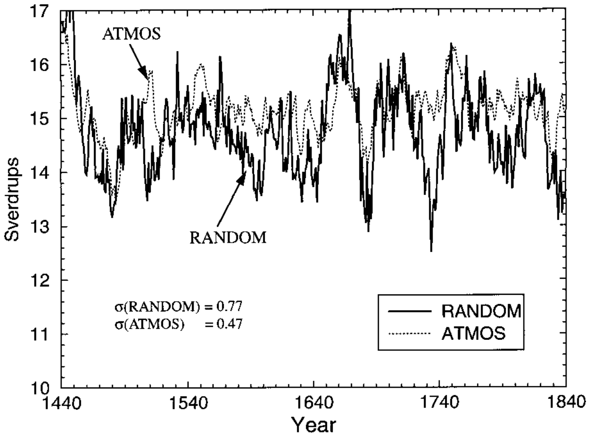

FIG. 4. Time series of THC from (i) ocean model driven by annual mean flux anomalies selected randomly from the coupled model output (solid line, RANDOM), and (ii) ocean model driven by annual mean flux anomalies from an extended run of an atmosphere-only model with a prescribed seasonal cycle of SSTs and sea ice (dashed line, ATMOS).

markable that experiment TOTAL is able to track the fully coupled model so well after this transient effect dissipates. There is, however, a persistent offset whereby the THC from experiment TOTAL remains approximately 1 Sv greater than the THC in the coupled model.

b. Assessment of large-scale coupling

The results in experiment TOTAL demonstrated that the THC variability may be driven in this ocean-only model using fluxes from the coupled model. We would like to evaluate to what degree the THC variability is a manifestation of a coupled air–sea mode. As described in the introduction, we regard a coupled mode as variability arising from a process in which the state of the ocean (SST) strongly influences the large-scale state of the atmosphere, which in turn feeds back coherently upon the state of the ocean. To evaluate whether the THC variability arises as part of a coupled mode, an additional experiment (RANDOM) is performed. For each year of this integration, annual mean surface flux anomalies are extracted from a randomly selected year of the coupled model integration (over the period from year 1441 to year 2000) and applied to the ocean model. In this manner there can be no correlation between the state of the ocean and the anomalous surface fluxes. This effectively precludes the existence of a coupled mode as described above (in which the state of the ocean influences the large-scale state of the atmosphere, and hence the air–sea fluxes). The THC time series from this experiment is shown in Fig. 4. This new THC time series is clearly independent from that in COUPLED or TOTAL, and yet it is also characterized by multidecadal fluctuations. This result clearly demonstrates that multidecadal THC variability can be generated without the presence of a coupled air–sea mode (in the sense described above).

There are, however, differences in the character of the THC time series between experiment COUPLED and RANDOM. In particular, the standard deviation of the THC time series from experiment RANDOM is 0.77 Sv, rather less than that in TOTAL (0.96 Sv) or COUPLED (0.98 Sv). Since the variance of the surface flux forcing is virtually identical to that in COUPLED or TOTAL, the difference may be due to air–sea feedbacks prohibited in RANDOM, an issue discussed further in section 4d.

It is also possible that some of the differences between RANDOM and COUPLED are due to the effects of large-scale ocean–atmosphere coupling. For example, Delworth et al. (1997) suggested that there may be atmospheric circulation changes in response to SST and sea-ice anomalies in the Greenland Sea. These are related to multidecadal fluctuations in the simulated East Greenland current and associated variations of sea-ice and freshwater export from the Arctic, which are in turn related to variations in the THC. The fundamental point, however, is that such large-scale coupling is not essential to the existence of the multidecadal THC variability. Such coupling does, however, modify that variability.

In experiment RANDOM there is no correlation between the state of the ocean and the anomalous surface fluxes, and we can conclude that the THC variability in RANDOM is not associated with a self-sustained oscillation of the type associated with mixed boundary conditions (Weaver and Sarachik 1991a,b) or sea-ice [Yang and Neelin 1993; Zhang et al. 1995; the reader is referred to Greatbatch and Peterson (1996) for further discussion]. We shall argue in section 4d that air–sea feedbacks, such as those that drive self-sustained oscillations under mixed boundary conditions, appear to play a role in leading to the difference in amplitude of the THC variability between COUPLED and RANDOM, but that the associated air–sea feedbacks are not fundamental to the oscillation in COUPLED.

At this point it is important to realize that an atmospheric model can generate its own internal low-frequency variability without the need to have dynamic coupling with the ocean (James and James 1989). Furthermore, such internally generated low-frequency variability is capable of driving significant low-frequency variability in the ocean. To illustrate this, we take the output from an extended integration of an atmosphere model (identical to the atmospheric component of the coupled model) run with a repeating prescribed seasonal cycle of SST and sea-ice thickness. The time series of annual mean surface flux anomalies from this experiment are then added to the climatological fluxes and used to drive the ocean-only model. The time series of the THC from this experiment (identified as ‘‘ATMOS’’) is also shown in Fig. 4. Note that since the SST repeats its annual cycle in this experiment, all surface flux variability is generated through processes internal to the

