THERMOHALINE CIRCULATIONS AND GLOBAL CLIMATE CHANGE

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Background

This report discusses research activities conducted under the auspices of DOE Grant No. DE-FG02-90ER61019 during the period 15 January 1992 - 14 December 1992.

"Thermohaline Circulations and Global Climate Change" is concerned with investigating the hypothesis that changes in surface thermal and hydrological forcing of the North Atlantic, changes that might be expected to accompany CO_2-induced global warming, could result in ocean-atmosphere interactions' exerting a positive feedback on the climate system. Because the North Atlantic is the source of much of the global ocean's reservoir of deep water, and because this deep water could sequester large amounts of anthropogenically produced CO_2, changes in the rate of deep-water production are important to future climates. Since deep-water production is controlled, in part, by the annual cycle of the atmospheric forcing of the North Atlantic, and since this forcing depends strongly on both hydrological and thermal processes as well as the windstress, there is the potential for feedback between the relatively short-term response of the atmosphere to changing radiative forcing and the longer-term processes in the oceans. Work over the past 11 months has proceeded according to the continuation discussion of last January and several new results have arisen.

Model Development and Data Sets

The model development phase of this project is mostly finished. Additional ports of the isopycnic/mixed-layer model of the North Atlantic were made to an IBM RS/6000/560 system (which is now available in-house at CIRES and has a substantial performance advantage over the Sun 4/360 used previously). Both the rectangular-basin version and the geographically realistic version of the hybrid model are being integrated on this platform. The rectangular-basin version is also being integrated on the i860 platform; these small systems are being used to explore the sensitivity of the 2°-resolution version of the model(s) to varying forcing. Also, this aspect of the work has been very helpful to model development in general because of the variations among the different compilers used. A result has been the evolution of a more robust numerical model than we had previously. In particular, the sensitivity of the different compilers to various aspects of numerical instability has led to greater understanding of model time-step requirements at different levels of vertical resolution, an unexpected sensitivity.

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Higher resolution versions of the realistic-basin version of the model are being integrated on larger platforms. Computer time at the National Center for Atmospheric Research (NCAR) has been augmented with time acquired from DOE at the National Energy Supercomputer Research Center (NERSC); the NCAR and NERSC Cray platforms are being used to explore differences in model behavior as the horizontal resolution is increased to 1° (which is a factor of eight increase in computation because the time step is also halved). Finally, in collaboration with R. Malone and S. Barr at Los Alamos National Laboratory (LANL), an eddy-resolving, 0.5°-resolution version of the model has been ported to the new CM-5 massively parallel processing machine there. This latter collaboration is a new effort begun during a visit last spring by the PI to LANL, during which early results of this project were presented in a seminar. Following this, last summer, S. Barr spent time at CIRES with the PI and co-PI R. Bleck working on the port of the model to FORTRAN-90 on the CM-5.

The other aspect of model development in this project has been the construction of model forcing from atmospheric data sets. Both the Comprehensive Ocean-Atmosphere Data Set (COADS) and the Oberhüber climatology based on COADS have been used for this purpose. Diagnostics based on this forcing set were presented at the International COADS Workshop held in Boulder last winter (a reprint from the Workship Proceedings is attached). One small project remains: the NCAR-developed Community Modeling Effort (CME) circulation model is being used by colleagues at the University of Miami to investigate far-North Atlantic phenomena, and the forcing set developed under this project will be expended to 80° N and used for this other World Ocean Circulation Experiment (WOCE) effort. This will be a very useful collaboration because it will allow model intercomparisons, something that was not previously envisioned to occur specifically under the auspices of this DOE-sponsored work. This and the LANL collaboration are expected to continue through the renewal phase of this project.

Other contributions associated mainly with the data set aspects of this project include seminars at the Pacific Northwest Laboratory and the Oak Ridge National Laboratory in the spring and summer of 1992, and the appearance of the paper discussing Great Lakes climate trends in the *Bulletin of the American Meteorological Society* (a reprint is attached).

Model Diagnostics

There are basically two separate, parallel efforts in this project that fall under the heading of ''model diagnostics:'' development of visualization tools and the actual scientific investigations using the model. In the former category are development of the interactive viewing and visualization tool for X-terminals (which has been successfully ported to LANL, where it is being evaluated in the 'alpha-test' mode) and the use of computer-generated video-tape loops to examine model results and diagnostics of the forcing set. A black-and-white copy of a screen dump from the viewing and visualization tool is attached as Plate I. This shows a plot of mixed-layer depth (as height) and temperature (as shading) for the basin model, with three other interactive windows that allow choices of (top-to-bottom, below the clock) visualized parameters, viewing angle, and color table. It needs to be emphasized that this black-and-white copy does considerable injustice to the color screen (it can be, however, photocopied). Experimental versions of video loops of plots such as that on Plate 1 and of the forcing data set were presented at the afore-mentioned seminars to good effect, and the discussion generated was quite helpful in both improving the production of the videos and explaining results from the data and model.

