The Influence of Deep Ocean Diffusivity on the Temporal Variability of the Thermohaline Circulation

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We investigate the influences of the diffusion coefficients for heat and salt in the deep ocean upon the stability of the Atlantic thermohaline circulation through a parameter space investigation that employs the GFDL Modular Ocean Model (MOM). The ocean general circulation model is configured to represent an idealized Atlantic basin and steadily (including an annual cycle) forced under the assumption of mixed boundary conditions. The impact on the results of the use of mixed boundary conditions is examined through additional sensitivity experiments to demonstrate that this choice of boundary conditions does not affect the main conclusions. The two primary sets of the experiments that we describe consist of sensitivity analyses for both horizontal and vertical diffusion coefficients; Bryan-Lewis type diffusion coefficient profiles are applied in such a way that one diffusion coefficient profile is varied while the other diffusion coefficient profile is fixed. We are thereby able to demonstrate that the choice of the horizontal diffusion coefficient plays a crucial role in determining the stability of the thermohaline circulation which is such that the thermohaline circulation exhibits very intense oscillations on a multi-millennium timescale when the horizontal diffusion coefficient of the deep ocean is set to a sufficiently small value. We demonstrate that the critical value required to realize an oscillatory solution of the thermohaline circulation lies well within the range of observed large-scale ocean diffusion coefficients, whereas the value of vertical diffusion coefficients affect not the bifurcation structure but the period of the millennial timescale oscillation.

1. INTRODUCTION

One of the most dramatic characteristics of climate variability during the last ice-age cycle is clearly that associated with the so-called Dansgaard-Oeschger (D-O) oscillation. This climate oscillation is most clearly observed as an oscillation of an ice-core derived temperature proxy, namely the oxygen isotope records based on mass spectrometric measurements on the ice cores from Summit, Greenland (e.g. GRIP, 1993; Taylor et al., 1993). The large amplitude millennium timescale oxygen isotope oscillations that are most evident during oxygen isotope stage (OIS) 3, once calibrated, are believed to correspond to atmospheric temperature varia-

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tions of amplitude 5 ~ 15 °C over the Greenland location. The timescale of each cycle of the D-O oscillation may extend to several millennia, with each cycle being characterized by a sudden warming out of the cold glacial state followed by a comparatively slow cooling out of the warm state back towards the cold state thus setting the stage for the next sudden return to the warm state.

The extent to which the impact of this millennium timescale climate variability influences the global climate system is still under active investigation. It is, however, both interesting and important that the variability of the deep North Atlantic thermohaline circulation (THC) has been closely correlated to the D-O oscillation evident in the ice core records. According to the analyses of Keigwin and Jones(1994), and of Rasmussen et al.(1996) more recently, both the relative amplitude and the period of the oscillation appear in marine records from the North Atlantic and correspond well to that of the atmospheric temperature proxy from Greenland.

Although a good correlation cannot immediately be taken to imply a direct physical connection, there is a good reason to believe that such a connection does in fact exist. The oceanic evidence analyzed by Keigwin and Jones(1994) and by Rasmussen et al.(1996) indicate that the strength of the deep circulation did indeed fluctuate on the D-O timescale during OIS 3. The thermohaline circulation (THC) in the North Atlantic is predominantly driven by North Atlantic Deep Water (NADW) production, and such NADW is formed primarily at the surface of the high latitude North Atlantic. Dense NADW naturally forms during the winter season when the surface of the North Atlantic is cooled intensely by the much colder air masses that travel across its surface from North America, and the ocean in turn releases very large amounts of heat to the atmosphere. The significance of this heat release can easily be understood by considering the relative warmth of northwest European winter climate compared with other parts of the world at the same latitude. The presence or absence of this oceanic heat source over the high latitude North Atlantic upon climate has been explicitly examined, for example, by Fawcett et al.(1997), and the shutdown and onset of the deep water formation process thereby shown to nicely explain the climate variation inferred to have occurred during the Younger-Dryas period as this is recorded in the Summit, Greenland ice core records.

The physical processes underlying the Dansgaard-Oeschger oscillation, however, have yet to be explained in an entirely satisfactory manner. Any such satisfactory explanation must clearly include identification of the properties of the climate system that support the observed "fibrillation" of THC strength that controls the intensity of the oscillation as well as the reason why the observed fibrillation occurs with significant amplitude only under glacial conditions (Peltier and Sakai,2001)).

There have in fact been a few recent theoretical attempts to explain the observed millennium timescale variability. Under full glacial conditions, global average temperature was much lower than present, and extensive continental ice masses covered both northern North America and Northwestern Europe. The earliest suggestion by Broecker et al.(1990) was that coupling between the continental ice sheets and NADW formation plays the central role; the idea being that intense NADW formation would cease whenever sufficient freshwater is delivered to the surface of the North Atlantic to sufficiently reduce the density of the surface waters over the high latitude North Atlantic. These authors suggested that the meltwater delivered by continental ice sheet disintegration is the cause; when NADW formation occurs, accompanied by intense heat release to the atmosphere this enhances melting of the continental ice sheets, and the consequent increase of the freshwater discharge onto the North Atlantic then suppresses NADW formation. Reduction of NADW formation then causes cooling of the atmosphere. This cooling reduces ice sheet melting. Once the meltwater discharge is decreased, the surface salinity gradually increases until the onset of the intense NADW formation occurs once more.

This mechanism appears entirely plausible on qualitative grounds, and some paleorecords do indeed indicate the occurrence of intense episodes of freshwater outflow onto the surface of the North Atlantic from the Laurentide ice sheet complex via the creation of vast "armadas" of icebergs, events which have been recorded in deep sea sedimentary cores in the form of horizons containing large quantities of ice-rafted debris. These are currently referred to as "Heinrich events" (e.g. Heinrich,1988). This series of events is considered to occur quasi-periodically on a deca-millennial timescale. According to the analysis by Bond et al.(1993), these episodic Heinrich events serve as pacemakers of a longer timescale climate cycle, now referred to as "Bond cycles", each cycle of which consists of several cycles of the Dansgaard-Oeschger oscillation of ever decreasing amplitude but with no related Heinrich events and thus no apparent connection to ice-sheet instabilities. Another difficulty with the original Broecker et al.(1990) hypothesis is the requirement of a very close and possibly nonlinear connection between melting of the Laurentide ice sheet complex and NADW formation. Since the ice sheet complex is situated "upstream" of the source of heat release from the North Atlantic surface that occurs via NADW formation, the impact of onset and shutdown of the THC may not affect the Laurentide ice sheet in the way required by the hypothesis. No evidence in support of the notion that episodes of intensive melting (mass loss) of the Laurentide ice sheets are synchronized with the Dansgaard-Oeschger oscillation has yet been found. Recent analyses, for example by Kreveld et al.(2000), show that minor ice rafting events can be observed on timescales similar to the Dansgaard-Oeschger cycles even through Holocene. These efforts have certainly increased our knowledge on the climate system, but we still require further information on the role the icesheets in the millennium timescale variability that occurred under glacial conditions.

There is another hypothesis as to the origins of the Dansgaard-Oeschger oscillation, however, that has recently been forthcoming. This hypothesis attributes the mechanism of the oscillation entirely to the internal dynamics of the North Atlantic thermohaline circulation itself under conditions in which a time independent freshwater flux anomaly is applied to the surface. The origin of this sort of internal oscillation in the thermohaline circulation may be traced to the "flush-collapse" type oscillation originally revealed in the THC analyses of Marotzke(1989) although no possible connection of this oscillation to any observed physical process was recognized. In our original analysis of this problem, Sakai and Peltier(1995), we performed a series of experiments in which a two-dimensional model of an idealized Atlantic basin was integrated under so-called "mixed boundary conditions". These analyses demonstrated that the Atlantic thermohaline circulation would be expected to exhibit oscillatory behavior when the net surface freshwater flux into the basin is sufficiently strong. Under constant anomalous freshwater forcing the period of the oscillation was shown to vary in the range from centuries (weak fluctuation) to millennia (very intense oscillation). Subsequent work (Sakai and Peltier,1996; hereafter referred to as SP96) employed a multi-two-dimensional-basin model of the global thermohaline circulation, analysis of which revealed the existence of a hydrologically controlled bifurcation in the thermohaline circulation under a localized but persistent freshwater flux anomaly. When a critical intensity of anomalous freshwater flux was applied with time independent amplitude onto the high latitude North Atlantic, the North Atlantic thermohaline circulation was shown to deliver very distinct millennium timescale oscillations. When the anomalous freshwater forcing was weaker than the critical intensity required to induce the bifurcation, however, the thermohaline circulation was found to be only very weakly time dependent. This structure has been further confirmed in Sakai and Peltier(1997; hereafter referred to as SP97), in which the global ocean model was coupled to an atmospheric energy balance model. In this configuration with explicit atmospheric feedback, the model was shown to require a somewhat stronger anomalous freshwater flux onto the high latitude North Atlantic in order to induce the Hopf bifurcation but beyond the bifurcation point the millennial timescale oscillation was shown to persist. The assumption made in these analyses, based upon the fact that the high latitude North Atlantic was surrounded by great continental ice sheets during OIS 3, is that the hydrological cycle was significantly modified in this circumstances such that the buoyancy flux at the surface of the high latitude North Atlantic was much enhanced. Clear observational support for this assumption is provided by Duplessy et al.(1991) whose sea surface salinity reconstructions for the last glacial maximum demonstrate that high latitude Atlantic sea surface salinity (SSS) was significantly reduced from modern. Nevertheless there are a number of issues that need to be addressed before we can be entirely confident that we have identified the correct explanation for the D-O oscillation.