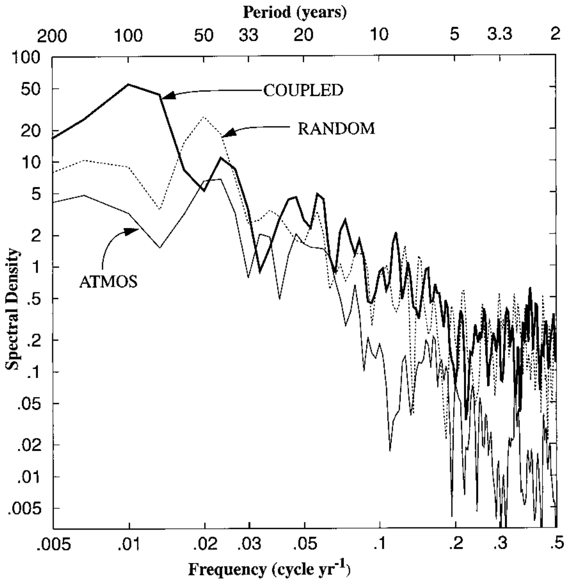

FIG. 5. Spectra of time series of THC from three experiments. The thick, solid line denotes results from the coupled model, the dashed line denotes results from experiment RANDOM, and the thin, solid line denotes results from experiment ATMOS. The spectra were computed using the Fourier transform of the lagged autocovariance function, using a Tukey window and a maximum of 150 lags. There were 400 points in each of the input time series.

atmosphere. There is clear multidecadal variability in this experiment, confirming that variability generated internally within the atmosphere model can drive significant interdecadal variability in the ocean model, and further strengthening the conclusion in the preceding paragraph concerning the nature of the variability in the coupled model. However, the amplitude of the variability is substantially smaller (the standard deviation of the THC is 0.47) in this experiment than in the previous experiments. A discussion of possible reasons for the reduction of variability is given in section 4d.

An added perspective on these results is afforded through inspection of the Fourier spectra of the THC time series (shown in Fig. 5) from the three experiments. All three spectra have a red character and are quite similar except for the offset in their amplitude. In the fully coupled model there is a peak at a timescale of approximately 70–100 yr, while there are peaks in the other two experiments at approximately 50 yr. Given the length of the model integrations (400 yr), it is debatable whether the differences in the timescales at which the peaks occur are statistically meaningful (especially when one considers the differences in terms of frequencies).

c. What are the relative roles of the various surface fluxes in exciting this variability?

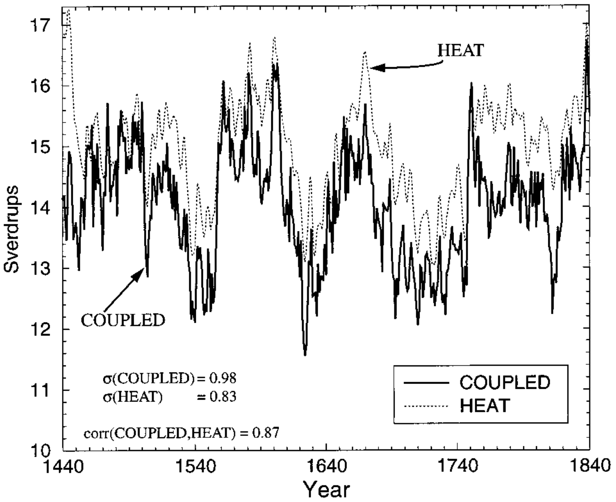

FIG. 6. Time series of THC from (i) coupled model (thick, solid line, COUPLED) and (ii) ocean model driven by time series of annual mean heat flux anomalies (dashed line, HEAT).

Given the success of the ocean-only experiment TOTAL in reproducing the THC variability from the coupled model, it is a relatively straightforward matter to evaluate the relative roles of the various flux terms in the multidecadal THC variability. Three additional experiments are conducted in which the ocean model is run with time series of surface fluxes from the coupled model. In all three experiments a repeating seasonal cycle of the climatological mean fluxes and flux adjustments is applied. In addition, for each experiment the time series of annual flux anomalies for one (and only one) of the three surface flux terms (heat, water, and momentum) is applied. In this manner, the separate responses of the THC to interannual variations in surface heat, water, and momentum fluxes are systematically evaluated.

Shown in Fig. 6 is the time series of the THC from the coupled model and the experiment in which there are only interannual variations of the surface heat flux (HEAT). It is clear that when only variations of the heat flux are applied a majority of the multidecadal variability of the THC is captured. The correlation coefficient between these two time series is 0.87. This result is consistent with Griffies and Tziperman (1995).

In contrast, the results from the experiments using only the water flux and only the momentum flux are shown in Fig. 7. The THC fluctuations in these experiments are much smaller. These results mean that fluctuations in the surface heat flux are the dominant term in generating the THC fluctuations. However, it should be noted that spectral analyses of the THC time series from experiments WATER and MOMENTUM (not shown) do show spectral peaks on the multidecadal timescale, thereby suggesting that these processes do have the potential for generating multidecadal THC variability. Their impact in this model, however, appears to be secondary to that of the heat flux variations. The relative importance of these terms may well depend on

