Annual report: Climate System Modeling Program
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Interdecadal Variability Project

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Progress Report for NSF and DOE
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Work Plan

Interdecadal variability project of CSMP

The CSMP proposal to NSF contained a description of a project to examine variability of the climate system on decadal-to-century time scales, with an emphasis on understanding the processes which led to climate variability over the past one to two centuries as a basis for validating models of potential future changes. The project thus focused first, on understanding, and second on understanding as a basis for the development of validation procedures for models intended for use in climate change applications. The principal activity of the first year of the project was a workshop on one of the major sources of interdecadal variability—the thermohaline circulation (THC) of the oceans. This workshop was focussed on review of the cutting edge science of the THC, and on identification of opportunities for future research. The workshop report is attached.

As a result of that workshop an informal group (THC Team) has formed to continue work on ocean-atmosphere coupling. We are currently recruiting two post-docs to work with the THC team in pursuing key questions. The Position Description, which appeared in EOS, is attached. The Post-docs will be filled under the terms of CSMP post-docs. The positions are UCAR post-docs, and the successful candidates may work at the university or lab locations of THC team members, at NCAR or at some combination of venues during their tenure. The intent of this program is to involve the post-docs in original and collaborative studies, including but not limited to theoretical studies, model intercomparisons or validation/verification studies for ocean GCMs. Postdocs will begin work in late 1994 or early 1995. Continued interaction with the ‘THC Team’ will be ensured by regular small group meetings. Overall progress will be monitored by the project chairs, and by the CSMP Project Scientist.

The second issue, contributing to long-term variability, is the issue of ‘multiple forcing’. It is increasingly evident that climate over the past few centuries may have responded to multiple anthropogenic forcings (carbon dioxide, sulfur, land surface changes, ozone), against a background of complex natural variability resulting from processes including the THC, ENSO variability, volcanic effects and other processes. The complexity of forcing in the real climate system renders validation of climate system models against the observed record a major challenge. We will convene a small workshop to begin discussing a strategy for developing strategies and data sets for climate system model validation in this context. While validation of climate system models against ‘average’ or climatological conditions is well-established, the development of climate system models designed to accurately reproduce transient changes will require rethinking traditional model testing. We will convene a small group of modelers and data analysts, together with statisticians to discuss this issue, compare ongoing efforts to requirements and begin a serious study of this problem. The group will include specialists on the atmosphere (physics and chemistry), oceans, land (land use, biology, biogeochemistry and hydrology) and industrial metabolism (records of industrial emissions). This workshop will be held in summer 1995.

The ‘Complex forcing’ workshop will be developed initially by Project Scientist Schimel (terres-
trial ecology and hydrology), Kevin Trenberth (atmosphere), an oceanographer (TBD, possibly Edward Sarachik) and an atmospheric chemist (TBD). Conclusions of the workshop will be reported in EOS, Bulletin of the AMS and the Ecological Society of America with an announcement to the community to become involved as the activity developed.
Meeting Report

The Oceanic Thermohaline Circulation

A workshop was held at the Institute for Geophysics and Planetary Physics of the University of California at Los Angeles (UCLA) on 13-15 October 1993 on the oceanic thermohaline circulation, its variability, and its role in the Earth’s climate system. The workshop was convened under the auspices of the Climate System Modeling Project (CSMP: F. Bretherton (U. Wisconsin), Director, and D. Schimel (NCAR), Project Scientist), as one of its major activities on interdecadal and centennial climate variability. CSMP is sponsored by the National Science Foundation, with additional support from the Department of Energy.

The thermohaline circulation (THC) is forced by horizontal buoyancy contrasts at the ocean surface due to the fluxes of heat and fresh water exchanged with the overlying atmosphere or sea ice, or the adjacent land through river run-off. By convention this term is confined to circulations at large spatial scales (≥ 1000 km) and buoyancy forcings that induce gravitational instability and convective overturning over an appreciable vertical interval (≥ 300 m), in at least some region within the span of the circulation. The THC is a major component of the climate system, because it transports laterally substantial amounts of heat, water, and chemical tracers, and contributes appreciably to the system’s variability.