The first of these concerns the impact of coupling between the THC and the wind driven circulation. The wind-driven circulation exerts significant influence on the sea surface salinity distribution and can thereby modify the impact of enhanced surface freshwater flux on the thermohaline circulation. Furthermore sea surface temperature changes induced by variations in the NADW formation process are likely to cause changes in the atmospheric circulation. Properties of the gyre circulation such as the Gulf Stream and the North Atlantic Drift, for example, are greatly influenced by the pattern of surface wind stress. These two currents play a primary role in conveying the high salinity water from low latitudes to higher latitudes. If these northward currents are weakened for some reason, this too results in a decrease of high latitude SSS.

A second issue that needs to be addressed concerns the influence of the very cold climate conditions that were characteristic of the glacial period. The experiments described in SP97 were conducted under the assumption of "modern" surface temperature conditions excepting those related to the hydrological cycle. The resulting sea surface temperature distribution that obtains when intense NADW formation is maintained in these experiments is therefore much closer to "modern" climate and therefore inappropriate to glacial conditions. Imposing a very cold climate, however, leads to a further enhancement of the impact of salinity changes in determining the density of sea water (e.g. Fofonoff,1985). Winton(1997) has recently argued that under extremely cold climate conditions the "North Atlantic" thermohaline circulation may also be destabilized and similar millennium timescale oscillation are produced through the temperature effect as we have shown are produced by hydrological forcing alone.

A third outstanding issue, and the one that will serve as primary focus of investigation in this paper, concerns the influence of the diffusion coefficients for heat and salt upon the behavior of the thermohaline circulation in a fully three dimensional model. A typical low-resolution ocean general circulation model (resolution > 1°) cannot resolve so-called "meso-scale" eddies that are the oceanic equivalents of atmospheric cyclones and anti-cyclones which are well resolved in atmospheric general circulation models even at modest resolution because of the order of magnitude difference between the Rossby radius of deformation for the atmosphere and that for the oceans. Since these eddies play a quantitatively important role in the horizontal mixing process in the oceans, some parameterization of their influence must be included in such low-resolution ocean general circulation models.

Examinations of the sensitivity of the modeled ocean general circulation to the choice of mixing coefficients in ocean general circulation models have, of course, been repeatedly performed in the literature for various ocean general circulation models, but these have been rather sharply focused on the impact on the steady state solution. The existence of multiple equilibria of the thermohaline circulation has itself, of course, been repeatedly discussed since appearance of the paper by Stommel(1961) who employed a simple 2-box model to demonstrate this possibility. Somewhat more quantitative analyses of the same property of the large scale ocean circulation have been provided recently by Rahmstorf(1995) using a ocean general circulation model. His results show no evidence of the existence of a millennium timescale oscillation. As described earlier in the Introduction to this paper, the existence of millennium timescale oscillatory solutions for the thermohaline circulation under certain boundary conditions has been previously demonstrated mostly on the basis of two-dimensional ocean models. Equivalent results derived on the basis of full three dimensional ocean general circulation models have as yet not been produced in demonstration of the continuing existence of an intense millennium timescale oscillation that could be connected to the Dansgaard-Oeschger oscillation. This will be the focus of the present paper.

Sakai and Peltier(1999; hereafter referred to as SP99) have more recently described a dynamical systems model which also appears to capture essentially the same mechanism of thermohaline fibrillation as previously obtained in the two dimensional models of the THC, and these analyses have suggested a possible explanation of the apparent discrepancy between the predictions of the two- and three-dimensional model results. One of the results reported in this paper suggests that the influence of diffusion processes on the existence of the oscillation may be extreme. Specifically it is demonstrated therein that by imposing very large (horizontal) mixing coefficients for the deep ocean in the dynamical system, the results of the 3-box model approach those of the Stommel box model of the thermohaline circulation which exhibits only steady multiple equilibria. On the other hand, the multiple equilibria become unstable and the dynamical system allows oscillatory solutions when the mixing coefficients in the abyssal ocean component of the system are small enough.

These previous analyses, although qualitative as they are based upon a highly simplified model of the thermohaline circulation, clearly suggest why strong millennium timescale oscillations have not been clearly revealed in past integrations of three-dimensional ocean general circulation models. These model may simply be employing mixing coefficients which are larger than the critical value below which oscillatory solutions become possible. The important question then becomes how weak horizontal diffusion processes must be before oscillatory behavior begins. If the critical value is much smaller than observed large-scale mixing coefficients in the deep ocean, then the millennium timescale oscillations that have been observed in simpler models may simply be an artifact of over-simplification. The primary purpose of the present paper is to attempt to answer this question through a sequence of numerical experiments using a conventional three dimensional ocean general circulation model. The detailed design of the experiments will be discussed in the next section in which the numerical model and its specific geometric configuration are considered. The results we have obtained in these experiments are described in the third Section and our conclusions together with a brief summary of the results are offered in the concluding fourth Section.

2. OCEAN GENERAL CIRCULATION MODEL AND DESIGN OF THE NUMERICAL EXPERIMENTS

All of the experiments that were conducted in the course of the present study have been performed using a stand-alone Ocean General Circulation Model (OGCM), specifically the Modular Ocean Model (MOM) Version 2.2 β that has been developed at the Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton, N.J.

For the purpose of these investigations, the numerical model has been configured in single idealized Atlantic basin mode. We specifically employ a so-called sector model that covers a rectangular domain in the longitude-latitude plane with a uniform depth of 5000 m. The longitudinal span has been held fixed to 60°, and the latitudinal extent is fixed to the range from 56°S to 80°N. In order to examine a wide range of horizontal diffusion coefficients, the horizontal resolution is chosen to be 2° in order to enable us to employ relatively small diffusion coefficients. This might be considered to constitute rather fine resolution for experiments of this kind that require very long integrations. The number of vertical levels is 16 and these are located at depths of 25, 75, 165, 265, 415, 585, 815, 1085, 1415, 1805, 2265, 2745, 3255, 3745, 4255, 4745 meters for t-cells, and 50, 120, 215, 340, 500, 700, 950, 1250, 1610, 2035, 2505, 3000, 3500, 4000, 4500, 5000 meters for w-cells.

For the purpose of these experiments, the surface boundary conditions are also idealized: prescribed seasonally varying sea surface temperature (SST) to which the time varying SST of the model is continuously restored, and the freshwater flux specified so as to include a localized high-latitude component of the forcing due to surface runoff during glacial conditions. The wind stress in both horizontal directions (longitude-latitude) is held fixed to zero for all of the analyses we shall perform in order to isolate the influence of three dimensionality from that of the wind driven circulation. A Neumann boundary condition, on the other hand, is employed for the salinity boundary condition. The latitudinal variation of the "salt flux", which is proportional to (minus) the combination of precipitation plus runoff minus evaporation, has been set to a form based upon a diagnosed "fresh water" flux at the surface by first imposing a fixed sea surface salinity using the standard parameter configuration of the OGCM. A number of different anomalous freshwater distributions have then been superimposed upon this "present salt flux" distribution, as in the previous analyses described in SP96 and SP97. The distribution shown as the solid line in Figure 1 is intended to represent the perturbed form of the flux that is assumed to obtain under ice-age conditions. As the dashed line we show the "modern"(without anomaly) distribution of freshwater flux for comparison.