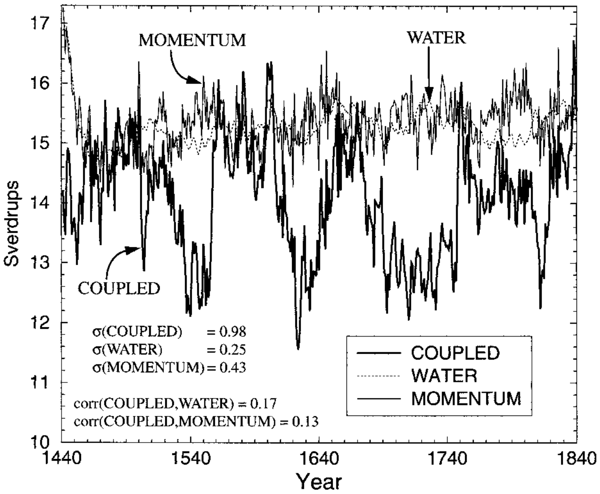

FIG. 7. Time series of THC from (i) coupled model (thick, solid line, COUPLED), (ii) ocean model driven by time series of annual mean water flux anomalies (dashed line, WATER), and (iii) ocean model driven by time series of annual mean wind stress anomalies (thin, solid line, MOMENTUM).

the mean climatology of the system, among other factors.

The relatively smaller impact of the water flux anomalies reflects the fact that the water flux anomalies have a smaller impact on surface density than heat flux anomalies over the convective region in this model. This relationship depends both on the amplitudes of the flux anomalies, as well as on the temperature of the upper ocean, since the thermal expansion coefficient of water depends on temperature. Therefore, the relative importance of these flux terms may well depend on the mean climatology of the system, and underscores the importance of simulating a realistic mean climate.

d. The role of thermodynamic feedbacks

The spectra of the THC time series from experiments COUPLED, RANDOM, and ATMOS have similar shapes (Fig. 5), but are offset in their amplitudes. To further analyze this result, we now compare the amplitudes of the fluxes driving the different experiments. Since the THC variability is primarily driven by the surface heat flux, we concentrate on the surface heat flux alone. Figure 8 shows the standard deviation of the annual mean flux anomalies from both the coupled model and the atmosphere-only model, and also their ratio. (Note that the interannual flux anomalies in COUPLED and TOTAL are identical—see Table 1.) Over most of the North Atlantic, the ratio is less than one, indicating that the annual mean surface heat flux variability used to drive experiment ATMOS is greater than that from the coupled model, despite the fact that the amplitude of computed THC variability is less in ATMOS than in COUPLED. This result is consistent with the work of Barsugli and Battisti (1998). These authors used a simple, stochastically forced, one-dimensional, thermodynamically coupled model and found that the amplitude of the surface flux variability is reduced by coupling. This result is actually quite similar to that found by Zhang et al. (1993) in the context of an ocean-only model. In ocean-only or atmosphere-only models that are run with either a strong restoring boundary condition on the SST or specified SST, the surface boundary condition forces the surface temperature to remain close to the specified SST by continually changing the surface heat flux. In the coupled system, the SST is less tightly constrained and the surface heat flux variability is less. This is what happens over most of the ocean when we compare COUPLED with ATMOS.

In Fig. 8c, there is one conspicuous exception to the Barsugli and Battisti result. This is the deep convection region, south and east of Greenland, where the amplitude of the surface heat flux variability is greater in COUPLED than it is in ATMOS. We attribute this departure from Barsugli and Battisti (1998) to the fact that in the deep convection area, where the density stratification is weak to considerable depth, it is possible to store heat in the water column during times when deep convection is inhibited. During such times the deep convection region is capped by freshwater. The heat stored is subsequently released when the atmospheric cooling is strong enough to punch through the freshwater cap, a process analogous (but on a much smaller scale) to the ''flush'' events that have been noted in ocean-only models run under mixed surface boundary conditions (Marotzke 1989; Weaver and Sarachik 1991b). Such a scenario may have taken place in the Labrador Sea at the time of the Great Salinity Anomaly [see Dickson et al. (1996) for a more detailed discussion]. In the late 1960s, the Great Salinity Anomaly was present in the Labrador Sea, and the North Atlantic oscillation (NAO; Hurrell 1995) was in a low index phase. Surface winds over the Labrador Sea were relatively light, leading to reduced surface heat loss compared to normal and no significant deep convection events. Deep convection was renewed in the severe winter of 1972, when the NAO index was high and surface heat loss, associated with outbreaks of cold, dry continental air from Labrador, became sufficient to break through the freshwater capping the Labrador Sea.

We suggest that the greater surface heat flux variance in the deep convection region in COUPLED compared to ATMOS explains the greater amplitude of the THC variability in the former. We suggest that a similar explanation can account for the increase in the amplitude of the THC variability from RANDOM to COUPLED because in RANDOM the air–sea feedbacks invoked in the previous paragraph do not operate. In particular, heat stored in the ocean during times when deep convective activity is reduced cannot be released to the atmosphere when deep convection is reactivated. This is because in RANDOM the surface heat flux is imposed on the ocean model and knows nothing of the state of the ocean and, in particular, the surface salinity and the presence or otherwise of a freshwater cap.

