*Natural Climate Variability on Decade-to-Century Time Scales*
*National Research Council, 1995*

# Low-Frequency Ocean Variability Induced by Stochastic Forcing of Various Colors

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## ABSTRACT

A primitive-equation global ocean general-circulation model with realistic geography has been forced with a variety of fresh-water flux models. The models' response appears as a number of fundamental eigenmodes. If the high-latitude forcing is of the order of 1 to 2 mm/day, then the dominant response has a period of roughly 300 years with significant variability in all the world's oceans. This response, partially documented by Mikolajewicz and Maier-Reimer (1990, 1991), occurs for forcing that is red or white in space and white in frequency. The transport of the Circumpolar Current fluctuates in response to this mode by a factor of two. In the Atlantic, the mode has a meridional circulation that extends over the whole basin/water column and a horizontal circulation that is clockwise. The most energetic portion of the Pacific circulation is more closely confined to the surface and more confused, although the associated attractor is fairly regular.

## INTRODUCTION

Increasing attention has been focused on the role of the ocean in forcing climate variations with time scales from decades to centuries. Among the various components of the global climate system, only the ocean seems at this stage of understanding to have the requisite thermal inertia. The atmosphere appears to have little memory beyond a few weeks, due to its small density and thermal capacity. Major changes in climate are associated with shifts in the planetary ice sheets, but the time scale of these changes is of the order of 1000 years or more, apparently too long for them to be a prime mechanism in forcing decade-to-century variations in other climate system components. Finally, changes in external forcing (e.g., solar radiation) and in some internal forcing (e.g., volcanoes) either have yet to be established or are currently thought to be too weak to affect other than local climate changes. The oceans thus remain as the most likely source of climate variability on time scales of 10 to 100 years or more.

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Recent work by a number of climate modelers has suggested that modest changes in atmospheric forcing can lead to radical changes in oceanic circulation that could have a dramatic impact on the global heat balance. The pioneering study of Stommel (1961) was apparently the first to suggest that the ocean's thermohaline circulation could exist in different, but stable, states. A spate of recent work with more complex models has confirmed that early work (see the comprehensive review of Weaver et al., 1993) and revealed many of the properties of the state transitions, as well as the sensitivity of the model results to subtle changes in the specification of the forcing—in these cases the flux of fresh water into and out of the oceans.

Most of the work to date has been done with simplified ocean models or steady-state fluxes of fresh water. The important work of Mikolajewicz and Maier-Reimer (1990, 1991) added a stochastic forcing term in the fresh-water flux and also used a full three-dimensional ocean general-circulation model (OGCM). Their result showed a quasi-periodic fluctuation in the thermohaline circulation; it had a time scale of the order of 300 years, and was most apparent in the Atlantic Ocean. Stocker and Mysak (1992) find significant spectral peaks in paleoclimate data with about the same period. Recently, Weaver et al. (1993) and Mysak et al. (1993) repeated that experiment (with a more simplified OGCM and rather arbitrarily defined flux fields) and described the relative importance of the stochastic term to the general model behavior.

The current paper expands on these earlier studies by examining the response of a realistic OGCM to different types of stochastic forcing. The model response to purely climatological forcing is compared to the additional response induced by stochastic forcing that is (1) white in both space and time, (2) red in space and white in time, and (3) red in both space and time, with the degree of redness determined by the coupling coefficients between the sea-surface temperature (SST) and SST gradients and the fresh-water flux field. This represents a coupled ocean-atmosphere model of a type that does not seem to have been previously explored.

## DESCRIPTION OF MODELS AND EXPERIMENTAL DESIGN

This section describes the ocean and stochastic atmospheric models used in this study. It also describes briefly how the coupled ocean-atmosphere model with feedback was constructed.

### *Ocean General-Circulation Model*

The OGCM used here is identical to that used by Mikolajewicz and Maier-Reimer (1990, 1991; MMR hereafter), which is described in detail by Maier-Reimer et al. (1993). It is a linear, primitive-equation model with a horizontal resolution of approximately 3.5° (an E-type grid) and 11 levels in the vertical. Unlike most of the modeling studies discussed above, this OGCM uses realistic geometry and ocean bathymetry. This is an important characteristic if one wishes to infer that the model results have relevance to the real world. The numerics are handled in such a way as to allow a time step of 30 days, thereby making extended integration feasible even on a workstation. At the surface (only) the heat-balance equation has a seasonally varying Newtonian damping to observed surface-air temperature climatology, while the salt balance uses a seasonally varying fresh-water flux to give realistic surface salinity fields (mixed boundary conditions). Seasonally varying wind stress (Hellerman and Rosenstein, 1983) is also used to force the model.

Again unlike most of the modeling work discussed above, the OGCM includes a simplified thermodynamic sea-ice model wherein the heat flux through the ice is proportional to the temperature difference between the underlying water and air temperature, and inversely proportional to the thickness of the ice. If one is interested in forcing an OGCM with fresh-water flux, then some representation of sea ice seems mandatory for a realistic simulation. In addition, the full UNESCO equation of state for sea water (see UNESCO, 1981) is used by the model to help properly represent the large-scale density changes associated with mixing. More details on the model and its construction can be found in the references above. These references also show that the model does a reasonable job of reproducing the major features of the ocean's general circulation as well as the distribution of temperature and salinity in the deep ocean.