The temperature conditions at the ocean surface need to be discussed in further detail in order to justify the use of a stand-alone OGCM in the study of thermohaline circulation stability. We have employed what are usually referred to as "mixed boundary conditions", a configuration that has on occasion been strongly argued against because of the possibility that the thermohaline circulation may be rendered over-sensitive under such conditions (e.g. Tziperman et al.,1994; Rahmstorf and Willebrand,1995). A conventional choice of relaxation constant for SST would be near one month, a choice that may be motivated on the basis of the strength of the temperature feedback needed in an energy balance model that is tuned to simulate "modern climate" (e.g. North et al.,1983). Apart from the issue of realism, the literature argues that by employing such a "short" timescale for relaxation towards the reference state SST the current mode of the thermohaline circulation (and thus the deep water formation process) may become overly (unrealistically) sensitive. For this reason, use of an explicitly described active atmospheric response is clearly desirable.

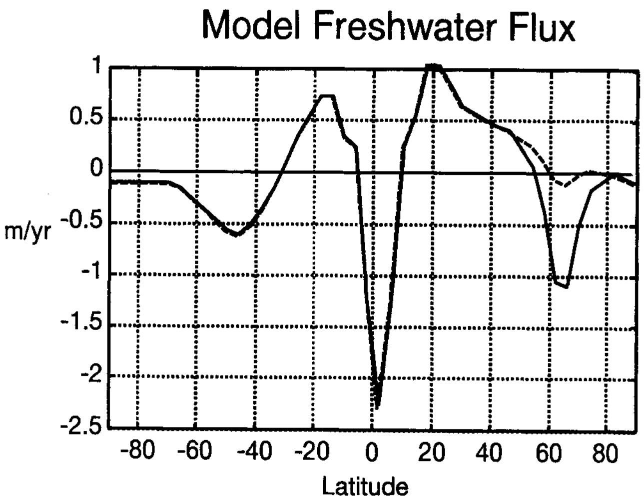

Figure 1. Model sea surface freshwater flux. A standard anomalous freshwater has already been superimposed at the high latitude North Atlantic (solid line). "Modern" distribution of the freshwater flux is also plotted as a dashed line for comparison.

We cannot at present consider employing a complete Atmospheric General Circulation Model (AGCM) as a practical candidate for this kind of investigation, because AGCMs are still prohibitively expensive. Further use of a diffusive energy balance model (EBM) as in SP97 might constitute an alternative option for the three dimensional integrations of the ocean component to be described herein. We have elected to reject this possibility in this instance, because the use of EBMs does not guarantee a realistic SST response, especially for the high-latitude Atlantic; if it were not for the large land mass (the North American continent) upstream from the ocean, the SST predicted by such an EBM may not be unreasonable. However, the air that travels over the continent becomes very much colder in winter than it would if it had traveled over the open ocean, and this cooling is not accurately captured in the EBM. The cold air mass can extract heat from the ocean much more efficiently than would a warmer air mass. This effect then reduces the effective characteristic time scale

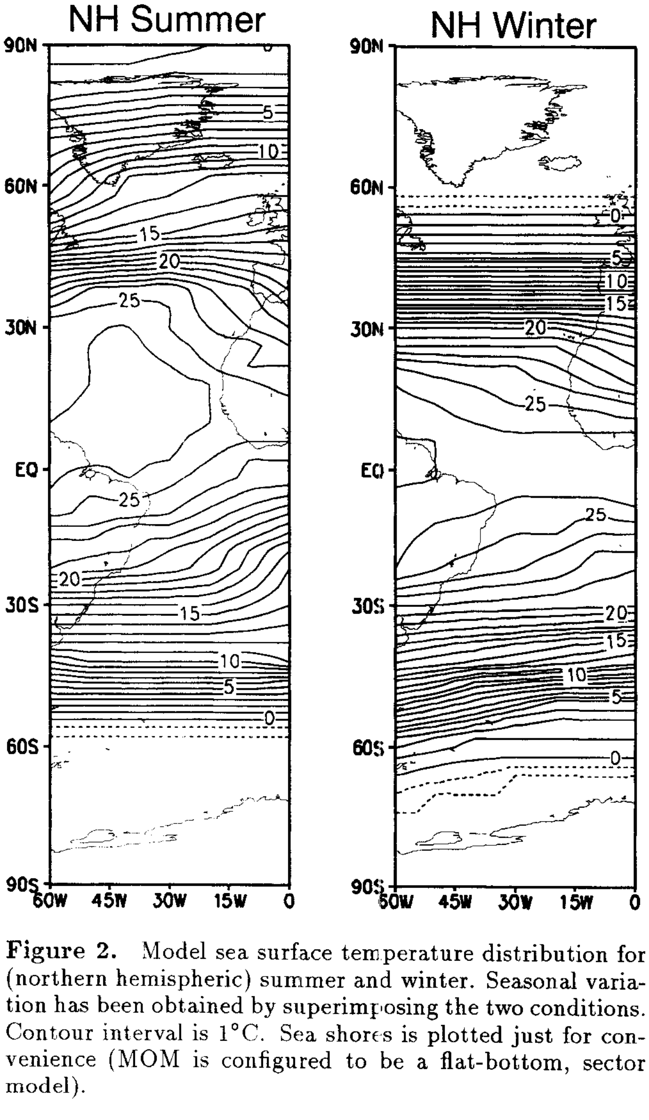

Figure 2. Model sea surface temperature distribution for (northern hemispheric) summer and winter. Seasonal variation has been obtained by superimposing the two conditions. Contour interval is 1°C. Sea shores is plotted just for convenience (MOM is configured to be a flat-bottom, sector model).

of SST relaxation to the reference SST to a value that is possibly much shorter than that which would be inferred on the basis of the EBM. The use of an EBM might be expected to overestimate the sensitivity of the THC more than one might infer through the use of the restoring boundary condition.

We have, therefore, decided to employ a very simple design for these initial three dimensional experiments on the stability of the thermohaline circulation, namely one based on the assumption of *mixed boundary conditions* and to leave investigation of the impact of more realistic surface boundary conditions to a future study.

The choice of a "best" relaxation timescale for the relaxation of SST towards some reference function of latitude is another question, and we will present the results of a set of sensitivity experiments that demonstrate the robustness of our conclusions against the variation of the time constant over a considerable range. As the "standard" restoring time constant, we will employ the value of 200 days which is approximately one order of magnitude larger than usually assumed for such restoring time constants, since this is expected to eliminate any "unphysical instability" that might be induced by employing the "short" restoring time constant often used in past experiments. In the additional experiments, results obtained when the time constant is set respectively to 50 days and 400 days will also be discussed. The reference SST field is constructed based upon the summer and winter climatology over the Atlantic sector (see Fig.2), and the reference SST pattern at every time step is obtained by superposition of the weighted mean from the two seasons.

The options employed to configure the GFDL MOM for the purpose of these experiments are those which might be considered standard for classical low-resolution OGCMs. In order to represent the vertical mixing related to the occurrence of sub-grid scale convection, a standard convective adjustment scheme has been employed. For the purpose of these experiments we will employ the simple horizontal/vertical representation of diffusion processes instead of an alternative isopycnal/diapycnal representation.

As the title of this paper indicates, our primary goal in these analyses is to understand how the choice of diffusion coefficients impacts the nature of THC time dependence that can be expected to occur under "glacial" conditions. We have adopted a simplest possible approach to this problem based upon the observational fact concerning ocean diffusion coefficients, namely that these vary most strongly as a function of depth as has been assumed, for example, in the seminal early analyses of Bryan and Lewis(1979). Although recent direct measurements of the large-scale mixing coefficients of the ocean have revealed that the range of upper ocean (e.g. Moum and Osborn,1986; Ledwell et al.,1993) vertical diffusion coefficients is $1 \sim 3 \times 10^{-5} \mathrm{m}^2/\mathrm{s}$, these direct observations cover only a very small fraction of the global oceans. Indirect measurements can help to improve this poor coverage of observational (direct) measurements of the diffusion coefficients. Olbers et al.(1985), for example, offer relatively wide coverage of such diffusion coefficient estimates for the North Atlantic. Their study presents analyses of the space-dependent mixing coefficients for both the horizontal (isopycnal) and vertical (diapycnal) directions and for two different ranges of depth, one is of the upper layer below the surface mixed layer ($100 \sim 800$m), and the other is of the intermediate layer ($800 \sim 2000$ m). By comparing the results from these analyses with those based upon direct measurements, the Olbers et al. analyses were shown to be in rather good agreement with the latter, at least for those locations from which direct observation were available for the vertical diffusion coefficients. Some may consider the analyses in Olbers et al.(1985) to be surprising. The diffusion coefficients for both directions were found to be highly space-dependent and cover a wide range extending over more than one order of magnitude. Furthermore, one finds that typical mixing coefficients that are employed in low-resolution OGCMs are rather large compared with the values obtained observationally. As opposed to the assumption in Bryan and Lewis(1979), the vertical mixing coefficient for the upper layer is found to be significantly larger than that for middle layer. For the horizontal (isopycnal) mixing coefficient, the assumption in Bryan and Lewis(1979) qualitatively agrees with the observational analyses, namely that the mixing coefficient assumes significantly larger values in the upper layer. Quantitatively, however, the values employed in global or basin-scale OGCMs may be an order of magnitude in excess of those inferred on the basis of observations. We have therefore elected to employ diffusion coefficients in the present work closer in magnitude to the observations. The actual profiles of the diffusion coefficients that we will employ in the experiments are described in the following section.