The spectra of the heat flux time series, averaged over the convective region of the coupled model, are shown in Fig. 9. There is a clear peak on the multidecadal timescale in the spectrum from experiment COUPLED, consistent with the multidecadal variability in the THC. This peak is partially attributable to the multidecadal variations in SST, since the air–sea heat fluxes depend on SST in the coupled model. What is critical, however, is that there is no such peak in the forcing spectrum for experiments RANDOM and ATMOS. The spectra for both experiments RANDOM and ATMOS are essentially white for all timescales greater than 2 yr. In both cases, there is still a multidecadal peak in the THC spectrum (see Fig. 5) without any such peak in the forcing time series. Thus, in response to the white noise forcing time series in RANDOM and ATMOS, which have equal variance at all timescales longer than 2 yr, the model ocean produces THC variability with a distinct multidecadal timescale. While the spectra of ATMOS and RANDOM look quite similar (in part because of the use of logarithmic axes), there is a systematic bias of ATMOS toward lower spectral values, consistent with the substantially smaller variance of the surface heat flux in ATMOS over the convective regions (see Fig. 8c).

While the time series of surface heat flux forcing for RANDOM and ATMOS are uncorrelated in time (as indicated by the spectra in Fig. 9), it is important to note that the fluxes have distinct spatial structures. Linear regressions were computed between the time series of surface heat flux and wind stress versus the THC for experiments COUPLED, RANDOM, and ATMOS (the technique is the same as described in section 2, with the exception that the time series can be lagged with respect to the THC time series). Shown in Fig. 10 are the regression maps, with the heat flux and wind stress leading the THC by 3 yr—this is the time at which the regressions are a maximum. The dominant pattern of heat flux variations associated with the THC variability is quite similar to the pattern of heat flux anomalies associated with the North Atlantic oscillation (NAO). The wind stress regressions are also shown, indicating the anomalous atmospheric circulation field that resembles the NAO. Note that this atmospheric flow (for COUPLED and RANDOM) is consistent with the inferred flow indicated by the sea level pressure regression shown in DMS93 (see Fig. 20 of DMS93). This NAO-like pattern corresponds to the dominant pattern of atmospheric variabilility diagnosed in both the coupled model and the atmosphere only model (Delworth 1996). While the regression pattern for experiment ATMOS does not correspond precisely to that in COUPLED and RANDOM, the enhanced ocean-to-atmosphere surface heat fluxes over the oceanic convective region south of Greenland is present, along with enhanced westerly winds at midlatitudes. Thus, one can speculate that low-frequency fluctuations in the NAO may have a profound influence on generating multidecadal THC variability. However, the regression patterns at other lags are not as closely related to the NAO, suggesting that atmospheric variability other than the NAO does contribute to the model THC variability.

e. *Dependence of THC variability on timescale of flux forcing*

It has been shown above that the THC variability can be excited by white noise (in time) heat flux forcing. Griffies and Tziperman (1995) suggested that the THC variability in the GFDL coupled model was a damped eigenmode excited by white noise (stochastic) atmospheric forcing. In such a framework, the eigenmode responds preferentially (resonantly) to some limited frequency range in the spectrum of forcing. We can explicitly examine this possibility by filtering the time series of the surface fluxes prior to forcing the ocean model. Thus, two additional experiments are conducted in which only the time series of heat flux forcing (from the coupled model) is used to force the model. In experiment HEAT_LP (HEAT_HP), the heat flux time series is first filtered such that all timescales shorter (longer) than approximately 20 yr are effectively removed. The ocean models are then integrated for 400 yr, and the respective THC time series are shown in Fig. 11. It is clear that the high frequencies (timescales shorter than 20 yr) contribute very little to the THC variability, which instead is driven by the low-frequency portion of the spectrum of heat flux forcing. This is also an indication of the essential linearity of this variability in the ocean model.

5. Summary and discussion

Delworth et al. (1993) showed that multidecadal variability in the thermohaline circulation (THC) of the North Atlantic was simulated in an extended control integration of the GFDL coupled climate model. The current paper is an extension of DMS93 in evaluating whether the multidecadal variability simulated in that experiment can be interpreted as a fundamentally coupled air–sea mode (in the sense of ENSO), or as a response of the ocean model to atmospheric surface flux forcing. The latter possibility could include a damped oceanic mode of variability, either self sustained or continuously excited by atmospheric forcing (Weaver and Sarachik 1991a; Greatbatch and Zhang 1995).

A suite of integrations is performed using only the oceanic component of the coupled model driven by time series of surface fluxes both from the coupled model and from a separate extended integration of the atmospheric component of the coupled model with a prescribed seasonal cycle of SSTs and sea-ice thickness.

Substantial THC variability on multidecadal timescales is excited in the ocean model using fluxes derived