Of more scientific interest are the results from model integrations. In Annual Progress Report No. 2, results of a numerical experiment involving the effects of interannual variability of the forcing on decade-scale changes in thermocline ventilation were discussed. Briefly, the fundamental result was that interannual variations in radiative heating at the ocean surface (as represented in the numerical experiment by a simple six-year square wave with total amplitude 50 W m^{-2}) significantly increases thermocline ventilation on the time scale of decades even though the net surface heating over the period of integration does not change. Clearly, this complicates the understanding of oceans' role in climate change by making explicit, coupled-model integrations necessary.

In the last year, this aspect of the investigation was extended to explore the influence of "synoptic"-scale forcing variations on the annual cycle. This was done with a simpler, one-dimensional version of the vertical mixing component of the hybrid circulation model, with the effects of horizontal advection prescribed and varied. This calculation has the advantage that model results can be compared directly to observations, which is not possible for the ventilation results. COADS/Oberhüber data (Fig. 1a) were used to construct a phase plot of surface heat flux (expressed so that a positive flux connotes oceanic heating) vs. sea-surface temperature (SST). The resulting hysteresis loop, which vaguely resembles a cross-section of a a potato, depicts the annual cycle of SST and a significant component of its time derivative, the surface heating. The shape of the loop is determined mostly by the behavior of the mixed-layer depth, which determines the thermal inertia of the system.

The diagram in Fig. 1a is based on data from the vicinity of Ocean Station C in the North Atlantic. Analogous diagrams based on data from other locations would reflect differences in the annual cycles of SST and mixed-layer depth, as well as horizontal advection and upwelling; the North Atlantic in the vicinity of Ocean Station C was chosen for this calculation because there is a strong sensitivity of the vertical mixing there to atmospheric processes (see the Proceedings reprint attached) and this is most germane to this research. Other locations tested, however, show a similar potato-like shape to the hysteresis loop.

Although there are a number of interesting features in Fig. 1a, this discussion will be limited to the winter/spring heating that begins in early January (slightly counter-clockwise from the lower-left 'J' in Fig. 1a, which denotes January 15). Even though the surface cooling is no longer increasing, the SST continues to decrease until about 15 February, following which increases in heating and SST are in phase. By 15 April (the 'A'), the SST has increased by about 1° C, and the surface flux is nearly two-thirds of the way to its 15 June maximum. This is the time period during which the seasonal thermocline forms, and in which water ventilated by the previous winter's air-sea interaction processes is injected into the deep ocean. Consequently, these seasons are the determining factors in the influence of the oceans on climate change on the scale of decades to centuries.

Figure 1b shows a simulation of the vertical mixing in the North Atlantic using a smooth annual cycle (that is, one in which monthly averages of the atmospheric forcing are smoothly interpolated on to the time integration of the model calculation). In this calculation, the (horizontal) advective heating was adjusted in such a way to match the 15 January model calculation to the data (the adjustment in this case was within 10% of the value taken from observations) so that the heating season begins in phase with the observations. Note, however, that the SST does not respond as quickly to the spring warming in the model as it does in the observations in Fig. 1a: by 15 April, there is virtually no SST increase, and this discrepancy continues until June. Clearly, the model is calculating too large a thermal inertia, so that the SST is responding too slowly.

Figure 1c shows a calculation in which the atmospheric forcing is perturbed on a time scale of five days. In this case, the wind speed was varied by 50% of its monthly mean using a 10-day wavelength square wave, so that the surface sensible heat flux and evaporation would be decreased and increased proportionally to the mean wind on a five-day time scale, a rough analogy to synoptic activity. Although the January-April SST increase is still only about half of that in the observations in Fig. 1a, the change from Fig. 1b is significant and suggestive of the importance of the influence of short-timescale atmospheric forcing on the oceanic influence on climate.

The processes responsible for this sensitivity of the ocean to atmospheric forcing involve the delicacy of the turbulence kinetic energy balance during the heating season, both in the mixed-layer model and in the real ocean (e.g., observations reported by Dickey *et al.* in the Journal of Geophysical Research, **96**, pp. 8643–8664). Small changes in atmospheric forcing can cause dramatic changes in oceanic mixing. This result was seen in the initial integrations of the hybrid model (reported in Bleck *et al., Journal of Physical Oceanography,* **19**, pp. 1417–1439) under the influence of smoothly varying atmospheric forcing, and the results in Fig. 1 suggest that atmospheric variability enhances the mixing sensitivity during the late winter and spring. The significance of this result must not be underestimated: in order for the role of the oceans in climate to be properly assessed, it is necessary to consider the effects of atmospheric forcing at least down to the synoptic time scale. In interactive, coupled atmosphere-ocean models, this has important implications for the mode of numerical integration and how often the modeled fluids actually "interact." In this regard, the initiative at LANL to directly couple an oceanic model on the CM-5 with an atmospheric model on a separate platform via a fast inter-platform data link seems especially attractive.

