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Thermohaline Circulations and Global Climate Change

Final Report

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MASTER

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Introduction

This report concerns research conducted with funding from the Carbon Dioxide Research Program (now the Global Climate Change Program) of the US Department of Energy via grant no. DE-FG02-90ER61019 during the period 15 July 1990 – 14 July 1994. This was a three-year award, extended to a fourth year (15 July 1993 – 14 July 1994) via a no-cost extension. It is important to emphasize that this award has been renewed for an additional two years (15 July 1993 – 14 July 1995) via grant no. DE-FG03-93ER61646 (with the same title). Because the project was originally envisioned to be a five-year effort, many of the important results and conclusions will be available for the Final Report of that second award. This report therefore concerns mainly preliminary conclusions and a discussion of progress toward understanding the central hypothesis of the research.

Summary of Contributions to Date

Published contributions resulting from either full or partial support of this award include:

Recent Great Lakes ice trends. *Bulletin of the American Meteorological Society,* **73,** 577-584 (With C.S. Hanson and B. Yoo) (w/ cover).

Climatological perspectives, oceanographic and meteorological, on variability in the Northwest Atlantic. *Journal of Geophysical Research (C),* **96,** 8517-8529. (With P. Cornillon, G. Halliwell, and V. Halliwell)

Fuzzy Cloud Concepts for Climatic Feedback Assessment. ARM Report, U.S. Department of Energy, Washington, D.C. [Extended abstract of invited talk at the Aspen Global Change Institute's Summer Science Session on Radiation Feedbacks and the Credibility of Atmospheric Models.] (in press)

Modeling Climatological Heat Storage in the North Atlantic Ocean. *Eos: Transactions of the American Geophysical Union,* **75,** (3, Suppl.), pp. 152-153. [Abstract of poster presented at the 1994 AGU Ocean Sciences Meeting].

Variation of the Subduction Rate in Response to Global Climate Change. *Eos: Transactions of the American Geophysical Union,* **75,** (3, Suppl.), p. 161. (With F. Horsfall, R. Bleck) [Abstract of paper presented at 1994 AGU Ocean Sciences Meeting].

Sensitivity of an Isopycnic-Coordinate OGCM to Parameterizations of Upper-Ocean Mixing. *Eos: Transactions of the American Geophysical Union,* **75,** (3, Suppl.), p. 189. (With G.R. Halliwell, F. Horsfall, R. Bleck) [Abstract of paper presented at 1994 AGU Ocean Sciences Meeting].

Rectification of Atmospheric Forcing by the Annual Cycle of the Oceanic Mixed Layer. Third Scientific Meeting of The Oceanography Society, April 12-16, 1993, Seattle, WA. (With R. Bleck) [Abstract of poster]

COADS as a Diagnostic Modeling Tool: Air-Sea Interaction and the Role of the Deep Ocean in Climate Change. Proceedings of the International COADS Workshop, Boulder, Colorado, 13-15 January, 1992, U.S . Dept. of Commerce, NOAA/ERL, Boulder CO, pp. 315-322.

In addition, formal seminars on topics related to the research supported by this award were given at the Los Alamos National Laboratory (2 seminars), the Oak Ridge National Laboratory, the Battelle Pacific Northwest Laboratory, and the University of Miami. A workshop was also convened, with partial support from this award, as discussed below. Other, as yet unpublished, contributions are discussed in and appended to this report.

Background

"Thermohaline Circulations and Global Climate Change" is ultimately concerned with investigating the hypothesis that changes in surface thermal and hydrological forcing of the North Atlantic, changes that might be expected to accompany CO2-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 CO2, 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. Figure 1, reproduced from the original proposal, summarizes this feedback hypothesis.

Observations of the oceans' behavior that would be sufficient to investigate this hypothesis empirically do not exist. Although remote sensing techniques (involving the use of acoustic tomography) are being proposed for such studies, the time required to accumulate the necessary data sets will place these studies in the category of "monitoring" rather than "predicting" climate change. While this is necessary, it is also important to develop understanding of these complex processes in advance of climate change in order to understand its potential effects on humanity; consequently, modeling studies are required.