### *Atmospheric Models*

The basis for constructing several of the atmospheric models is a 10-year integration of the Hamburg climate model (ECHAM3, T42 resolution; see Roeckner et al., 1992) forced by anomalous global SSTs. This integration was conducted as part of the Atmospheric Model Intercomparison Project (AMIP). The results, made available to us courtesy of L. Bengtsson, give monthly, globally gridded anomalies of fresh-water flux from the model and the observed SST and SST gradients that produced them. The distribution of the long-term mean and standard deviations of the fresh-water flux (E − P) are shown on Figure 1. In another study, we show that the flux and atmospheric moisture fields produced by this model compare well with observations of these same quantities where such comparisons are possible (Pierce et al. (unpublished manuscript, 1994)). The following atmospheric "models" were derived from this basic data set.

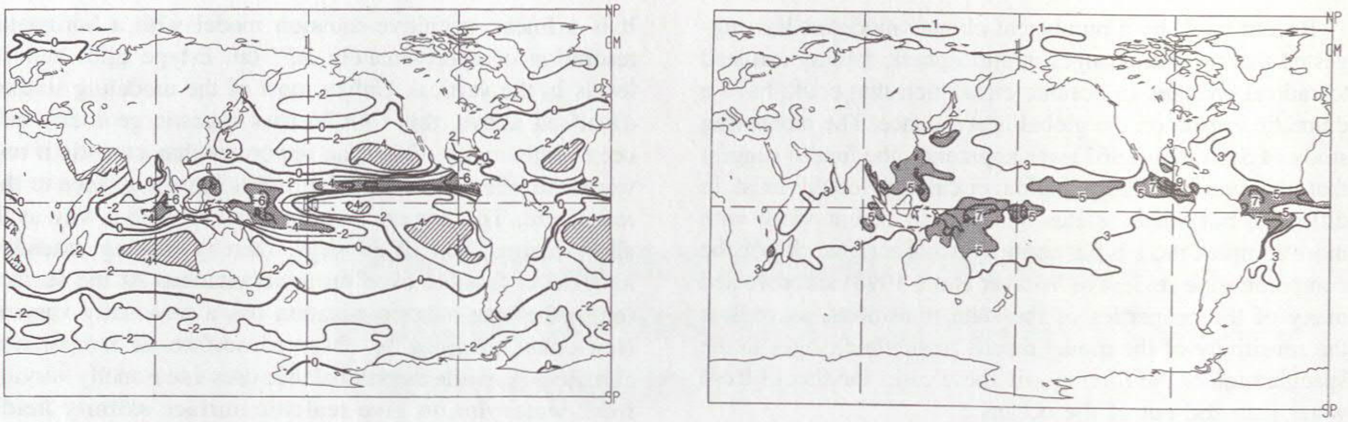

FIGURE 1 Mean (left) and standard deviation (right) of (E − P) from ECHAM3 T42 AGCM AMIP run.

White-White (WW) Atmospheric Model

At a given ocean-model grid point the anomalous fresh-water flux for each time step was obtained from a set of normally distributed random numbers with zero mean and standard deviation of *s* mm/day. Values of *s* in the range 1 to 3 mm/day are approximately equal to the amplitude of the seasonal cycle of fresh-water flux that forces the OGCM. These values are also approximately equal to rms values obtained from the AMIP run, and to an independent estimate obtained by Roads et al. (1992) from the National Meteorological Center (NMC) analysis. The same procedure was used at each individual ocean-model grid point, so that the anomalous fresh-water flux that drove the OGCM had no spatial correlation in its covariance field and was uncorrelated in both space and time, i.e., white in both wavenumber and frequency space. We refer to this as the white-white or WW model.

Red-White (RW) Atmospheric Model

The AMIP fresh-water flux anomaly field was represented as a series of empirical orthogonal functions (EOFs). The first 15 of these spatial functions $e_n(x)$ and their associated eigenvalues $l_n$ were retained. At each time step of the OGCM, an anomalous global fresh-water flux field was constructed as the linear combination of products of the $e_n(x)$ and n-random number with zero mean and standard deviation $l_n$. This model had the spatial structure of the fresh-water flux field from the T42, which was highly spatially correlated (red in wavenumber space) while being random in time (white in frequency space). Note that each EOF mode carried the same variance, $l_n$, as in the AMIP run. This type of stochastic atmospheric model is conceptually similar to but quantitatively different from that employed by MMR, and we refer to it here as the RW model.

Red-Red (RR) Atmospheric Model with Feedback

The AMIP data were used to develop a regression model relating the SST and SST gradients to the anomalous fresh-water flux. The model used the 15 leading EOFs of the AMIP fresh-water flux and SST fields. The regression model was nearly global in nature, covering all ocean points where sea ice never occurred. In most regions it captured 80 to 90 percent of the variance in the original AMIP fresh-water flux data set (only 15 EOFs).[5] However, the interesting fact was that the regression model captured a minimum of 96 percent of the variance associated with the first 15 EOFs. This result in turn suggests the highly linear relation between the SST and SST gradients and fresh-water flux. The basic approach to constructing such an atmospheric model can be found in Barnett et al. (1993).

Incorporation of the SST and SST gradient into the model obviously allows for a feedback between the ocean and pseudo-atmosphere and represents a type of coupled model not previously attempted on a global scale (although such a coupled model has produced good simulations of El Niño events (Barnett et al., 1993)). The relatively slow changes in SST ensure that the atmospheric model will be red in frequency space. The large-scale spatial correlations in both SST and fresh-water flux produce a wavenumber dependence that is also red, so this model was called the red-red or RR model.