These results suggest that the initial computational strategy outlined in this project needs refinement, and this refinement is the topic of the accompanying renewal proposal. Meanwhile, the initial questions posed in this project are being pursued in detail as the topic of a dissertation by Ms. Fiona Horsfall, a graduate student at the University of Miami supervised by the co-PI, Prof. R. Bleck and supported by the UM subcontract of this award. Her dissertation proposal (a draft is enclosed) is concerned with how the hybrid model responds to long-term variations in surface forcing, with particular attention paid to the ventilation problem. The role of short-term variability in these processes is, however, a more complex problem, as outlined in the renewal proposal.

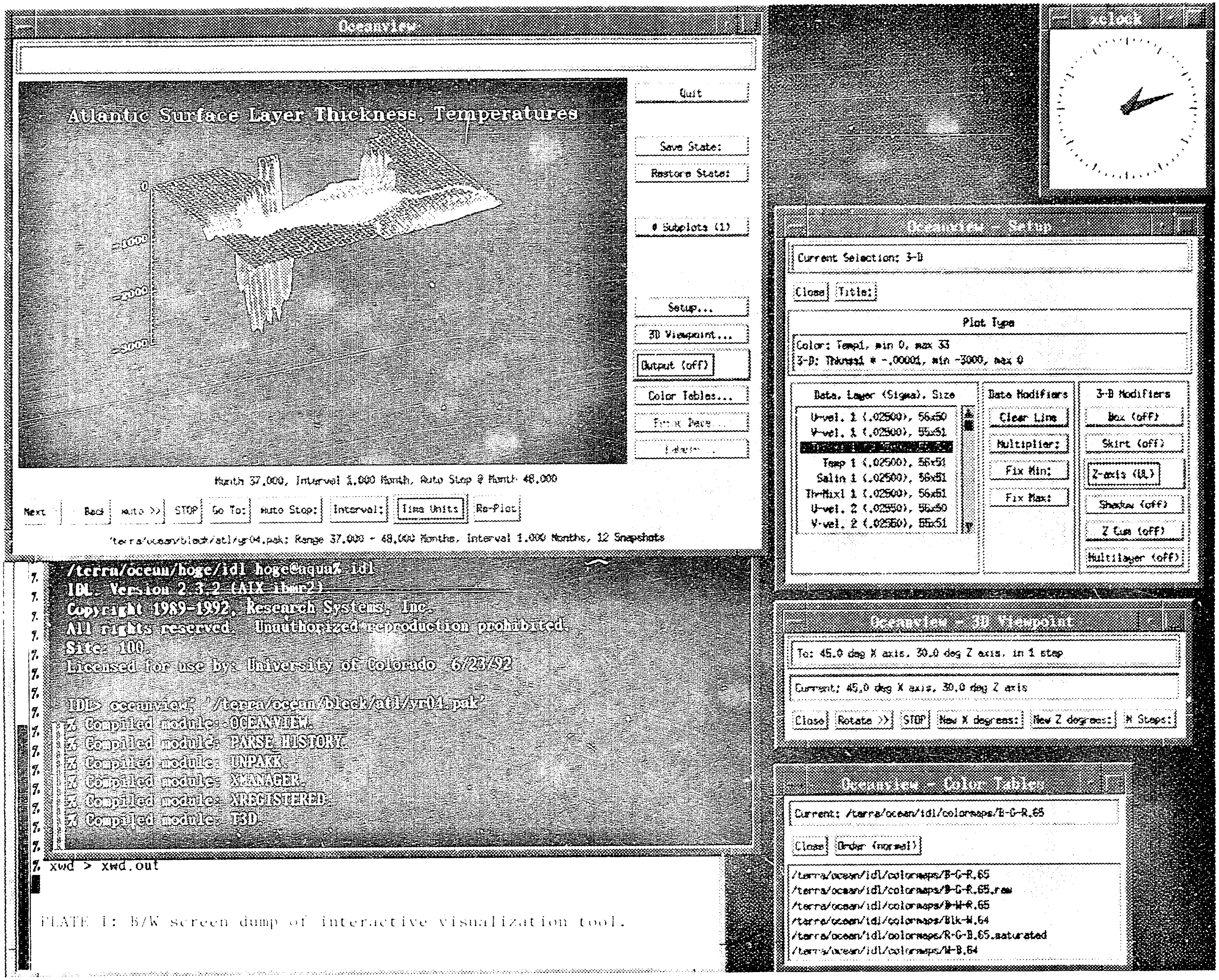

PLATE 1: B/W screen dump of interactive visualization tool.