On a global scale, the THC is known to be in a “delicate” balance, because of the opposing senses of the heat and water forcing patterns [Stommel, 1961]: the ocean water’s density increases with salinity (hence -haline) and decreases — mostly — with temperature (hence thermo-). In the tropics and sub-tropics, the ocean experiences a net gain of heat primarily through strong insolation and a net loss of water through strong evaporation; the
former is gravitationally stabilizing and the latter destabilizing. In contrast, in sub-polar regions a net loss of heat occurs due to the cooler overlying atmosphere (destabilizing) and a net gain of fresh water through precipitation, river run-off, and polar ice influx and melting (stabilizing). The sense of the circulation, therefore, will be an appropriately weighted sum of these competing influences. In the present climate, deep convection occurs primarily in sub-polar regions, most intensely in the North Atlantic Ocean, with diffuse upwelling and surface return flow in other ocean basins (see Figure 1). The associated THC pattern is commonly referred to as the global "conveyor belt" [Broecker, 1987]. But sinking can occur, and has occurred in the geological past, in low latitudes, when the salinity effect exceeds the thermal one.

In recent years, research has emphasized the THC's apparent sensitivity. There is increasing empirical evidence of its variability on interdecadal, centennial, and millennial, as well as on longer paleoclimatic time scales. Furthermore, many different modeling approaches have shown that the THC's nonlinear fluid dynamics can arrive at alternative equilibrium states under a specified forcing distribution [Bryan, 1986], as well as yield spontaneous oscillations at the range of frequencies observed [Weaver et al., 1991]. This can occur in either ocean-only models with steady forcing or in ocean models coupled with the thermal and hydrological cycles of the atmosphere and cryosphere [Delworth et al., 1993].

The time was ideal for a workshop to assemble researchers involved in THC modeling, to compare views and identify fruitful directions for future work. The explosive expansion of interest in and work on the THC still permitted most leaders, and many just entering the field, to fit into a room and engage in lively discussion. About 30 invited and 20 local participants attended, from North America, Europe, and the Far East.

The workshop was organized into five topics: i) The Empirical Evidence for THC
Variability, ii) Simple and Idealized THC Models, iii) Methodologies, iv) THC in General Circulation Models (GCMs), and v) Coupled Models. Each topic was addressed by two or three invited speakers, followed by discussion. In addition, at the end of each of the three days, an open session for broader interactions was held, animated by two or three short presentations.

The first topic encompassed talks by T. Stocker (U. Bern, Switzerland), on paleoclimatic variability, and L. Mysak (McGill U., Canada), on decadal-to-centennial variability. After a brief review of the former, Stocker examined the equilibrium state of a simple coupled ocean-atmosphere model that nevertheless shows similarity with the current THC. His ocean model has three separate, two-dimensional (i.e., zonally averaged) Primitive Equation basins (representing the Atlantic, Pacific, and Indian oceans) that connect in the Antarctic Circumpolar region, while the atmospheric model is of the energy-balance type with latitudinal variations only. This coupled model was used to investigate the response to a large fresh-water input in the North Atlantic due to ice-sheet melting; the resulting changes in the THC were comparable to climatic proxy records of $^{14}$C and $\delta^{18}$O during the Younger Dryas event [Kennett, 1990]. Mysak reviewed the empirical evidence for distinct modes of interdecadal variability in the Arctic region and proposed a feedback loop between Canadian rainfall, run-off into the Arctic, sea-ice cover and deep convection in the Greenland Sea, and atmospheric cyclogenesis [Mysak et al., 1990].

Simple models have the advantages of computational economy and ease of interpretation. Two-dimensional Boussinesq ocean models have been widely used to investigate multiple THC equilibria [Thual and McWilliams, 1992]. A review of these solutions was presented by O. Thual (CERFACS, France), with particular attention to their one-dimensional asymptotic limit of small aspect ratio, for which certain analytic results can be proved. As part of the discussion of the invited papers on the first two topics, C. Vreugdenhil (Royal
Netherlands Met. Inst. — KNMI) presented a theoretical analysis of a parameterization of wind-driven, zonal pressure gradients that appears in Stocker's ocean model. C. Quon (Bedford Inst. Oceanogr., Canada) showed some new solutions from his two-dimensional model with M. Ghil, including their bifurcation to oscillations with a centennial time scale for strong enough forcing or weak enough diffusion. J.-Y. Yang (UCLA) reviewed a two-dimensional ocean model that exhibits interdecadal oscillations in response to weak white-noise stochastic forcing when it is coupled to a simple sea-ice model.