### *Experimental Setup*

The basic model was run for 4000 years of simulated time forced only by the seasonal cycle. The state of the ocean at that time was taken as the initial condition for all subsequent runs. Four different basic simulations were

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[5] The main model skill (and the AMIP signal) lay between 30°N to 30°S. It captured only 20 to 50 percent in the highest latitudes, and this turned out to be an important shortcoming.

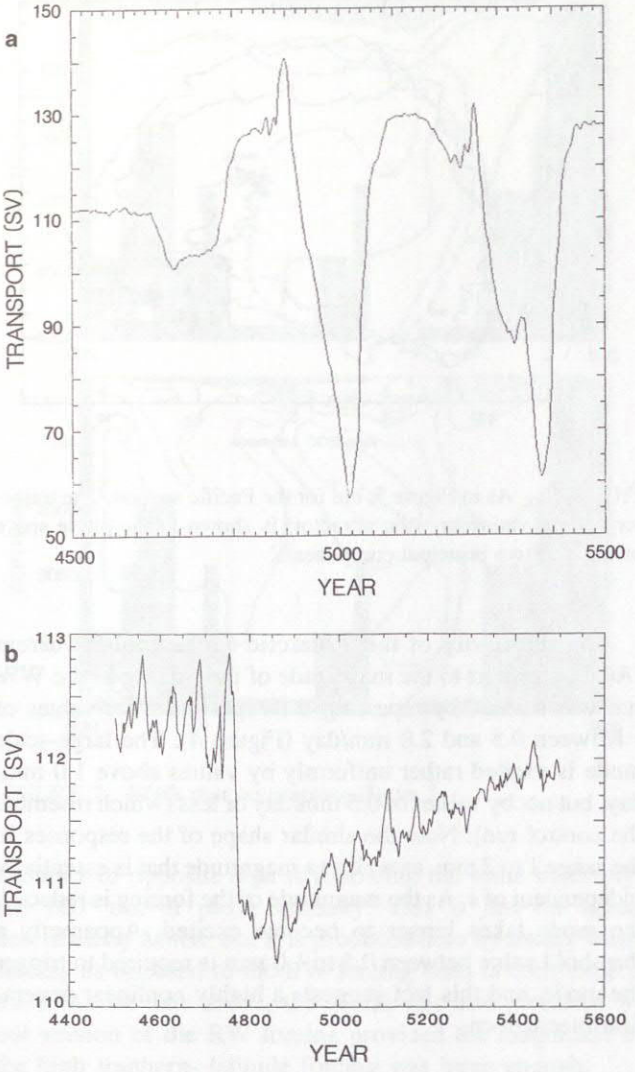

FIGURE 2 Transport (sverdrups) through the Drake Passage for OGCM forced by white-white noise (a) and red-white (b) noise.

carried out: The first was a continuation of the climatology run for an additional 1500 years. Results from this run have the designator C. Each of the three stochastic, anomalous fresh-water flux models was mated to the OGCM and run for 1500 years. The first 500 years of each integration were discarded, leaving the remaining 1000 years for analysis. The designators for these runs are WW, RW, or RR depending on which atmospheric model was used. All three anomaly runs included the same seasonal cycle, fresh-water flux, wind stress, and pseudo-heat flux forcing used in the climatology run.

## RESULTS

This section briefly summarizes some of the more interesting results of the four experiments described above. Since this research effort is in the very early stages, these results are presented in descriptive form.

### *Antarctic Circumpolar Current Response*

The model-simulated transport through the Drake Passage is shown in Figure 2 for several of the experiments. The C run shows nearly constant transport close to that observed, with annual variations of less than 1 percent (no illustration shown). The WW run, on the other hand, for $s = 2$ mm/day shows large variability, wherein the transport can change by 50 percent (Figure 2a). The time scale for this fluctuation is of the order of 300 years; it seems to be the mode of variation previously found by MMR (see below). By contrast, the RW run (Figure 2b) shows a step-like jump but otherwise low interdecadal variability. The feedback or RR run (not shown) is much like the RW run but with almost no high-frequency variability.

We deduced from the above results that the spatial correlation in the fresh-water forcing was not particularly important to the model response. Similarly, we concluded that it is the magnitude of the forcing in the high latitudes (only) that really affects the model behavior. We confirmed these conclusions by rerunning the RW case, but with the magnitude of the forcing increased by a factor of 5 for latitudes above 40°, where the RW atmospheric model was deficient in energy. This increased forcing brought the magnitude of the flux up to the order of 1 mm/day and corrected for the model's low variability in that region. The resulting transport through the Drake Passage (Figure 3) now resembles that found in the WW run with regard to both magnitude and time scale. In addition, similar experiments showed that it was the $E - P$ flux south of 40°S that generated the MMR mode, while the flux in the northern ocean was of little significance other than local.

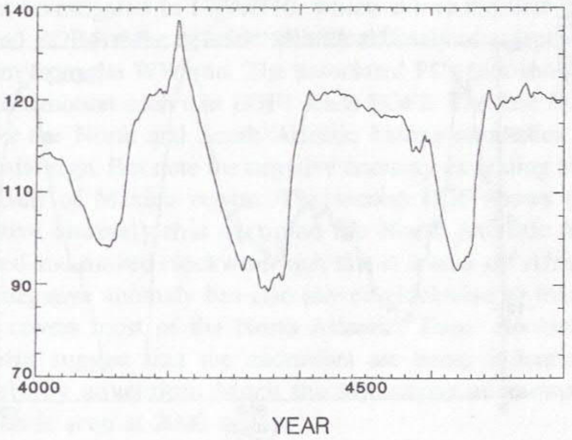

FIGURE 3 Same as red-white transport in Figure 2b, but run with variability above 40° latitude increased by a factor of 5.