This investigation has involved the use of an ocean model that is particularly well-suited for studying the effects of surface forcing on the deep-ocean circulation. The model consists of an isopycnal circulation model that calculates deep circulations and interacts with a surface mixed-layer model. Since its initial development, the Miami Isopycnal Coordinate Ocean Model (or MICOM) has been distributed to user groups at institutions in the US and Europe for further refinement and use on a variety of ocean circulation problems. As noted above, this award partially funded a meeting of these user groups, the First MICOM Workshop, in Miami in early 1994. In addition, there have been initiated exchanges with the Cray Research Corporation to develop a massively parallel version of the MICOM code. This project has therefore help to effect the initial stages of technology transfer between the academic and private sectors.

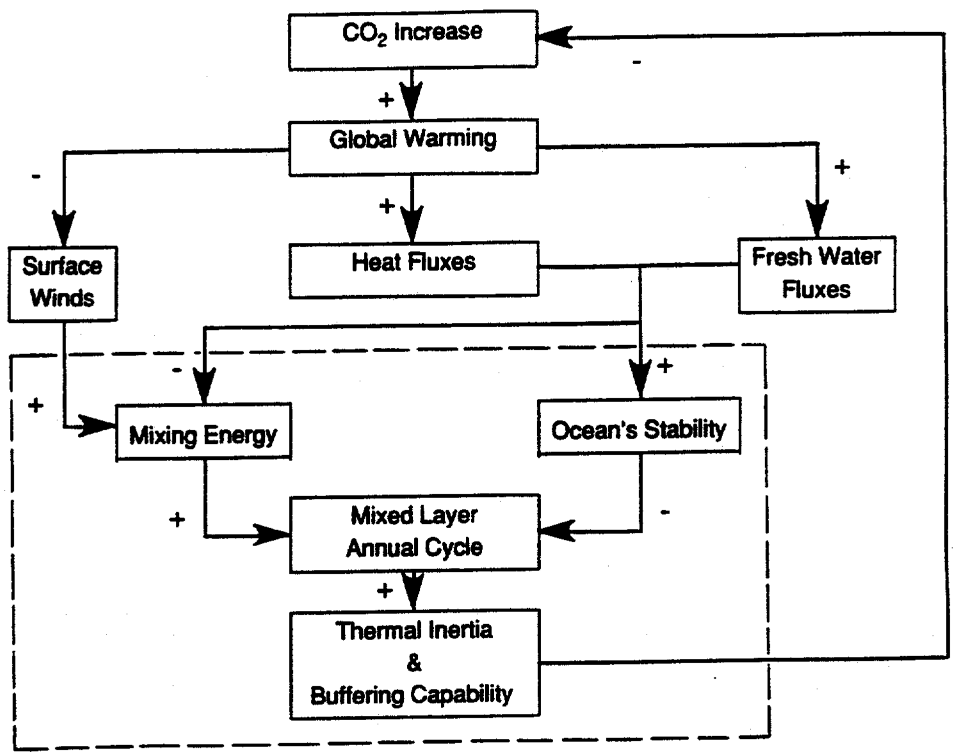

Fig. 1 Schematic of climatic feedback between global warming and the thermohaline circulation, with the oceans' role (the topic of this investigation) in the dashed box. The algebraic signs indicate amplification (+) or attenuation (-) associated with individual links, in the sense of the response that *increases* in the source box tend to induce in the receiving box. The net feedback for any single closed loop is determined by the multiplicative effect of the +/- signs, so that an even (odd) number of minus signs implies positive (negative) feedback.