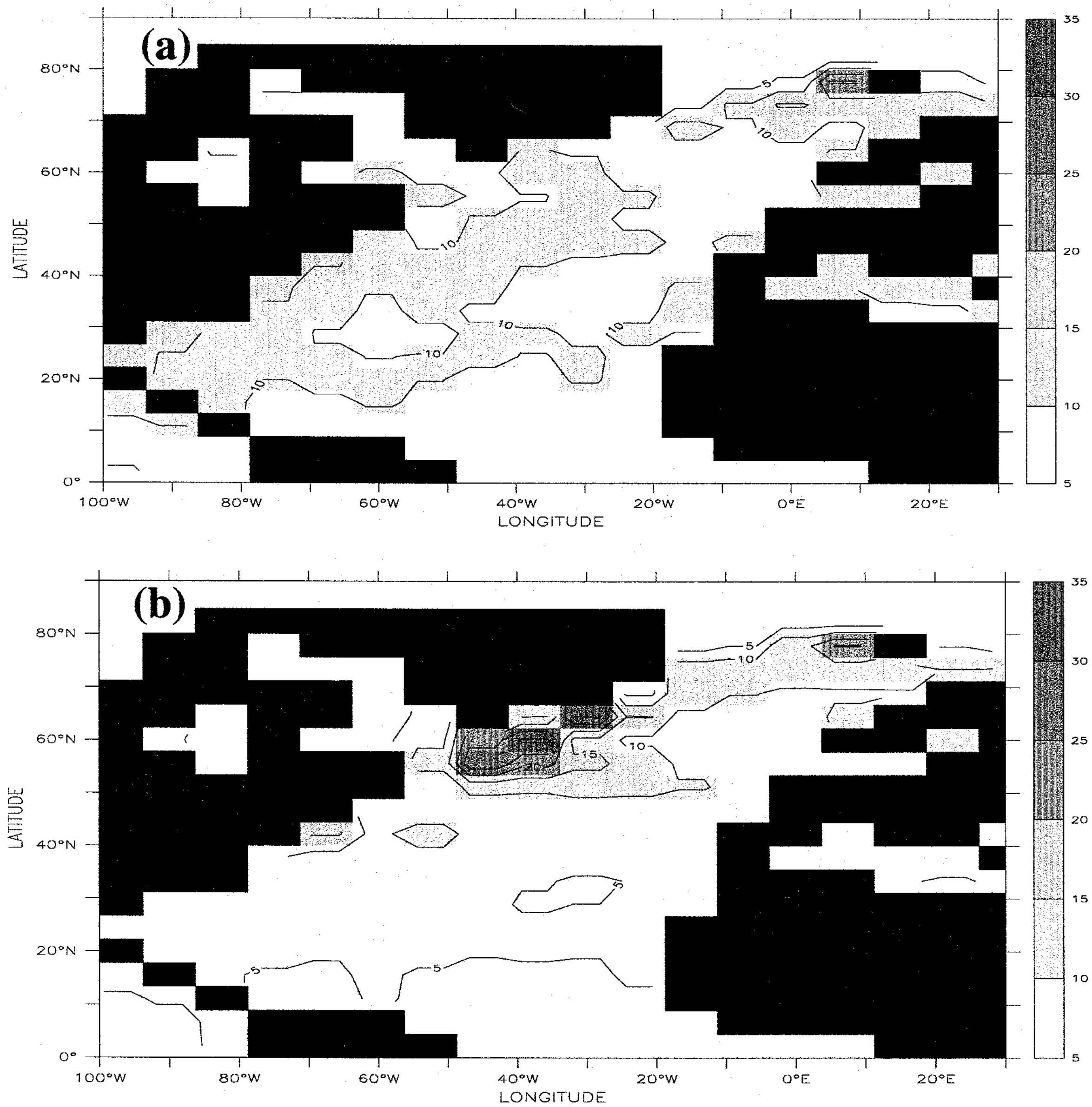

FIG. 8. (a) Standard deviation of annual mean flux from the atmospheric model run with a prescribed seasonal cycle of SSTs and sea ice. Units are W m^{-2}. (b) Standard deviation of annual mean heat flux from the coupled model. Units are W m^{-2}.

from the coupled model but selected randomly in time (denoted as experiment RANDOM). In this manner, the surface fluxes do not depend on the state of the ocean. This demonstrates that a substantial fraction of the multidecadal THC variability can be generated in the absence of a strong coupled air–sea mode (like ENSO). The forcing in this experiment also eliminates local air–sea feedbacks such as are associated with ocean-only oscillations found under mixed boundary conditions (Weaver and Sarachik 1991a,b) or sea ice (Yang and Neelin 1993; Zhang et al. 1995). In addition, the ocean model driven by fluxes from an atmosphere model run with a prescribed seasonal cycle of SSTs and sea-ice thickness (denoted as experiment ATMOS) also excites multidecadal THC variability, although with a reduced amplitude.

The analyses presented in this paper suggest that the THC variability in DMS93 does not depend critically on the existence of a coupled air–sea mode (as defined in the introduction). Rather, our results support the view that the THC variability is driven by low-frequency variability generated internally within the atmospheric model. There is evidence, however, that air–sea coupling can modify the amplitude and timescale of the THC variability in the GFDL model. We suggest, for example, that local air–sea coupling through the thermodynamics