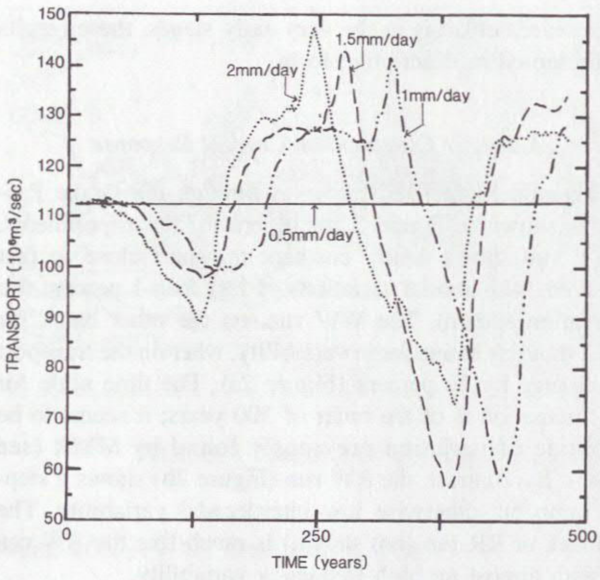

FIGURE 4 Drake Passage transport for white-white forcing with different levels of fresh-water flux variability. Atmospheric models and observation/analyses suggest that values of 1 to 2 mm/day are realistic in the higher-latitude regions.

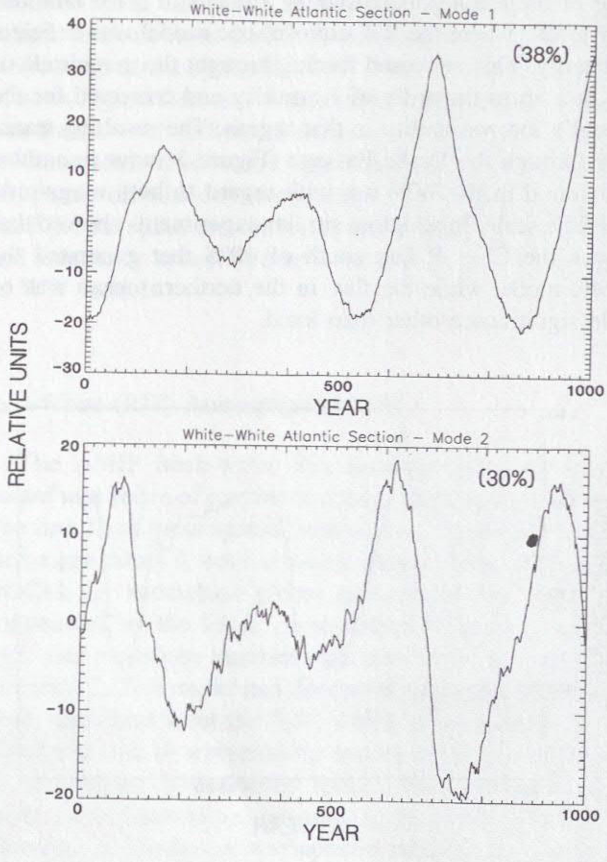

FIGURE 5 Principal components for Atlantic salinity section EOFs: white-white forcing.

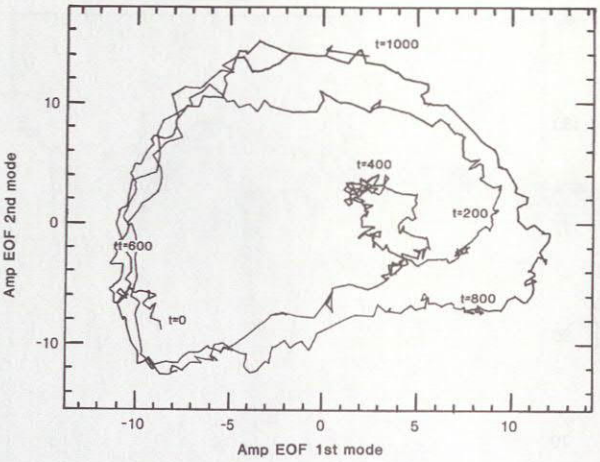

FIGURE 6 As in Figure 5, but for the Pacific section. The trajectory of the variability (the attractor) is shown in the phase space of the first two principal components.

The sensitivity of the Antarctic Circumpolar Current (ACC) transport to the magnitude of the forcing in the WW run was studied by repeating the experiment for values of *s* between 0.5 and 2.0 mm/day (Figure 4). The large-scale mode is excited rather uniformly by values above 1.0 mm/day, but not by values of 0.5 mm/day or less (which resemble the control run). Note the similar shape of the responses in the range 1 to 2 mm, as well as a magnitude that is essentially independent of *s*. As the magnitude of the forcing is reduced, the mode takes longer to become excited. Apparently a threshold value between 0.5 to 1.0 mm is required to trigger the mode, and this fact suggests a highly nonlinear generation mechanism.

### *Meridional Structure*

Salinity and temperature data from the WW run[6] were saved along key meridional sections in both the Pacific and the Atlantic and subjected separately to EOF analysis. The principal components (PCs) for modes 1 and 2 for both oceans are shown in Figure 5 in standard format and in Figure 6 in two-dimensional phase space. It is clear that the roughly 300-year oscillation described above extends into the high latitudes of both major oceans. In the Atlantic, the PCs are in quadrature, and this means that the salinity anomalies propagate. The sense of the motion revealed by the EOFs (Figure 7) is that more (or less) saline water moves northward from Antarctica in the near-surface waters to the central North Atlantic where it sinks and returns at depth to the Southern Ocean. While this is happening, an

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[6] Given the similarity in the responses of the OGCM to different atmospheric forcings, we concentrate in the rest of the paper on the results of the WW run.