Although small scale diffusivities for heat, salt, and momentum may differ by orders of magnitude, on somewhat larger scales the effective values of these diffusion coefficients may differ significantly. In the current investigation we will simplify the experimental design (at least in part to conform to the restrictions imposed by the MOM structure) by assuming that the diffusion coefficients for heat and salt are identical in both the horizontal and vertical directions. The model allows incorporation of different values for the diffusion coefficient for momentum (spatially uniform values only). For simplicity of experimental design we have elected to employ single conservative choices for the horizontal and vertical values of this coefficient, namely $2.5 \times 10^5 m^2/s$ for the horizontal value (e.g. see Weaver et al.,1993) and $10^{-4} m^2/s$ for the vertical value. Our choice for the vertical viscosity might be considered somewhat smaller than values typically employed in OGCMs (usually in the range between $O(10^{-4}) \sim O(10^{-2})$, e.g. Bryan and Lewis,1979; Weaver et al.,1993; Danabasoglu and McWilliams,1995), but this value is still much larger than the observed vertical diffusivity for heat or salt.

3. RESULTS AND DISCUSSION

We have analyzed the results of two main sets of experiments and two subsidiary sets of experiments. In the first two subsections, we present the results obtained through analyses intended to examine the stability of the thermohaline circulation against changes of either horizontal or vertical diffusion coefficients separately. The final two subsections present results that are intended to demonstrate the robustness of the conclusions from the first two subsections, namely concerning the influence of lowering SST, and the influence of the use of varying relaxation times in the restoring boundary condition for SST.

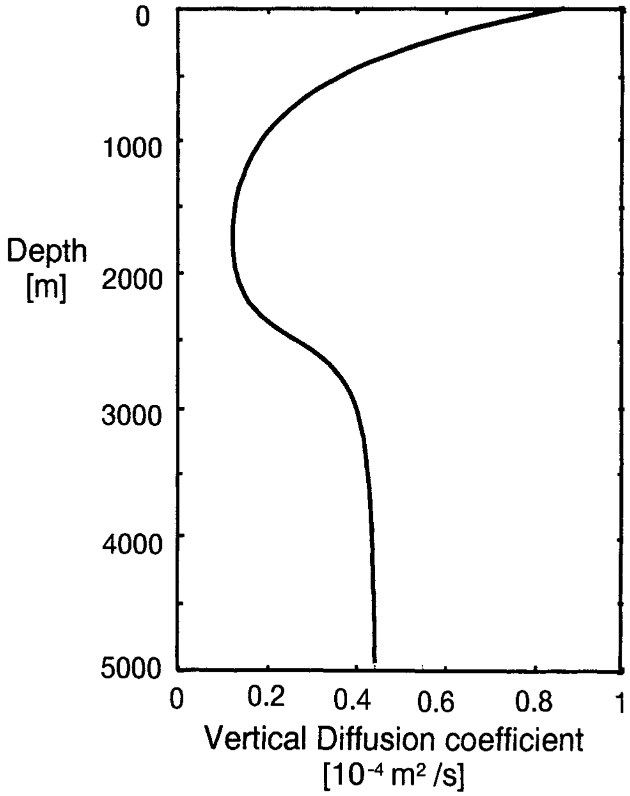

Figure 3. Standard profile of the vertical diffusion coefficient distribution for the experiments with varying horizontal diffusion coefficients.

3.1. The Influence of the Horizontal Diffusion Coefficients

As discussed in the previous section, choosing one specific value for the horizontal diffusion coefficient in an OGCM would constitute a poor reflections of reality. A further issue concerns the fact that typical horizontal diffusion coefficients employed in low-resolution OGCMs are generally taken to be equal to the largest value inferred anywhere on the basis of observations. We have therefore performed a first set of experiments in which the vertical profile of horizontal diffusion coefficient is varied with keeping the vertical diffusion coefficient fixed to a specific profile. Figure 3 shows the standard vertical diffusion coefficient profile for this set

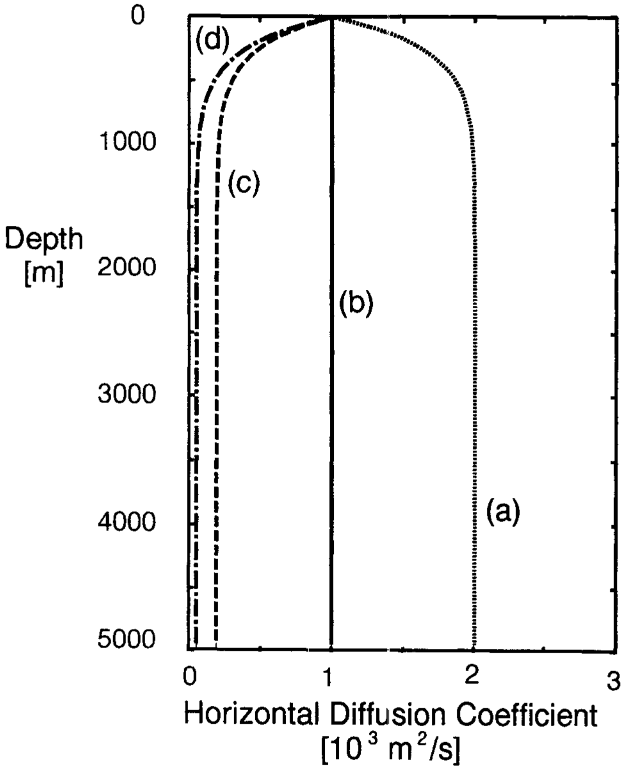

Figure 4. Horizontal diffusion coefficient distributions for the experiments with the fixed vertical diffusion coefficients distribution. Four different profiles correspond to the representative experiments to be shown herein. Labels correspond to those of the results that are later presented.

of experiments. The vertical diffusion coefficient is enhanced near the surface, which differs from the traditional "Bryan-Lewis" type profile but is based upon the observations. The influence of the choice of such a "standard" profile is directly investigated in the following subsection. Figure 4 on the other hand shows the range of horizontal diffusion coefficient profiles to be employed in our first series of experiments. We have performed more than 10 integrations employing a much wider range of profiles in a "trial and error" manner, and choose the set of profiles shown to be representative of the range of behaviors of the THC. The profiles (c) and (d) are, again, similar to the traditional "Bryan-Lewis" profile, with the exception that the depth at which the diffusion coefficient changes is here taken to be shallower than in their original study. One might refer to the value of $10^3 m^2/s$ as a "canonical" value of the horizontal diffusion coefficients (profile (b)), since many OGCMs employ a value for this parameter that is near (or even larger than) this number.

Since the nature of the THC oscillation that we intend to demonstrate that is also supported by the MOM has already been discussed in the literature (SP96,97), no useful purpose will be served in the present paper by repeating such discussion. It will suffice to simply point out the long timescale oscillation of the thermohaline circulation, when this exists, is supported by the latitudinal contrast of upper layer North Atlantic salinity between the very saline interior that forms in low middle latitude due to excess of evaporation over precipitation and the less saline high latitude water. It will suffice for present purposes to simply present the time series of THC strength that the model delivers when the vertical profile of the horizontal diffusion coefficient is varied. In order to represent basin scale thermohaline circulation strength, we will employ time series of basin averaged overturning streamfunction. If the solution for the idealized Atlantic basin thermohaline circulation that obtains under steady seasonal forcing approaches a statistically steady state, the basin averaged overturning streamfunction should remain relatively fixed to a constant value.

Figure 5 shows such time series of THC strength for the four cases. Inspection of these results will demonstrate that there exists a bifurcation in the nature of the solutions for the idealized Atlantic thermohaline circulation that is induced simply by changing the horizontal diffusion coefficient for the deep ocean, even when there exists a time independent salinity flux variation at the surface. The model either enters an effectively steady state characterized by intense NADW formation if the horizontal diffusion coefficient is taken to be as large as those employed in typical low-resolution OGCMs, or it exhibits flush-collapse type oscillations on multi-millennia timescale when the deep ocean diffusivities are significantly reduced. The former cases appear to be similar to that of a modern state of the THC circulation, and thus the value of the basin average overturning streamfunction in these cases can be considered to correspond to that of a modern North Atlantic. This bifurcation is exactly the same as predicted in SP99. The first conclusion from these experiments, therefore, is that, as suggested on the basis of our previous work based upon the use of much simpler models, enforcing *uniformity* of the deep water mass through the use of very large horizontal mixing coefficients in the abyssal ocean eliminates the oscillatory solution that may otherwise be induced by changing steady surface boundary conditions (adding a sufficiently large fresh water flux anomaly at high northern latitudes).