Methodological talks were given by M. Ghil (UCLA) and J. C. McWilliams (Nat'l Center Atmos. Res. — NCAR). Ghil emphasized the need for a hierarchy of models in treating both the global THC — on interdecadal and longer time scales — and the wind-driven circulation of the upper ocean — tropical and extratropical, on seasonal and interannual time scales. Successive bifurcations, from single to multiple equilibria and on to periodic and aperiodic solutions, were shown for both types of circulation, in models of differing realism and complexity. McWilliams presented the theoretical basis for a new quasi-adiabatic parameterization of mesoscale eddy-transport effects oriented along surfaces of constant density. He showed that equilibrium GCM solutions using this parameterization have substantially improved temperature and salinity patterns and fluxes for the present THC.

The equilibrium state of the THC can be calculated in global GCMs with realistic geography and forcing patterns. R. Toggweiler (NOAA Geophys. Fluid Dyn. Lab., Princeton — GFDL) presented both low-resolution GCM and observational evidence suggesting that the present state of the conveyor belt is not being well modeled as yet in certain important aspects, including excessive upwelling of deep water in tropical regions and excessive poleward transports across the Antarctic Circumpolar Current. U. Mikolajewicz (Max-Planck Inst. Meteorol., Hamburg, Germany — MPI) examined his GCM solutions for their response to meltwater forcing. He showed that whether and for how long the THC collapses is dis-
concertingly sensitive to the form of the surface boundary condition for fresh-water flux, as commonly used in uncoupled ocean models. He also showed GCM solutions with centennial oscillations in response to white-noise stochastic forcing in the surface fresh-water flux.

Providing focus to the second day's open session, P. Cessi (Scripps Inst. Oceanogr. — SIO) presented an interpretation of stochastically driven oscillations in a simple box model in which vertical fluxes are asymmetric with respect to gravitationally stable and unstable states. R.-X. Huang (Woods Hole Oceanogr. Inst. — WHOI) demonstrated that interdecadal oscillations can spontaneously arise in a three-dimensional, rectangular-domain ocean model forced only by steady fresh-water fluxes, with no wind stress or heat flux. Both F. Chen (UCLA) and F.-L. Yin (U. Washington, Seattle) presented oscillations in a similar model with wind, heat, and water forcing. Yin offered an interpretation of these simplified GCM results as “flip-flop” convective oscillations, in terms of a simple box model with competing horizontal exchange tendencies to become fresher at shallow levels and warmer at deep levels.

Coupled ocean-atmosphere models of varying degrees of complexity were presented. The simplest model in this class was introduced by J. Marotzke (MIT); it had “box” models for both media, with the fluid-dynamical transport processes approximated as ad hoc diffusive exchanges. He used it to interpret several key processes in the dynamics of ocean-atmosphere coupling. E. Birchfield (Northwestern U.) discussed box-type models in THC variability in which water-inventory changes for land ice are a significant element in developing spontaneous oscillations with periods of millennia and longer.

S. Manabe (GFDL) presented new solutions for two alternative equilibrium states in his coupled ocean-atmosphere GCM that have substantially different THC intensities. He also showed interdecadal oscillations in this model that involve changes in the Labrador
Gyre circulation and the patterns of convection and sea-surface temperature there. Finally, Manabe presented the centennial-scale response of his coupled GCM to increasing CO₂ in the atmosphere: a collapsing conveyor belt does or does not become reestablished, depending upon the late-time level of the CO₂ concentration.

Leading last day's discussion, R. Saravanan (NCAR) showed two equilibrium states in a different coupled model: the ocean is a two-dimensional Boussinesq model and the atmosphere is a two-level representation of the three-dimensional Primitive Equations, with simplified radiative transfer processes. P.-F. Jin (U. Hawaii, Manoa) presented results on the interaction of the seasonal cycle with coupled ocean-atmosphere instabilities in the tropical Pacific, using a hybrid coupled model, with a shallow-water ocean and diagnostic atmosphere. A. Robertson (UCLA) discussed interannual and interdecadal variability in coupled GCMs from UCLA and MPI.