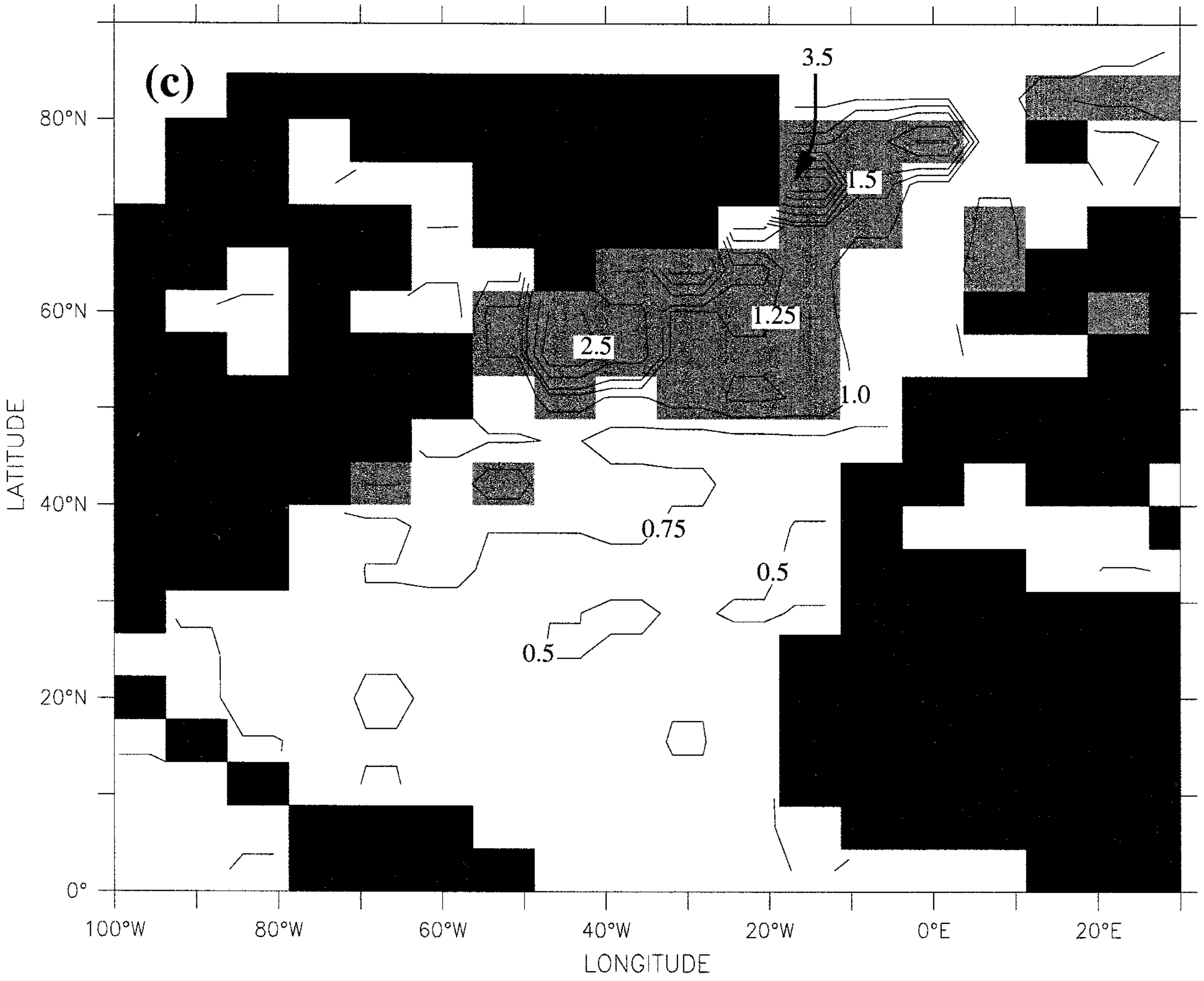

FIG. 8. (*Continued*) (c) Ratio of standard deviation of annual mean surface heat flux in the coupled model to that from an atmosphere-only model. Regions where this ratio is greater than 1.0 (indicating a larger standard deviation in the coupled model than in the atmosphere-only model) are denoted by gray shading and typically correspond to oceanic convective regions. Contour interval is 0.25 from 0 to 1.5, and 0.5 for values greater than 1.5.

accounts for the enhanced amplitude of the THC variability in the coupled model in comparison with that driven by fluxes from the uncoupled atmosphere model. Timmermann et al. (1998) suggest that the THC variability in their coupled model at the Max Planck Institute (MPI) is indeed related to a coupled air–sea mode. It appears that the THC variability in the GFDL and MPI models may be rather similar in nature, but with differences that result from differing responses of the model atmosphere to extratropical SST anomalies.

The presence of extratropical air–sea coupled modes depends to a large extent on the nature and magnitude of the response of the atmosphere to SST and sea-ice anomalies. A number of studies using the atmospheric component of the GFDL coupled model (see Kushnir and Held 1996) have shown a relatively small response of the atmosphere to midlatitude SST anomalies. In contrast, coupled models in which the atmosphere responds more strongly to midlatitude SST anomalies (as in the atmospheric component of the coupled model used by Timmermann et al. 1998) may contain modes of variability in midlatitudes that depend to a greater degree on large-scale air–sea coupling. It is thus a central issue to achieve a better understanding of the nature of the atmospheric response to midlatitude SST anomalies.

While the THC variability in the GFDL and MPI coupled models may have somewhat different mechanisms, there are nonetheless substantial similarities in the spatial patterns of simulated SST, SSS, and SLP anomalies in the North Atlantic [e.g., compare Figs. 6 and 20 of DMS93 with Fig. 14 of Timmermann et al. (1998)]. This suggests that this pattern of variability is not critically dependent on the model formulation. Further, the observational evidence presented in Delworth and Mann (2000) demonstrates that a pattern of vari-