Another important aspect of these results is that the period of the oscillation is rather insensitive to the magnitude of the horizontal diffusion coefficients when smaller values than those needed to induce the bifurcation are introduced. This will be clear by comparison of the results obtained for profiles (c) and (d) in Figure 5.

The deep ocean diffusivity differs by a factor of 4 in the abyss yet the period of the resulting oscillation remains approximately the same.

In the box model analyses described in SP99, one of the essential conclusions was that the behavior of the three-box model deviates significantly from the behavior of Stommel's two-box model because of the separation assumed to exist between the deep water mass in the high latitude North Atlantic and the deep water mass in the low latitude Atlantic. By increasing the efficiency of mixing between these two deep water reservoirs it was shown that the three-box model reduces to the classical Stommel model which allows only multiple equilibria of the kind further analyzed in the recent work by Rahmstorf(1995). By allowing the deep water mass to remain heterogeneous by reducing the horizontal diffusion coefficients, the analyses discussed above show that the 3-D OGCM similarly supports an oscillation in the thermohaline circulation, and that this occurs, as in the simple 2-D and box models, on the millennium timescale.

An issue which requires further discussion then concerns the question as to whether the reduction of the diffusion coefficients in the abyssal ocean that is required to allow the model to support the millennium timescale oscillation is physically plausible. In fact the required reduction of the diffusion coefficients under these boundary conditions is only to a value of $0.3 \times 10^3 m^2/s$, approximately one-third of the "canonical value" usually employed in low-resolution OGCMs. According to the analyses of Olbers et al.(1985), the observed value of the diffusion coefficients is in fact much less than this value throughout most of the North Atlantic Ocean, even in the intermediate water layer that extends from 800 to 2000 m depth Although the representation of diffusion processes in these model experiments is rather primitive, the important point implied by the results is simply that the requirement for the existence of the solution in which the THC strength is oscillatory is simply that the horizontal diffusion coefficients be only slightly smaller than the (overly large) value usually assumed in low-resolution OGMCs. This also explains why some low-resolution OGCMs fail to reproduce the millennium time scale oscillation; if the horizontal diffusion coefficient is taken to be larger than the critical value, then the oscillatory solutions cannot be realized. In the ensuing subsection we will focus upon the factor that most strongly controls the period of the millennium timescale variability.

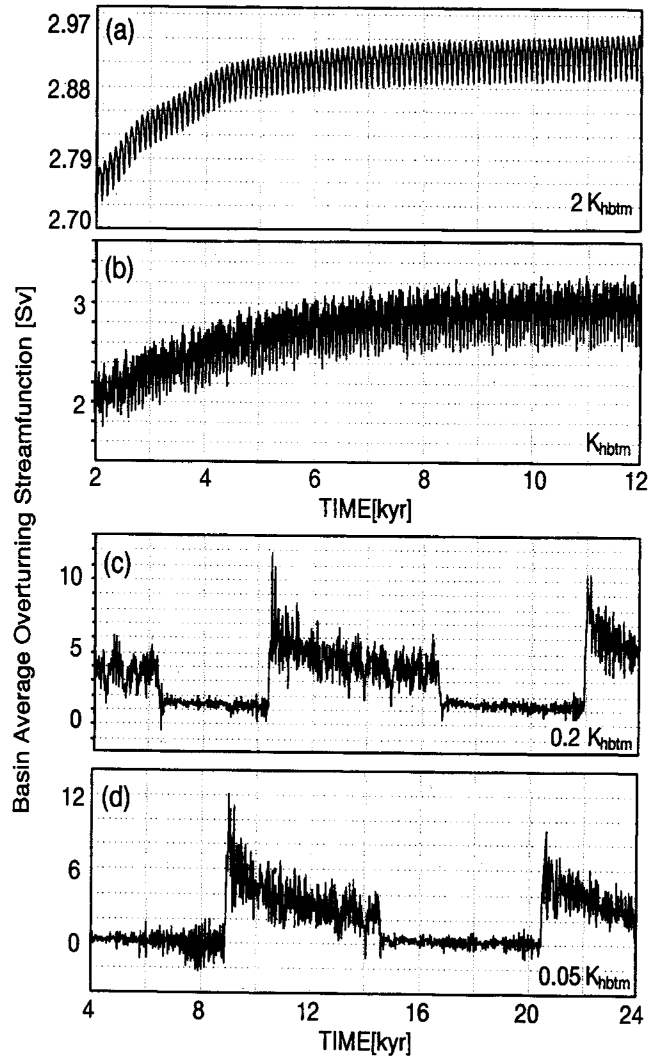

Figure 5. Time series of basin averaged overturning streamfunction. Four cases correspond to the varying horizontal diffusion coefficients respectively: From top to bottom, the largest K_h case (a), the "canonical K_h case" (b), a small K_h (c), and a smaller K_h case (d). Note that the time axis differs for lower two plates: the upper two plates show the time series of 12,000 model years, whereas the lower two plates show that of 24,000 model years. Labels denotes the diffusion coefficients shown previously.

A brief summary of the bifurcation structure that has already been discussed in our previous papers is as follows: the smaller value of the horizontal diffusion coefficient of salinity and temperature (and thus density) reduces northword transport of saline water in the North Atlantic upper-layer and maintains the density contrast in the deeper layer beneath. These direct influences enhance the distinction between watermasses (namely, the upper-layer of the middle latitude North Atlantic, the high latitude North Atlantic, and the deep-layer of the low-middle latitudes of the Atlantic) which is necessary to drive the THC oscillation. As a result, the density of the deep water relative to that of the surface of the high-latitude North Atlantic is increased when the THC system is in the stagnant phase of an oscillation cycle.

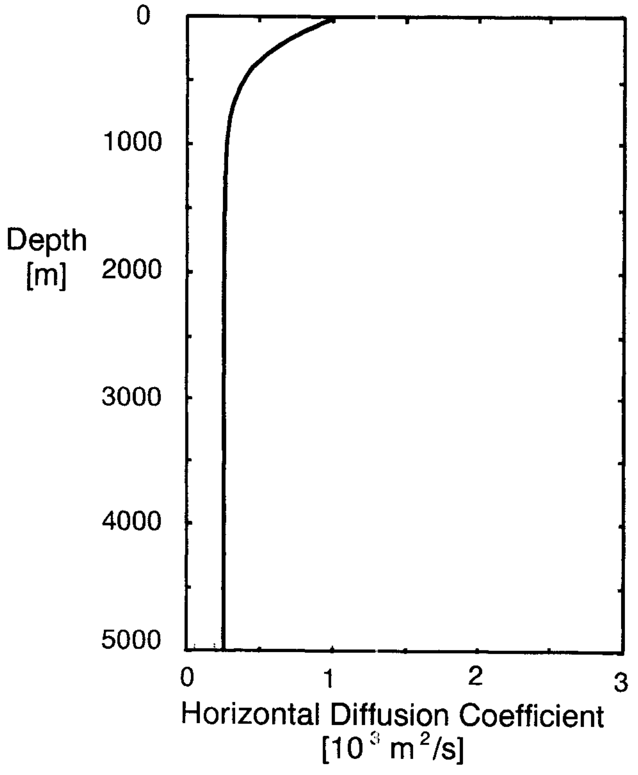

Figure 6. Standard profile of the horizontal diffusion coefficient distribution for the experiments with varying vertical diffusion coefficients.

3.2. The Influence of the Vertical Diffusion Coefficients

The existing literature on the oscillatory model of behavior of the THC, as represented for example by SP96, has already provided some insight into the factors that control the period of the oscillation in the simple two-dimensional hydrodynamic models. This timescale is primarily controlled by the time required, in the absence of motion, for diffusion to restore the density of the surface waters in the high latitude Atlantic to a convectively unstable state following the collapse phase of the oscillation. The time taken to restore the (potentially high) density of the surface water to the unstable state by increasing salinity in the low middle latitude region where evaporation exceeds precipitation will clearly involve the efficiency of vertical mixing to a significant degree, an influence upon which we will focus on this subsection.