The three discussion sessions were conducted by R.-X. Huang (WHOI) and W. R. Young (SIO), W. Dewar (Florida State U.) and T. Opsteegh (KNMI), and J.D. Neelin (UCLA), respectively. Each formulated a set of questions, that were addressed by the short presentations and by the subsequent general discussions.

It is clear from the invited and contributed presentations, and from the focused discussions, that modeling the THC is an exciting but not yet wholly successful enterprise. Table 1 summarizes some, but far from all of the striking results about THC variability on different time scales.

Simplified models give intriguing but fragmentary indications of what the important processes and feedback loops are. The comprehensive GCMs – either idealized or detailed – have largely unexplored solution spaces and important deficiencies, most notably in their parameterizations of small-scale processes. The associated necessity – still present for
most coupled GCMs – of introducing artificial adjustments ("flux corrections") to provide a stable equilibrium solution for the present climate is particularly bothersome.

Acquiring additional empirical evidence about the THC is essential to guide and test the ongoing modeling efforts. Relevant THC observations must be representative of its large space and time scales. Particularly useful are (a) the chemical, isotopic, and faunal information in deep-sea and ice-sheet cores on paleoclimatic time scales, (b) archeological reconstructions of the physical properties of climate in the past few hundred years, and (c) reliable, long-term monitoring of oceanic water-mass distributions in the future.

In the modeling enterprise, the hierarchy of models used heretofore needs to be cultivated systematically further, with simple models providing ideas and detailed ones the confidence in their correctness. As the number of proposed mechanisms for THC variability increases, a way of eliminating some as less likely has to be developed. The time- and space-scale disparity between the atmosphere and oceans should be put to good use in formulating better coupled models, without "flux corrections." The productive exchange of ideas generated by the workshop should help encourage creative solutions of some of these problems.

It is a pleasure to thank the speakers, discussion leaders, session chairs and all the participants for their contributions to the success of the THC workshop. The able logistic support of S. Chavez (NCAR) and D. Musselman (UCLA) made it a pleasure as well.

This report was prepared by Michael Ghil and James McWilliams.
References


Kennett, J. (Ed.), The Younger Dryas, Paleoceanogr., 5, 6 (Special Issue), 835-1055, 1990.


Table 1. THC Oscillations

<table>
<thead>
<tr>
<th>Time Scale</th>
<th>Phenomena</th>
<th>Mechanism</th>
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<tbody>
<tr>
<td>Decadal</td>
<td>Three-dimensional, wind-driven + THC</td>
<td>Localized surface-density anomalies and gyre advection</td>
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<tr>
<td>Centennial</td>
<td>Loop-type, Atlantic-Pacific circulation</td>
<td>Conveyor-belt advection of high-latitude density anomalies</td>
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<tr>
<td>Millenial</td>
<td>Relaxation oscillation, with “flushes” and superimposed decadal fluctuations</td>
<td>Bottom-water warming, due to high-latitude freshening</td>
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Figure captions

Fig.1 Schematic diagram of an Atlantic meridional cross section from North Pole (NP) to South Pole (SP), showing mechanisms likely to affect the THC on various time scales. Changes in the radiation balance $R_{in} - R_{out}$ are due, at least in part, to changes in extent of Northern Hemisphere (NH) snow and ice cover, $V$, and they affect the global temperature, $T$; the extent of Southern Hemisphere ice is assumed constant, to a first approximation. The change in hydrologic cycle expressed in the terms $P_{ev} - P_{rain}$ for the ocean and $P_{snow} - P_{abl}$ for the snow and ice is due to changes in ocean temperature. Deep-water formation in the North Atlantic Subpolar Sea (North Atlantic Deep Water: NADW) is affected by changes in ice volume and extent, and regulates the intensity $C$ of the THC; changes in Antarctic Bottom Water (AABW) formation are neglected in this approximation. This in turn affects the system’s temperature, and is also affected by it (after Ghil et al. [1987]).