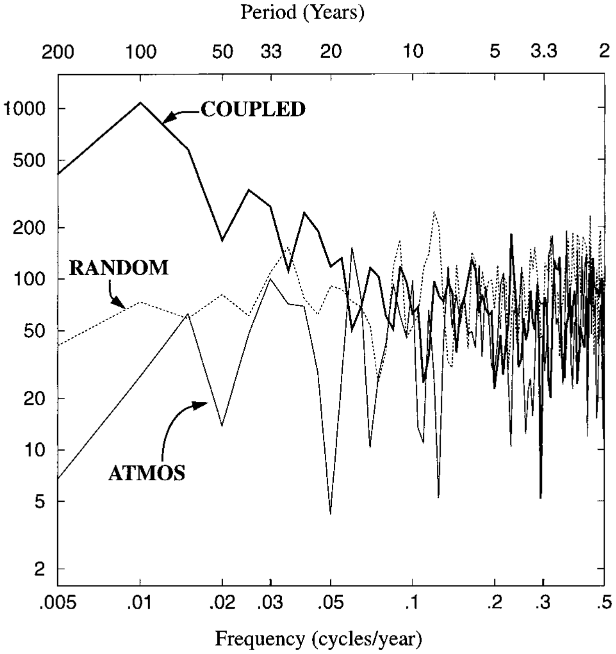

FIG. 9. Spectra of the time series of annual mean heat flux from experiments COUPLED (heavy, solid line), RANDOM (dashed line), and ATMOS (solid, thin line). The heat flux time series (400 yr in length) were averaged over the region 55°–15°W and 50°–70°N prior to the calculation of the spectra. The spectra were computed by taking the Fourier transform of the lagged autocovariance function, using a Tukey window and a maximum of 150 lags.

ability with a distinct multidecadal timescale also exists in the real climate system.

Dickson et al. (1996) have analyzed ocean observations from the North Atlantic and have related the changes in deep convective activity to the changing phase of the North Atlantic oscillation (Hurrell 1995). These authors find strong evidence of the direct impact of the changing atmospheric circulation on the underlying ocean. While their study does not rule out the existence of a dynamically coupled atmosphere–ocean mode of variability over the North Atlantic, it is consistent with our conclusion that the THC variability in the GFDL model is primarily a response to low-frequency variability generated internally within the atmosphere model.

While the surface fluxes in RANDOM and ATMOS are uncorrelated in time and have white noise spectra for timescales longer than 2 yr, there are distinct spatial structures present in the flux fields. The dominant spatial pattern of surface heat flux anomalies responsible for the multidecadal THC variations corresponds closely to the North Atlantic oscillation (NAO) for RANDOM, and somewhat less so for ATMOS. Thus, one can speculate that low-frequency fluctuations in the NAO may have a substantial influence on generating multidecadal THC variability, consistent with the observational analysis in Dickson et al. (1996).

Recently, Weaver and Valcke (1998; hereinafter referred to as WV98) reached somewhat different conclusions regarding the nature of the THC variability in the GFDL coupled model. WV98 states that ‘‘we therefore conclude that the variability found in Delworth et al. (1993) is not an ocean-only mode and is a truly coupled phenomenon.’’ The differing conclusions of the two studies can be partially attributed to the different nature of the surface flux forcing used to drive the ocean models. A comparison of the surface heat fluxes used in WV98 (kindly provided by Dr. A. Weaver) to those used in the current study showed that the standard deviations of the annual mean heat fluxes in WV98 were approximately an order of magnitude smaller than those in the current study over the convective regions of the North Atlantic. Thus, the smaller THC variability seen in WV98 (see Fig. 7 of WV98) is a direct consequence of the smaller variability in the surface heat flux forcing. Since the amplitude of the surface flux forcing (on annual and longer timescales) used in the current study is more representative of the flux variability felt in the fully coupled model, we feel that the results of the present paper can better address the question of whether the THC variability in DMS93 is part of a coupled air–sea mode. We agree with the conclusion of WV98 that the variability in DMS93 cannot be attributed to the existence of a self-sustaining ocean-only mode, but do not agree that the variability is therefore necessarily a fully coupled ocean–atmosphere mode.

Our results suggests that the THC variability arises from a damped mode of the ocean system, continuously excited by low-frequency atmospheric forcing. This is in agreement with the results of Griffies and Tziperman (1995), and is also consistent with the speculation in DMS93 that ‘‘the irregular oscillation is triggered by nearly random surface buoyancy forcing of heat and water fluxes.’’ In our terminology (as discussed in the introduction), this type of process is not a coupled mode, since large-scale feedback of the ocean onto the atmosphere is not a necessary condition for the existence of this variability. However, such feedbacks can clearly modify the nature of the THC variability.

The differing conclusions between the current study and WV98 also point out the differing definitions of what constitutes a ‘‘coupled’’ mode. Part of the differing conclusions between WV98 and the current study derive from different interpretations of the phrase ‘‘coupled mode.’’

The results of the current study highlight the need for improving our understanding of the nature and magnitude of the atmospheric response to extratropical SST anomalies. It is clear that this process is fundamental in affecting the spectrum of variability produced in coupled models [see the review by Latif (1998)]. Recently obtained results using a higher-resolution version of the coupled model analyzed in the current study show multidecadal variability similar in character to that in Delworth et al. (1997), and are suggestive of some degree of large-scale response of the atmosphere to high-lati-