Outline

The contributions listed above deal largely with a variety of problems associated with development and application of the MICOM to the climatic feedback depicted in Fig. 1. Initial results from the model related to this feedback were included in the paper "Variation of the subduction rate in response to global climate change"; additional results will be presented here. The basic problem of quantifying the feedback is being investigated as a Ph.D. dissertation project by Ms. Fiona Horsfall (whose graduate research assistantship has been funded by this award), and the defense will be held in the spring of 1995, at which time full results will be discussed.

The remainder of this report discusses certain aspects of the contributions listed above and the relevance of their results to this research. These discussions are to be considered to be complementary to the several annual progress reports associated with this award; these other reports are included here as Appendix I. In addition, new results associated with the sensitivity of oceanic subduction processes to changing surface forcing are presented.

Summary

The progress reports in Appendix I report on research activities associated with model development, the construction of an appropriate climatological surface forcing dataset for the model, the development of visualization tools to examine model output, and tests of various mixed-layer formulations in a one-dimensional mode. These reports are self-explanatory.

Additional work on the mixed-layer formulation is discussed in Appendix II. It was recognized at an early stage that the mixed-layer physics included in the original version of the MICOM, based on the overly simplified Kraus-Turner mixed-layer model, would not be sufficiently realistic to simulate the long-term behavior of the real ocean. More recent work has used the dissipation formulation due to Gaspar to overcome these deficiencies. However, unrealistic behavior of that formulation was discovered, and the discussion in Appendix II presents a solution to this problem. Briefly, the Gaspar approach allows the turbulent mixing efficiency to become negative under certain conditions, and the approach taken in Appendix II solves this unphysical behavior by having that efficiency asymptote to zero under those conditions. This new approach will be included in future work, and it will likely be published as an appendix to a more complete paper.

Finally, Appendix III presents results directly pertinent to the hypothesis outlined in Fig. 1 above. These results represent one forcing scenario of several to be included in Ms. Horsfall's dissertation. It suggests that the hypothesis in Fig. 1 is validated for positive feedback.

These results compare a control integration with an integration forced by both increased winds (both stress and wind stirring) and increased surface heating (associated with decreased turbulent fluxes forced by increased air temperatures). These are competing effects from the ocean's perspective, because the increased wind forcing will enhance overall circulation and cause deeper mixed layers, while increases in heating tend to cause shallowere mixed layers. Figures 1a and 1b compare meridional cross-sections for March, when the mixed layer is deepest; it can be seen that wind forcing dominates in low- and mid-latitudes, causing deeper mixed layers in the experimental integration and that the increased surface heating causes shallower mixed layers north of about 55° N, even though the wind forcing is increased uniformly over the basin. The differences for September, when the mixed layer is most shallow, are much less pronounced (Figs. 2a and 2b).

The evolution of a numerical tracer, shown in Figs. 3a, 3b, and 3c, differs dramatically for the two experiments, with the changing wind forcing dominating in the subtropics and the increased heating dominating poleward of about 45° N. This can be seen by the increases in tracer in Layers 2-6 in the experiment; these layers are confined to the tropics and subtropics. Begining with Layer 7, which surfaces in the 40°–50° N zone, the control tracer is larger than the experimental tracer. The differences in Layer 10 are particularly dramatic.

In addition to the latitudinal differences discussed in more detail in Appendix III, these results allow inference that the ability of the oceans to buffer climate change may be sensitive to the changes in forcing associated with an altered climate, and that the net effect may be, as can be deduced from Fig. 1 above, positive. To the extent that global warming is associated with increased air temperatures (as well as a net increase in radiative heating of the surface), these results show that high-latitude thermocline ventilation will be suppressed. Because most GCM simulations of global warming are also associated with temperature increases that are larger at high latitudes than at low latitudes, the resulting decrease in the meridional temperature gradient would tend to lead to decreases in wind forcing, so results opposite to those shown here would apply, and these would enhance the suppression of thermocline ventilation at all latitudes. More details of these results will be included in Ms. Horsfall's dissertation.

Annual progress reports #1, 2 & 3; preprints and reprints cycled separately.