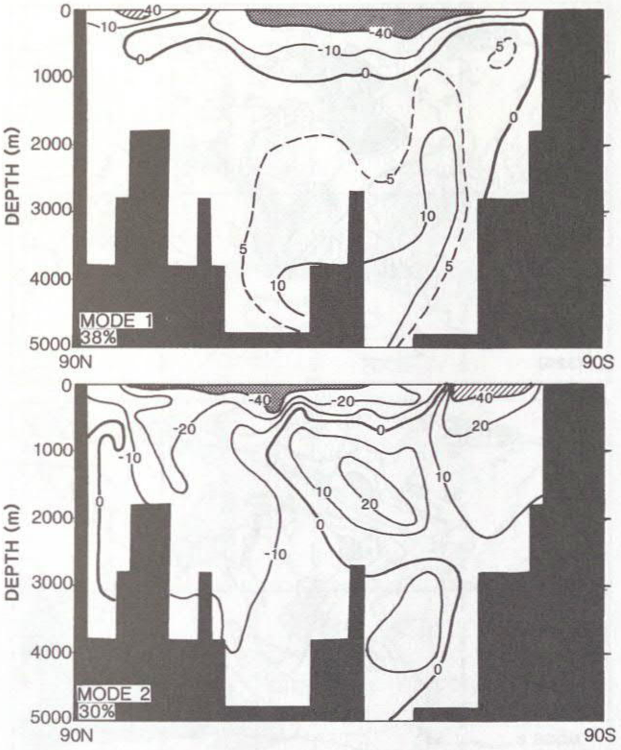

FIGURE 7 EOFs that accompany Figure 5.

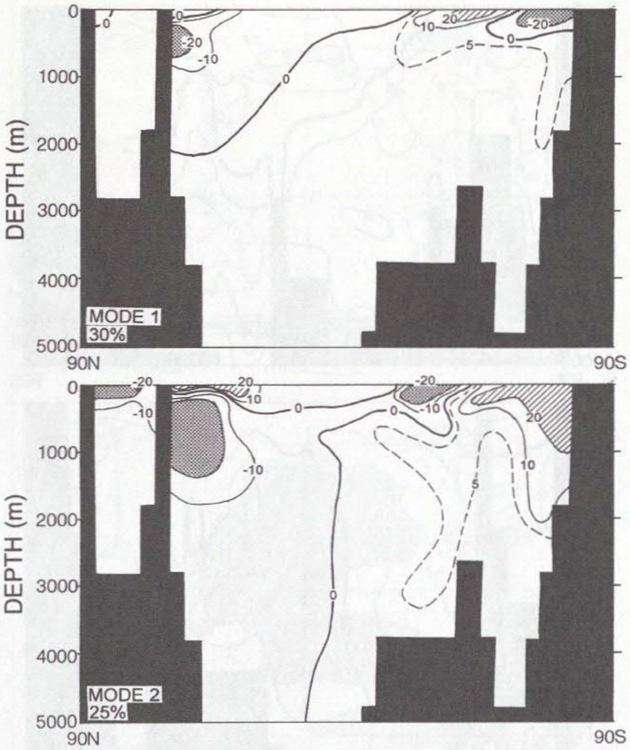

FIGURE 8 EOFs that accompany Figure 6.

anomaly of opposite sign is following the same trajectory, but 180° out of phase spatially. This is just the signal described by MMR, but it is produced here by totally white forcing as opposed to the RW forcing used in their experiment. As we saw above, the signal was also produced by our version of the RW forcing provided the magnitude of the high southern- latitude forcing was large enough.

The form of the signal in the Pacific (Figure 8) is somewhat like that found in the Atlantic. The two PCs form a rather simple attractor (Figure 6) and are in quadrature again, suggesting a propagating signal in the salinity field. The time scale is roughly 300 years, as found above. A major difference between the two oceans is that the signal does not penetrate in strength to the same depth it was found to in the Atlantic. The signal appears to propagate from one end of the ocean to the other, but is closely confined to the upper layers of the water column and has more spatial structure than in the Atlantic.

The simple correlation between the ACC transport fluctuations (Figure 2) and the variability of the salinity along the Atlantic-Pacific sections is shown in Figure 9. In the Atlantic, the plus-minus signature of the correlation field is indicative of the propagating signal discussed above. Note that major reductions in the strength of the ACC accompany reduced salinity over most of the South Atlantic to depths of the order of 1000 m. This is countered by increased salinity in the North Atlantic and in the deeper parts of the entire Atlantic. The signature of the ACC variability in the Pacific is identical to that in the Atlantic, but only in the North Pacific. Most of the Pacific, even to the greatest depths, is more or less in phase with the ACC signal. However, the absolute values of the correlation in the Pacific are less than those found in the Atlantic.

### *Horizontal Structures*

The horizontal structure of the low-frequency MMR signal is investigated in Figure 10, which shows the first and second EOFs of the Atlantic salinity anomaly at a depth of 700 m from the WW run. The associated PCs (not shown) suggest motion such that EOF1 leads EOF2. The first EOF shows the North and South Atlantic having anomalies of opposite sign. But note the negative anomaly extending into the Gulf of Mexico region. The second EOF shows the positive anomaly that occupied the North Atlantic has rotated and moved clockwise such that it is now off Africa. The negative anomaly has also moved clockwise so that it now covers most of the North Atlantic. These clockwise motions suggest that the anomalies are being influenced mainly by advection. Much the same type of anomaly motion is seen at 2000 m also.