While first keeping the vertical profile of horizontal diffusion coefficient fixed to the standard profile shown on Figure 6, we will present the results obtained from a series of experiments in which the vertical diffusion coefficients is varied. The sequence of profiles for the vertical diffusion coefficients are shown on Figure 7 where they are labeled (a), (b) and (c). The profile of horizontal diffusion coefficients shown on Fig. 6 has been selected to be such that oscillatory solutions of the THC are allowed according to the analyses described in the last subsection and to be well within the range required by the analyses of Olbers et al.(1985)

In describing the results obtained with this sequence of models we will once again present time series of basin averaged overturning streamfunction. Figure 8 shows the results for the three cases. The central plate in this series shows the results employing the same K_v profile as that employed in the previous subsection (profile (a) on Figure 7). The upper and lower plates show the results obtained either by reducing or by increasing K_v at the surface, respectively profiles (b) and (c) on Fig.7. Inspection of these results indeed verifies our expectations based upon the results of the previously discussed 2-D models, namely that the period is very sensitive to the choice of the vertical diffusion coefficient. The smaller the vertical diffusion coefficient, the longer the period of the millennium timescale oscillation of the overturning circulation in the idealized North Atlantic basin.

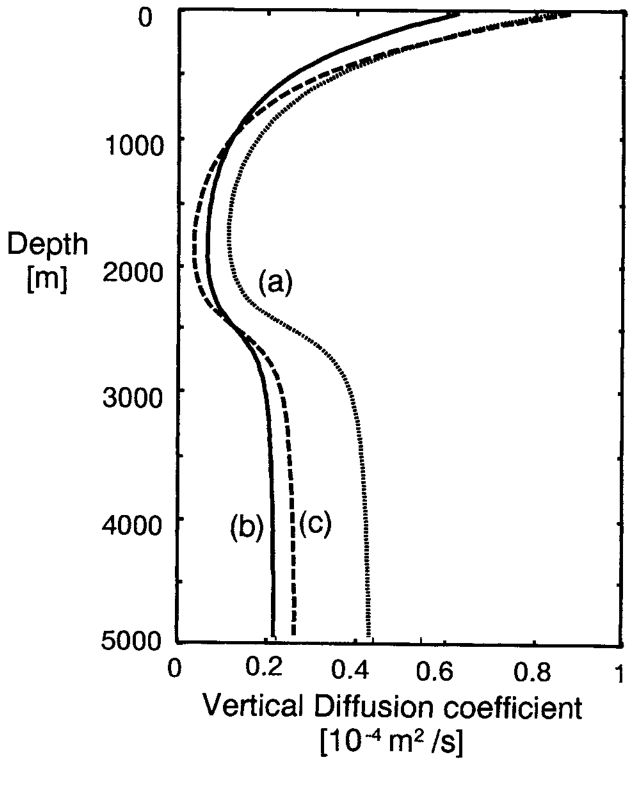

Figure 7. Vertical diffusion coefficient distributions for the experiments with the fixed horizontal diffusion coefficients distribution. Labels correspond to those of the results that are later presented.

Considering the nature of the oscillation already described in the previous series of papers (SP96,99), a simple and physical explanation of this result follows immediately. The duration of the "off state" of intense NADW formation is determined by the rate at which high salinity water accumulates in the upper layer of the low latitude North Atlantic. This process is of course very sensitive to the value of the vertical diffusion coefficient. The smaller the diffusion coefficient, the longer the time required for surface high salinity condition to diffuse into the deep halocline layer. We do not consider, on the other hand, that the duration for the "on state" of intense NADW formation is influenced in any significant way by the magnitude of K_v as will be further discussed in the following subsection.

3.3. The Impact of Varying the Restoring Time Constant for SST

In this subsection, we present the results from two experiments that are intended primarily to demonstrate the insignificance of any possible "over-sensitivity" introduced by the use of mixed boundary conditions. We need to re-emphasize here that the physically correct value of "the" restoring time constant that is employed in a mixed boundary conditions formulation is not known. Furthermore it is almost certainly the case on physical grounds that no such unique value should exist. It will suffice to provide two physical examples of circumstances that would lead one to expect that this time constant should be strongly space dependent. A first example is the previously mentioned case of the high latitude North Atlantic during winter. Very cold air outflows from North America serve to maintain the surface temperature of the high latitude North Atlantic Ocean just above the freezing point over open water. A second example concerns the equatorial Pacific Ocean. This region of the ocean experiences no similar atmospheric forcing as that of the high latitude North Atlantic. One therefore has good reason to suspect that the restoring time constant appropriate for the equatorial Pacific should much longer than that appropriate for the high latitude North Atlantic.

In order to demonstrate the insignificance of the choice of restoring time constant for SST on the existence and properties of the THC oscillation, we will present herein the results from three experiments in which the restoring time constant on SST is varied. In these experiments, the diffusion coefficients have been held fixed to the same vertical and horizontal profiles shown on Figure 9, whereas the restoring time constant is varied through the sequence 50, 200 (standard), 400 days.

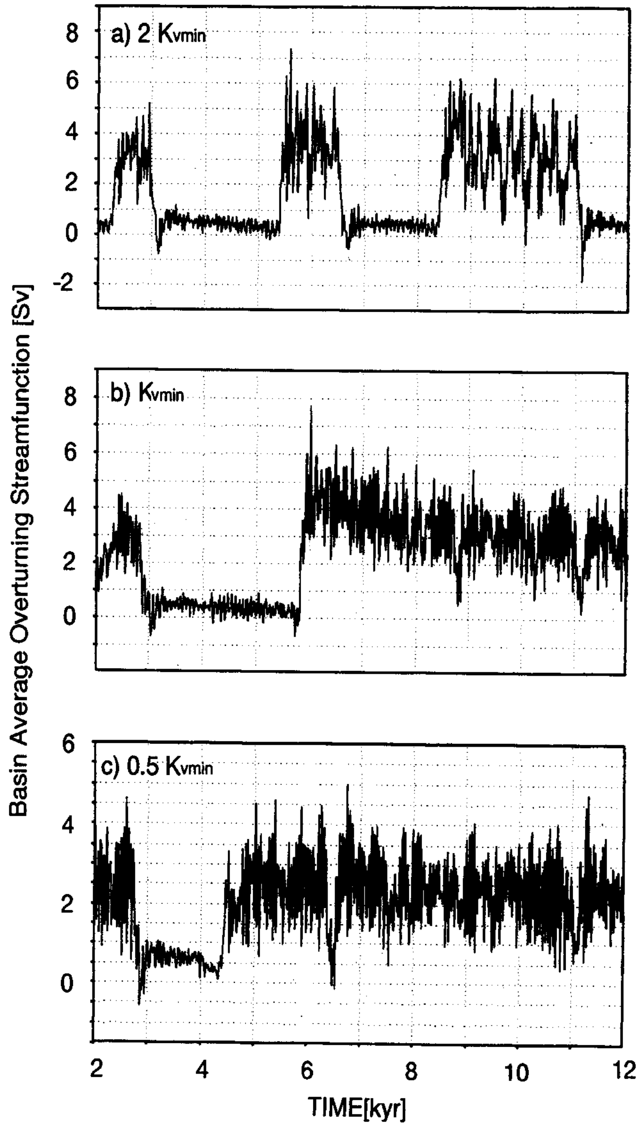

Figure 8. Time series of basin averaged overturning streamfunction. Three cases correspond to the varying vertical diffusion coefficients respectively: From top to bottom, the largest $K_{v,minimum}$ case (a), the medium $K_{v,minimum}$ case (b) which is the same as the previous subsection, and a small $K_{v,minimum}$ (c). Labels denote the diffusion coefficients shown previously.

Insofar as the surface boundary condition on freshwater flux is concerned, we have successfully applied the same boundary condition shown on Fig.1 to the case when the time constant is set to 50 days as before (as well as to the 200 day base case), but we were obliged to slightly modify this surface boundary condition in order to obtain the oscillatory solution when the restoring time constant was set to 400 days (Figure 10). It is important to emphasize here that the purpose of presenting these results is to demonstrate that the millennium timescale THC oscillations may continue to exist even

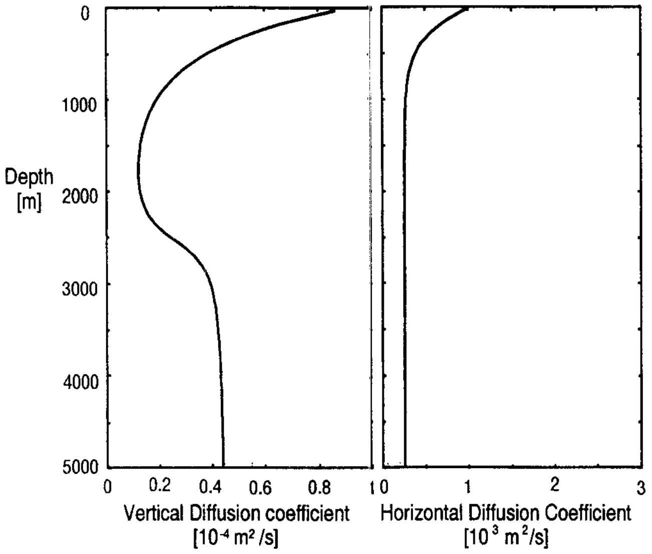

Figure 9. Horizontal and vertical diffusion coefficient profile for the experiment with varying restoring time constants for SST.

when the restoring time constant for the SST is set to an *unphysically* large value. Figure 11 shows the time series of the basin average overturning streamfunction obtained for all three of these cases. It will be clear by inspection of these results that when the time constant is reduced to 50 days from the base value of 200 days the period of the oscillation is also significantly reduced and the pulse shape substantially modified. Similarly, as the restoring time constant is increased the period is increased and the system significantly stabilized.