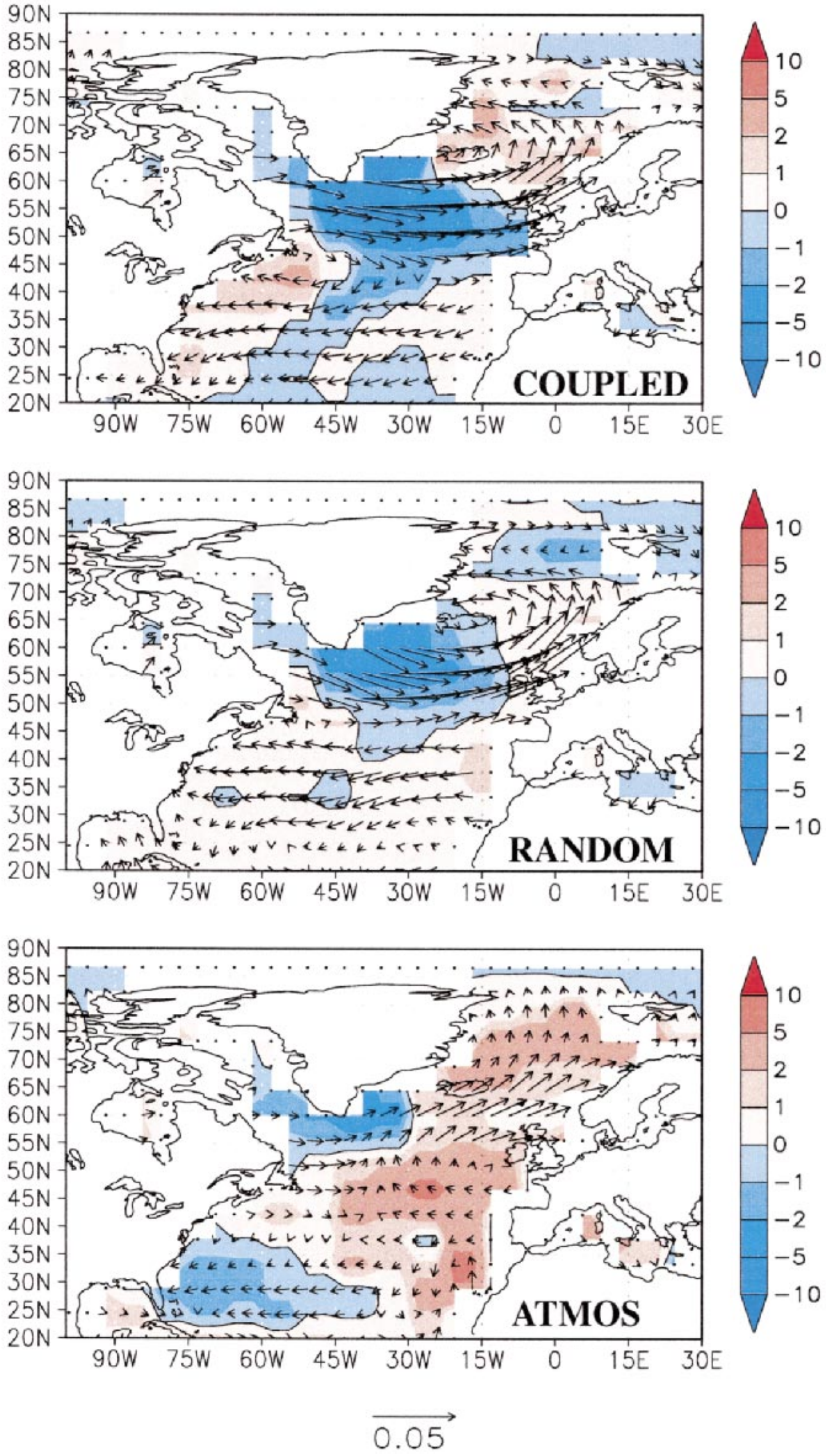

FIG. 10. Regressions of surface heat flux (color shaded, units are W m^{-2} Sv^{-1}) and surface wind stress (vectors, units are dyne cm^{-2} Sv^{-1}, magnitude indicated by the vector at bottom) vs the THC time series for a lag of −3 yr. This denotes conditions 3 yr prior to a maximum in the THC index, and corresponds approximately to the time when the flux anomalies have their largest amplitude. (a) Experiment COUPLED; (b) experiment RANDOM; (c) experiment ATMOS.

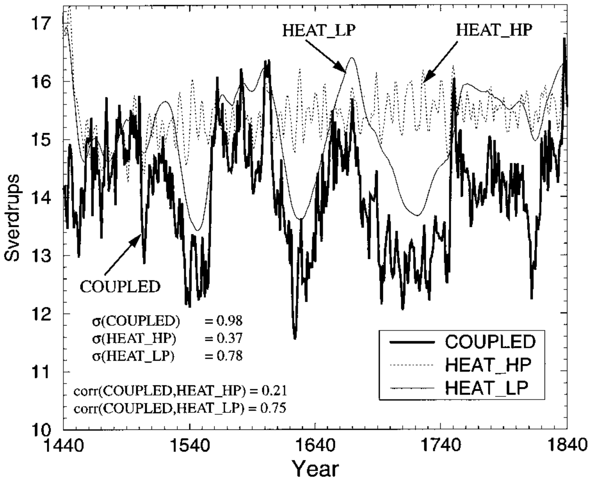

FIG. 11. Time series of THC from (i) coupled model (thick, solid line), (ii) experiment HEAT_HP (dashed line), and (iii) experiment HEAT_LP (thin, solid line).

tude SST and sea-ice anomalies. Thus, while the results of the current study demonstrate that multidecadal variability can be generated without a large-scale response of the atmospheric circulation to the state of the ocean, the results do not preclude that possibility in the real climate system.

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