The simple correlation between the ACC index and the salinity anomalies at 700 m and 2000 m is given in Figure 11. The entire Indian, North Pacific, and North Atlantic

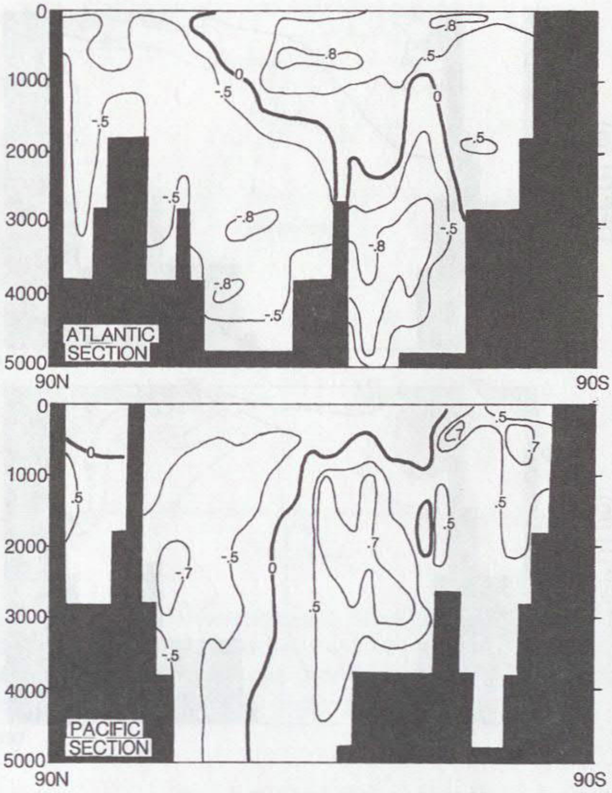

FIGURE 9 Correlation between Drake Passage transport and salinity variability along the meridional sections for the white-white forcing experiment.

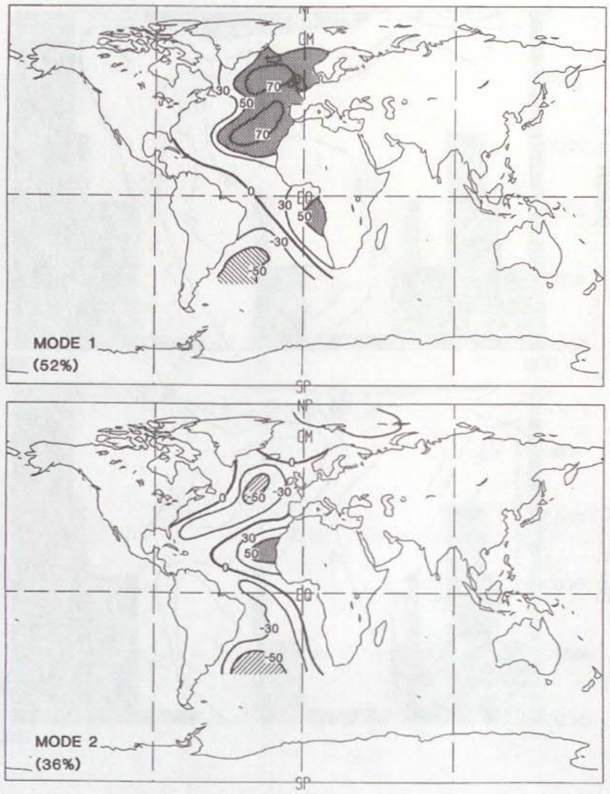

FIGURE 10 Leading EOFs of Atlantic salinity field at 700 m from the white-white run.

oceans are in antiphase with the ACC at 700 m. Much the same pattern holds in these regions at 2000 m. The South Pacific and South Atlantic vary in phase with the ACC at both depths, but an unexpectedly strong signal (positive) is apparent in the western Equatorial Pacific. At 700 m the strongest signals are in the Indian Ocean, but at 2000 m this distinction is held by the South Pacific and the North Atlantic. It is obvious that the ocean mode of variation discussed here is truly global in extent.

### *Levels of Variability*

The rms variability of the salinity field from the WW and RR runs is shown in Figure 12 for depths of 75 m. The RR run produces far more variance in the salinity field, especially in the deep ocean (e.g., 2000 m, not shown) where rms values of 0.06 to 0.08 psu are common in higher latitudes. The spatial distribution of the variability between the two runs clearly shows the importance of large-scale air-sea interactions in forcing the model. If the RR run is at all realistic, then the coupling between the two media needs to be taken into account in studies of interdecadal variability. It is interesting that the spatial structure of the modal response was similar between all the runs, even if the levels of variance were not. This suggests the response is a leading "eigenmode" of the global ocean model that is easily excited by a wide range of forcing.

## SUMMARY

A reasonably sophisticated, realistic OGCM has been forced with annual cycles of wind stress, temperature, and fresh-water flux, and also with anomalies of fresh-water flux. The latter anomaly model simulations range from forcing that is white in both space and time to a model that is red in both domains and also incorporates feedback between the fresh-water flux and local SST.