A further issue that warrants discussion here concerns not only the period of the oscillation but more specifically the duration of the "on" phase of intense NADW formation. In previously analyzed examples of the "flush-collapse" oscillation of the thermohaline circulation, the "on" phase was found to occupy only a very small portion of each cycle. One extreme example was produced by the three-box model discussed in SP99 which has essentially identical boundary condition to the fixed (non restoring) SST case. In this box model, the "on" phases were realized only as very sharp spikes in the time series of THC strength. For the purpose of the ensuing discussion we will exclude the time series obtained for the case that employed the longest restoring time constant, since this analysis differed not only in the restoring time constant for SST but also in the surface salinity flux. It has already been simply demonstrated that different surface salinity flux distributions may result in different periods for the oscillation (e.g. SP97).

By employing a very long restoring time constant we influence the nature of THC time dependence in two important ways, the first concerning the stagnant phase of the oscillation and the second the intense NADW formation phase. Concerning the stagnant phase, a very long restoring time constant for SST enhances the stability of the thermohaline circulation, which leads to an increase in the threshold for the instability that is ultimately induced by low latitude salinity accumulation. Concerning the intense phase of NADW formation it is helpful to refer to SP97 in which a 2-D ocean model was coupled asynchronously to an energy balance atmospheric model. In that analysis we included atmosphere-ocean feedback, and the resulting time series of the activity of the thermohaline circulation were shown to differ significantly from those obtained by employing the stand-alone version of the ocean model in a way similar to the way we are using the 3-D OGCM in the present sequence of experiments. In this more realistic circumstance the duration of the "on" phase of intense NADW formation was shown to be stretched compared to the stagnant phase. This change in the duration of the "on" phase is an easily understood consequence of the atmospheric response. In both the long relaxation time and coupled atmosphere-ocean analyses, oceanic heat release that occurs as a result of very intense NADW formation disturbs the SST field locally over the high latitude North Atlantic where temperatures are increased. Both by employing the EBM to explicitly compute this feedback and using a longer restoring time constant for SST enhances the role of this process, by increasing the efficiency of the negative feedback that it applies on the intensity of NADW formation. When NADW formation increases, the "air" above the region warms and this reduces the density of

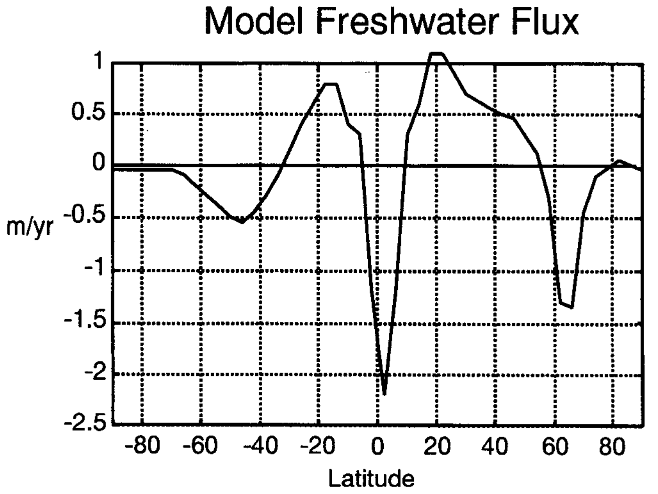

Figure 10. Model sea surface freshwater flux for the case when the restoring time constant is set to 400 days.

the sea water with which it is in contact so that further intensification of NADW formation is suppressed. This SST control on the rate NADW formation reduces the rate of consumption of saline water stored in the low-latitude upper layer. The "on" phase therefore can persist for a longer period of time then it would do in the absence of such a negative (atmospheric) feedback process as in the SP99 box model results.

The question of what might constitute a "correct" choice for the restoring time constant for SST in stand-alone ocean models remains an open question for reasons that have already been discussed in the preceding sections. To adequately address it, we will, in analyses to be described in subsequent work, employ a strategy based upon the judicious use of coupled atmosphere-ocean models in which the atmospheric component of the coupled structure is better approximated than it can be using the energy balance formalism.

3.4. The Impact of Lowering the Surface Temperature to Ice-Age Conditions

Before closing this section, we will present the results obtained from one further experiment. This was undertaken to demonstrate the impact upon the THC oscillation of lowering the sea surface temperature to the extent that occurred under glacial conditions. We do not wish to argue here for the reality of the temperature field we will employ to mimic ice-age climate. Since we seek only to develop on the basis of the experiment a qualitative argument as to how lowering the surface temperature will tend to further increase the extent to which the salinity flux (freshwater flux) will dominate the process of deep water formation.

This issue has already been addressed to some degree in Winton(1997), and so our analyses are intended to re-confirm his conclusions. The primary difference between the present experiment and those reported in previous subsections is that surface temperature will be fixed so as to better represent "cold climate" condition by uniformly reducing SST by 4°C except in those regions where surface temperature would be thereby reduced below the freezing point of sea water. The distribution of the freshwater flux is set to be identical to that in the previously performed experiments except for the high latitude anomaly. For the present purposes this high-latitude anomaly is reduced by approximately 30% *to a level such that the millennium timescale oscillation would no longer occur under modern climate conditions* (Figure 12).

Figure 13 shows the time series of basin averaged overturning streamfunction from the integration. One can clearly see that the same oscillation in thermohaline circulation intensity is produced under "glacial" boundary conditions as that obtained previously. Of course the reduction in surface air temperature for the high latitudes during the full glacial period was likely larger than the global estimate of 4°C, so that the influence of lowering SST may play a more important role in the ice age than that which would be inferred on the basis of this experiment.

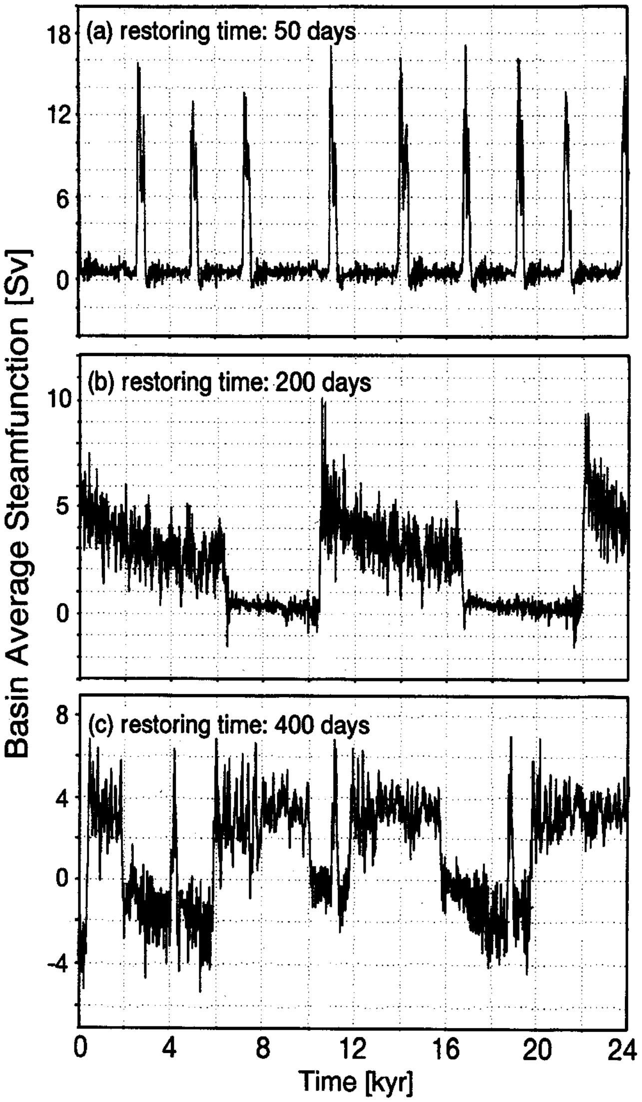

Figure 11. Time series of basin averaged overturning streamfunction. Three cases correspond to the different restoring time constant for SST. From top plate to bottom plate, the shortest case: (a) 50 days, the standard case: (b) 200 days, and the longest days: (c) 400 days.