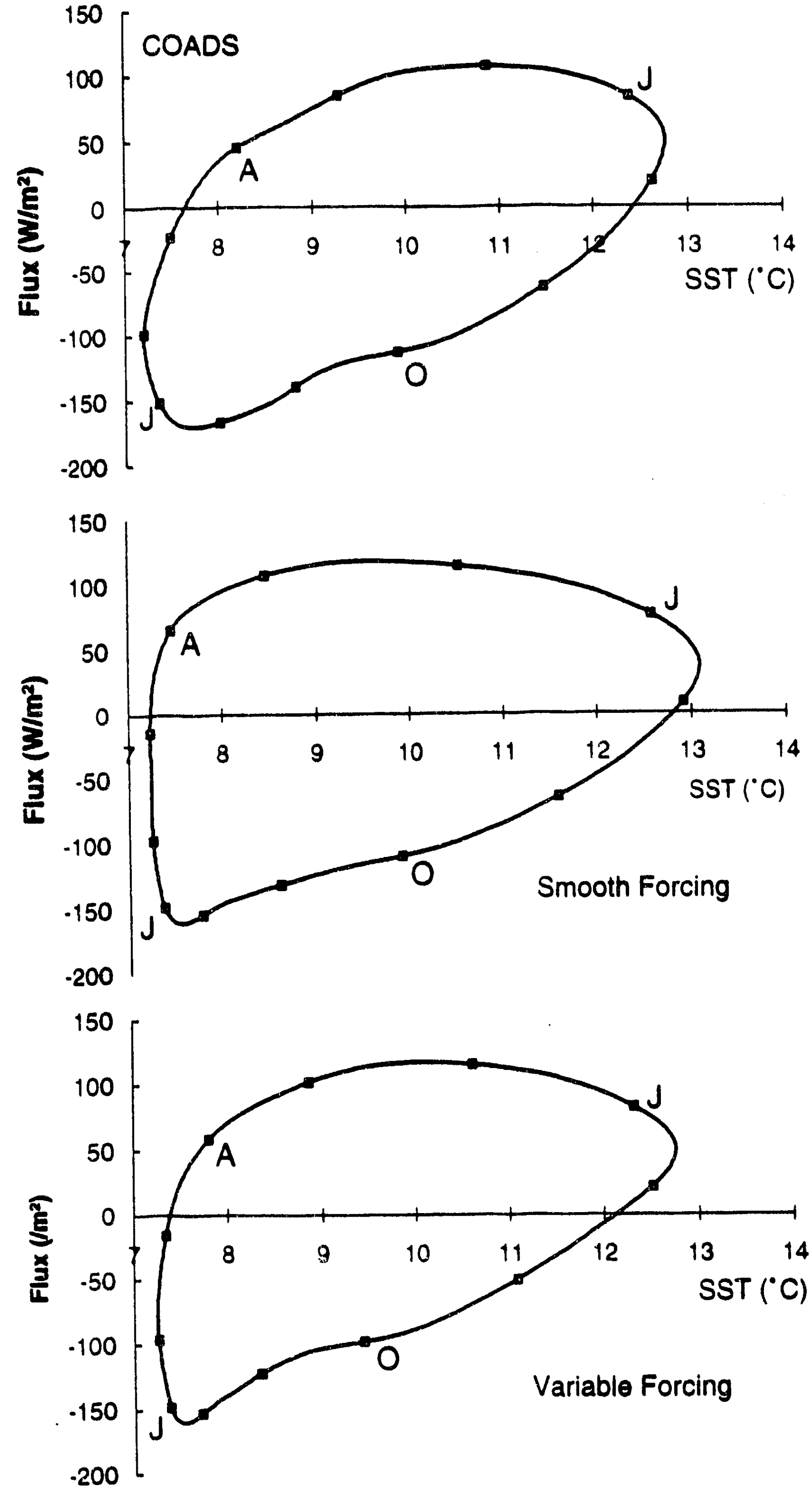

Figure 1. (a) Top: SST-surface flux hysteresis loop from data in the vicinity of Ocean Station C in the North Atlantic, where thermocline ventilation by the annual cycle of the mixed layer is particularly effective. Symbols denote the middle of each month. (b) Middle: One-dimensional model simulation using smoothed annual cycle of atmospheric forcing. Note January-June SST discrepancy. (c) Bottom: One-dimensional simulation with atmospheric forcing perturbed by quasi-synoptic variability. Note that SST response is significantly improved compared to panel (b). This shows the importance of synoptic-scale variations in atmospheric forcing to the annual sysle of SST and, by inference, thermocline ventilation.

Reprints Received

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