The results of these simulations show a richly structured response. One prominent mode is that discovered by Mikolajewicz and Maier-Reimer (1990, 1991). We found that mode is driven principally by anomalous fresh-water flux in the higher latitudes of the Southern Hemisphere. The spatial structure and details of the forcing are not as important to the mode as the magnitude of the forcing. Monthly anomalies greater than 1 mm/day will excite the mode, while values below 0.5 mm/day do not. Atmospheric-model results and NMC analyses suggest that realistic values of anomalous fresh-water flux in the high latitudes are of the order

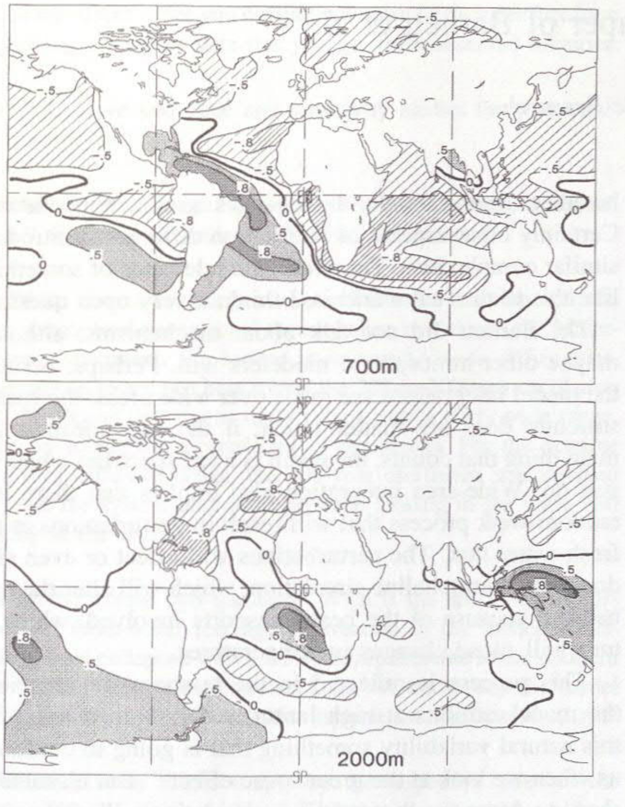

FIGURE 11 Correlation between Drake Passage transport and salinity variations at 700 m and 2000 m for the 1000 year white-white run.

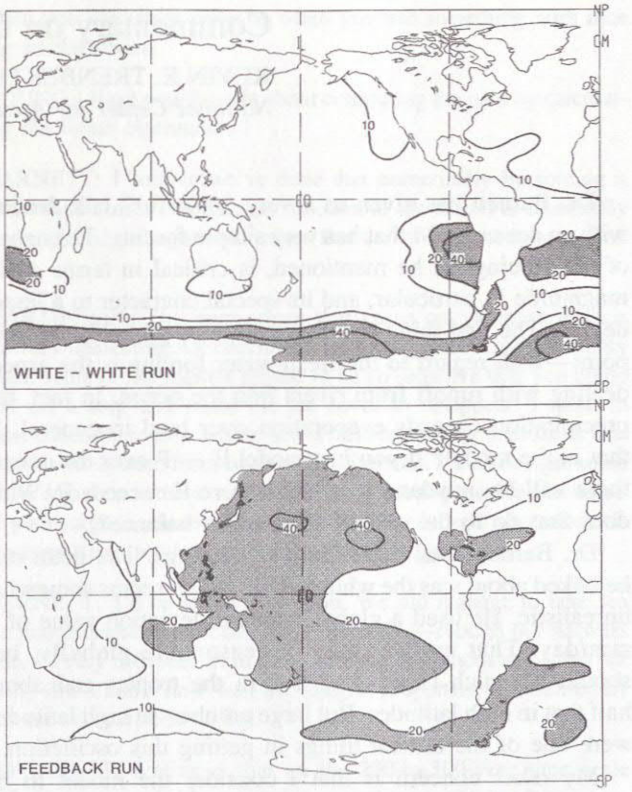

FIGURE 12 Standard deviation of salinity (psu) at 75 m from two noise-forced runs.

of 1 to 2 mm/day, so the forcing required for this mode in the OGCM may not be unrealistic.

The principal mode referred to above has expressions in all major oceans, and is also associated with changes in the transport of the ACC by a factor of two. The mode in the Atlantic is associated with a meridional overturning of the entire ocean and a horizontal circulation that is clockwise. The mode in the Pacific does not penetrate in strength as deeply as in the Atlantic, and it appears to have a more difficult time extending across the equator.

The levels of interdecadal variability produced by the model for virtually all of the atmospheric forcing models we used was surprisingly large in view of the coarse OGCM resolution. If these levels of variance were found in the real-world ocean, they would represent an important level of change.

## ACKNOWLEDGMENTS

This work was supported by the Department of Energy through its Computer Hardware, Advanced Mathematics, and Model Physics (CHAMMP) effort under contract DE-FG03-91-ER61215, and by the National Science Foundation under Grant NSF ATM88-14571-03. The Deutsche Forschungsgemeinschaft and the Sonderforschungbereich 318 provided support for U. Mikolajewicz. M. Schultz helped with the drafting and T. Tubbs carried through many of the key computations. R. Wilde was supported under the NSF program for undergraduate research (REU).

# Commentary on the Paper of Barnett et al.

KEVIN E. TRENBERTH
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Dr. Barnett has given us a very "colorful" talk dealing with an ocean GCM that has very simple forcing. The nature of the forcing, as he mentioned, is critical in terms of its magnitude in particular, and its special character to a lesser degree. The first thing that I thought of—probably a minor point—with regard to the fresh-water forcing is the aspect dealing with runoff from rivers into the ocean. In fact, the precipitation exceeds evaporation over land in general. Is that in the model? If you just model E − P over the ocean, there will be imbalances, because there E exceeds P. What does that do to the overall fresh-water balance?