4. SUMMARY AND CONCLUSIONS

The influence of deep ocean diffusion coefficients upon the stability of the Atlantic thermohaline circu-

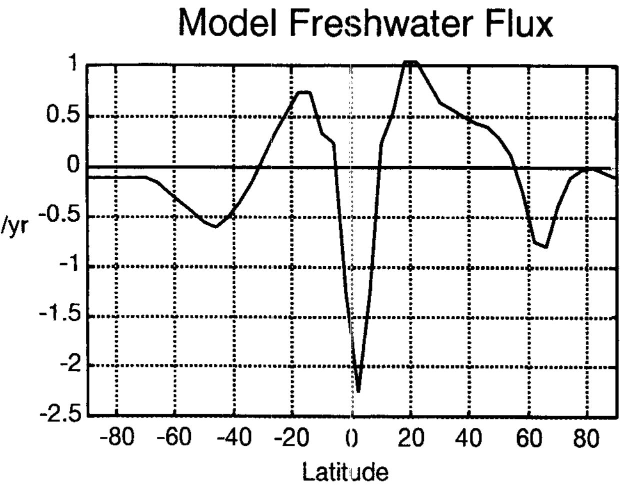

Figure 12. Model sea surface freshwater flux for a cold climate case. Anomalous freshwater in the high latitude North Atlantic is reduced approximately by 30%.

lation has been investigated by employing the three-dimensional GFDL Modular Ocean Model (MOM). The ocean general circulation model was configured to represent an idealized Atlantic basin and integrations of the model were performed under so-called mixed boundary conditions; that is with prescribed seasonally varying sea surface temperature to which the time varying SST of the model is continuously restored, and freshwater flux specified so as to include a localized high-latitude anomaly intended to mimic the influence of surface runoff during glacial conditions. The model is integrated, for each of the sensitivity analyses performed, for more than 10,000 model years in the absence of explicit wind stress forcing so as to focus upon the nature of the lowest frequency variability associated with the THC.

Depth dependent diffusion coefficients of temperature and salinity for the horizontal and vertical directions were employed in the numerical model, and a series of sensitivity experiments to investigate the impact of these coefficients on the nature of THC time dependence have been performed. The coefficients have been varied within the range of observations: $O(10^2) \sim O(10^3) m^2/s$ for the horizontal direction, and $O(10^{-5}) \sim O(10^{-4}) m^2/s$ for the vertical direction.

We derive two main conclusions on the basis of these experiments, beyond the now well established fact that the three dimensional ocean general circulation does deliver intense millennium timescale oscillation under steady boundary conditions, a fact previously demonstrated in SP97 and SP99. A first conclusion is that the horizontal diffusion coefficients for the abyssal ocean strongly control the stability of the system and thus determine the existence of the oscillatory solution, a result that is consistent with the conclusions in SP99. When the horizontal diffusion coefficients for the deeper layer (i.e. below 2000 m) are taken to be less than a critical value, the millennium timescale oscillation is produced by the model. The critical value of the horizontal diffusion coefficient turns out to be, in the experimental configuration employed herein, approximately $3 \times 10^2 m^2/s$. Although this value is considerably smaller than those typically employed in low-resolution ocean general circulation models, observational estimates for the large-scale horizontal mixing coefficients, for example those by Olbers et al.(1985), clearly show that the actual value lies near this throughout most of the layer of North Atlantic intermediate water. It is of interest, and will lead to a further conclusion, that even imposing a horizontal diffusion coefficient that is less than the critical value affects the period and pattern of the oscillation insignificantly. Our second conclusion is that a factor which most strongly affects the period of the millennium timescale oscillation is the vertical diffusion coefficient at the depth of the thermocline and halocline.

Additional sets of experiments were also performed in order to demonstrate the robustness of these primary conclusions. One set was designed to investigate the influence of the lower temperatures which correspond to ice-age conditions. By lowering sea surface temperatures every where by 4°C (but maintaining the lowest temperature to -2°C), we were able to confirm the fact that lowering the temperature does enhance instability, as specifically discussed in Winton(1997), though

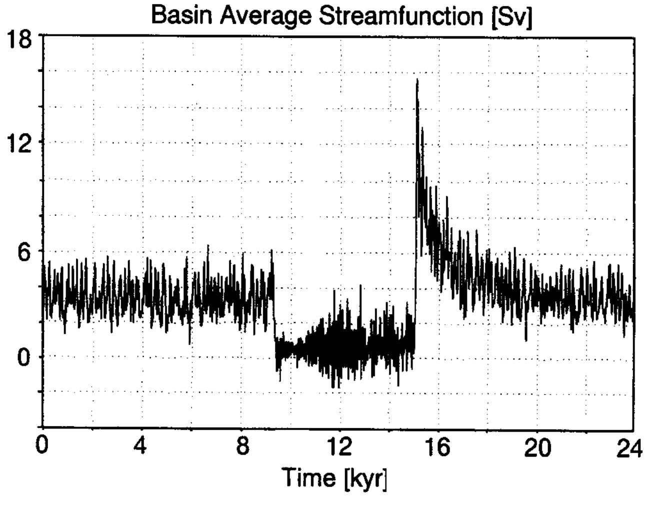

Figure 13. Time series of basin average overturning streamfunction. The result is obtained under a "cold climate" condition in which SST is set to have 4°C lower temperature than the modern SST that has been employed in this paper (the lowest temperature is still set to the freezing point of sea water).

the model continues to deliver an oscillation of the same kind as appears with somewhat weaker anomalous freshwater flux. Another set of experiments consisted of integrations with different assumed values for the restoring time constant for SST. The purpose of this set of experiments was to justify a posteriori the use of the mixed boundary conditions. We thereby confirmed that THC oscillations of the same kind are observed for the different values of the restoring time constant that range from tens of days to hundreds of days, although the period of the oscillation certainly differs: when the restoring time constant is short the THC cycle consists of a very intense and brief period of intense NADW formation followed by a relatively long period during which the THC is stagnant. With a long restoring time constant, however, the THC cycle consists of a relatively longer period of intense NADW formation followed by a shorter stage in which no NADW forms and the THC is stagnant.

Taken together the results obtained here suffice to demonstrate the robustness of the conclusion that the thermohaline circulation of the Atlantic Ocean supports millennium timescale oscillations, even when a fully configured ocean general circulation model is employed in the analysis. Our analyses have therefore further established the plausibility of our primary thesis that the millennium timescale Dansgaard-Oeschger oscillation observed in the deep ice cores from Summit, Greenland are due to an intrinsically nonlinear oscillation of the Atlantic THC that is expected to exist when the freshwater flux is in the vicinity of, but less than, the flux that would be required to shut down the circulation entirely.

According to recent analyses by Bond et al.(1997), distinct but much less significant ice-rafting events compared with the Heinrich events have been observed. Since these events are evident even after the last deglaciation, they are clearly connected to ice-rafting from the remaining icesheet, namely Greenland. In this paper we are not yet in the position to fully discuss the dynamic linkages between icebergs from Greenland and the North Atlantic THC under modern climate conditions, but it is useful to point out a few implications of the current work and previous papers: because we observe no strong oscillation in the temperature proxy for the Dansgaard-Oeschger oscillation corresponding to ice-rafting events during the Holocene, these minor ice-rafting events are unlikely to be a major factor in the mechanism underlying the Dansgaard-Oeschger oscillation. According to our previous analyses (SP99), however, the North Atlantic THC is somewhat sensitive to perturbations on the same timescales or longer than those characteristic of the primary THC oscillation. Therefore it is quite possible that such ice-rafting events play a role as a pacemaker of the Dansgaard-Oeschger oscillation. This issue will be further investigated in future work.

In the next step of this on-going series of investigations, however, we intend to further verify the validity of the theory by exploring more explicitly the influence on the internal variability of the thermohaline circulation due to atmospheric feedback. The analyses reported in SP97 suggest that this influence is important, based upon an analysis of the coupling that employed an atmospheric EBM to represent the feedback onto the surface of the ocean. In the next step in the further development of this idea we will be obliged to use a more fully articulated model of the atmosphere that includes explicit dynamic effects. An analysis of this kind will also enable us to fully investigate the interaction between the wind driven circulation and the thermohaline circulation.

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