Dr. Barnett used three kinds of forcings. The main one he talked about was the white/white, which seems somewhat unrealistic. He used a global standard deviation value of 2 mm/day. That number may be reasonable globally, but should be much larger than that in the tropics and about half that in high latitudes. But large numbers at high latitudes were one of the critical things in getting this oscillation.

My other concern is that I consider the model to be unnaturally constrained. Any time you use an idealized atmosphere, the nature of the fluxes into the model ocean and the ability of the atmosphere to feed back and adjust in various ways are limited. For instance, can the climate system adjust to compensate for the fresh-water flux? The parameterization derived here for the red/red case, especially in the tropics, does indicate that the fresh-water flux can be altered substantially by changes in sea temperatures. Certainly other aspects of land-ocean differences introduce similar complexities. Therefore, the relevance of something like this to the real world is, I think, a very open question.

Dr. Barnett did not talk about mechanisms, although maybe other atmospheric modelers will. Perhaps, because the model integrations are made over wide areas, the spatial structure does not matter much; if the area mean is the main thing that counts, the result is a red spectrum whatever you do. Wide-area integration also implies that there is a random-walk process that will result in perturbations in the fresh-water flux. The perturbations will affect or even shut down the thermohaline circulation, which will alter the heat balance because of the heat transports involved, which in turn will cause changes in temperatures.

This process is reflected in the temperature variations the model exhibits at high latitudes. Dr. Barnett asks, "Is this natural variability something that is going to confound us when we look at the greenhouse effect?" But ultimately, shutting down the thermohaline circulation will change the temperatures enough that they will probably cause the thermohaline circulation to jerk back into action at some point and advect fresh water around. Might this be part of the mechanism that results in an oscillation? I do not know. I think the bottom line is the question of these models' relevance to the real world.

# Discussion

BARNETT: That last question does need to be kept in mind, but for a full-ocean GCM our model does quite a good job of reproducing the main features of the global ocean.

TRENBERTH: Isn't the forcing at high latitudes much higher than in the AMIP run?

BARNETT: Not much. We picked 2 mm/day because it's a fairly good global average, and I think it's fairly realistic. I believe some other models using a smaller figure still get the oscillation.

SARACHIK: Why did you choose to show the transport of the Antarctic circumpolar current, and what was the structure of the changes in it?

BARNETT: It's a simple diagnostic for the system. If you have no signal there, you won't have much anywhere.

BRYAN: I'd like to respond to Kevin's comment about runoff. For the North Atlantic, I believe that runoff is dominant at very high latitudes simply because the coastline is so extensive by comparison with the ocean area. If you also take into account the tremendous Arctic fresh-water discharge, the total runoff is much greater than the local net precipitation.

BARNETT: This runoff effect has been included in a couple of models for the Hamburg greenhouse runs, and it's my impression that it didn't make much difference. If it is large, though, it should be fairly simple to put into these kinds of models.

TRENBERTH: Runoff might affect the nature of feedbacks, and clearly on time scales that cover the melting of major ice caps it would become critical.

WEAVER: It seems to me that you do have a sort of parameterization of the runoff, since you obtain your mean fresh-water flux from diagnosing a spun-up state that you got from observed salinities.

MYSAK: Have you done any sensitivity studies for your model's parameters?

BARNETT: No, though others have. It's tuned to today's climate. I don't think it's particularly diffusive, for instance.

MYSAK: One of the things we were interested in doing with the very simple two-dimensional thermohaline model was the Maier-Reimer experiment. We looked at its sensitivity to diffusivities, for example, to see just how robust the 200-to-300-year oscillation was. We found that it was fairly robust over a fairly wide range, and very robust for a certain set of parameters. For the extreme of a very diffusive ocean, the 200-year oscillation was damped out, and the system alternated between sinking in the north and sinking in the south.

LEHMAN: I have two questions. What is the sensitivity of this model to fresh-water forcing? Convection in the model Maier-Reimer used collapsed with a .02-sverdrup increase to the northern part of the North Atlantic. Second, do you know why the model is more sensitive to Southern Hemisphere forcing than Northern?

TRENBERTH: It might simply be the respective sizes of the oceans. If you're doing random forcing that has no spatial structure, you need a large area to integrate over to get a decent-sized signal.

BARNETT: The odd thing is that you get about the same answer when you use white noise as when you use something with nice big spatial scales.

YOUNG: Have you thought about computing the gain by calculating the linear eigenmodes?

BARNETT: I believe we've done that numerically by forcing it with white noise. The transfer function of the model is essentially the empirical orthogonal function. But we've barely begun to look at it.

MARTINSON: The fluctuations that come out of these models are very interesting. Of course it's hard to equate them with reality when some of the regions appear to be so sensitive that you could spit off a ship and cause the ice cover to disappear. I think in most cases there is a whole set of self-regulating feedbacks that prevent the system from overturning like that. I'd like to get some of us together to look at the fine-scale local processes in terms of your larger-scale results and see whether indeed your model is representative in what you might call a budget sense.

BARNETT: I'd be glad to join you. We did manage to take sea ice into account and not destroy it too badly—though our answers weren't very different from those of models without any—but we really don't know how well the integral properties represented by this model resemble reality.

MYSAK: My feeling is that on the 200-to-300-year time scale the sea ice is probably not going to influence the results.

TRENBERTH: Ah, but having ice in the model allows for many other feedbacks to the atmosphere that make the system even more complex.