

LARGE-SCALE OCEAN-ATMOSPHERE COUPLING AND
THE OCEAN'S ROLE IN CLIMATE Final Technical
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NUMERICAL SIMULATION OF LARGE-SCALE
OCEAN-ATMOSPHERE COUPLING
AND THE OCEAN'S ROLE IN CLIMATE



FINAL TECHNICAL REPORT

Submitted by
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ABSTRACT

An overview of the principal research findings made during the course of the NASA-supported project "Numerical simulation of large-scale ocean-atmosphere coupling and the ocean's role in climate" is given. In a series of 16-month comparative numerical integrations, this research has served to emphasize the sensitivity of the seasonal climate simulated by an atmospheric GCM to the degree of interaction accorded to the underlying ocean, especially in the tropics. New insight into the physical mechanisms involved in the maintenance of climate has been provided by detailed diagnoses of the simulated balances of angular momentum, heat and energy. A highlight of the research is the first successful interannual integration of a synchronously coupled ocean-atmosphere GCM with realistic geography and seasonal insolation, whose preliminary results are given in an appendix. The abstracts of the various scientific reports prepared with either the full or partial support of this grant are also given in an appendix.

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1. Introduction and General Description

It is generally conceded that the ocean plays an important if not dominant part in the maintenance of climate, and hence is a potentially important factor in climatic change. Surprisingly little quantitative information, however, is available on the ocean's climatic role. The basic purpose of the research program on "Numerical simulation of large-scale ocean-atmosphere coupling and the ocean's role in climate" was to develop new information on this question by the performance of a series of new numerical experiments and the development of new diagnostic techniques for the analysis of the simulated climate. In this report we will summarize the principal findings of this research, and relate it to other activities in climate research and large-scale ocean-atmosphere interaction. Reference may be made to the various reports prepared under the program (and listed in Appendix B by title and abstract) for further detail.

Most of the solar radiation reaching the earth's surface falls into the ocean, and the absorption and storage of this energy in the upper ocean layers is an important thermal reservoir from which the atmosphere derives much of its heating in both sensible and latent forms. This high thermal inertia of the (upper) ocean dictates that the ocean's temperature will change relatively slowly as a result of this heat exchange with the atmosphere. Simulating the large-scale structure of these seemingly small changes in ocean temperature and especially in sea-surface temperature, is therefore the most important requirement of the oceanic part of a coupled ocean-atmosphere GCM, at least as far as the (atmospheric) climate is concerned.

These features create a basic difficulty for the simulation and analysis of the interaction of the ocean and atmosphere on climatic time scales: first, because of the mismatch in the characteristic response times or time scales of the ocean and atmosphere to obtain an equilibrium climate, it is necessary to simulate many years for the ocean as compared with the relatively few years (or even seasons) necessary for the atmosphere, and second, because of the sensitivity of the atmosphere to the ocean, especially as a source of latent heat in the tropics, it is necessary to simulate the sea-surface temperature with relatively

high accuracy. As summarized in Table 1, all previous integrations of coupled ocean-atmosphere models have effectively accelerated the ocean's time scale by the use of asynchronous coupling schemes. While this may make little difference to the simulated equilibrium climate, it completely masks the synoptic- and monthly- scale interactions between the atmosphere and ocean which may be crucial to the evolution of seasonal and annual climatic states of the coupled system.

Rather than make a single integration of the fully-coupled model over perhaps a decade, it was decided instead to make a series of shorter-term experiments in which the transient evolution of the climate could be examined under a variety of assumptions regarding the ocean. As summarized in Table 2, these parallel simulations were each started with the same (atmospheric) initial conditions and each extended over the same 16-month period during which the insolation underwent its normal seasonal cycle. Although none of these experiments were long enough to establish the equilibrium climate, they are sufficient to show the dependence of the climate's transient evolution on the model's treatment of the ocean. The atmospheric GCM used in all of these experiments was the OSU two-level model, whose seasonal performance in the control run has been reviewed by Schlesinger and Gates (1981a); a comprehensive documentation of this model has recently been prepared by Ghan *et al.* (1982).

2. Summary of Principal Research Findings

The research carried out under this project can conveniently be classified as that involved in the design and analysis of the comparative GCM experiment series with various treatments of the ocean as shown in Table 2, the development and application of improved models, and the development of new diagnostic techniques for the analysis of observed and simulated climatic data. The highlights and principal findings in each of these areas are briefly described below, with reference made to the project reports where more detail is given. In the case of the last or coupled GCM experiment, further detail is given in Appendix A of this report.

Table 1

SUMMARY OF COUPLED GCM INTEGRATIONS

Model reference	Number of levels in ocean	Atmosphere/ ocean coupling ratio	Geography	Insolation
Manabe (1969a)	-	swamp	idealized	annual
Manabe (1969b) Manabe and Bryan (1969)	5	1:100	"	"
Wetherald and Manabe (1972)	9	1:100	"	seasonal
Manabe <i>et al.</i> (1975)	-	swamp	realistic	annual
Manabe <i>et al.</i> (1975) Bryan <i>et al.</i> (1975)	12	1:100	"	"
Manabe (1977)	12	1:365	"	seasonal
Manabe <i>et al.</i> (1979)	12	1:285	"	"
Washington <i>et al.</i> (1980)	4	1:5	"	"
Gates <i>et al.</i> (1983)	6	1:1	"	"

Table 2

SUMMARY OF GCM EXPERIMENT SERIES* WITH
VARIOUS TREATMENTS OF THE OCEAN

Experiment description	Sea-surface temperature
Control	Prescribed variation (monthly climatology)
Halved surface evaporation	"
Annual average SST	Fixed (annual climatology)
No ocean	-
Slab (fixed depth)	Calculated
Variable-depth mixed layer	"
Variable-depth mixed layer and thermocline	"
Coupled ocean	"

*Each 16-month simulation uses the OSU two-level GCM with the same initial conditions.

a. Comparative GCM experiments with various treatments of the ocean.

The principal conclusions from this research are:

- In comparison with the atmospheric control experiment in which the sea-surface temperature is assigned its monthly climatological variation, the use of constant sea-surface temperatures (equal to the climatological annual average) results in a moderation of the seasonal variation of temperature over both continents and oceans, and an approximate halving of the seasonal variation of precipitation (Schlesinger and Gates, 1981b). This experiment shows that the seasonal climatic cycle is significantly influenced by the seasonal variation of sea-surface temperature as well as by the seasonal variation of insolation.

- When the oceanic evaporation is taken as one half the value it would have in the control under the same conditions, the precipitable water is decreased by about half, along with a decrease in the atmospheric temperature, relative humidity and precipitation (Schlesinger and Gates, 1981b). This experiment shows that the intensity of the hydrological cycle and hence the atmospheric latent heating is significantly dependent upon the efficiency of the evaporation parameterization over the oceans.

- When the global oceans are replaced with bare land at sea level, the temperature contrasts between the continents and the locations of the (present) ocean would be lessened, while the seasonal temperature contrast between the hemispheres would be increased with warmer summers and colder winters. In this case the atmospheric water vapor, cloudiness and precipitation are also greatly reduced, with the maximum rainfall found in the high latitudes of the summer hemisphere (Schlesinger and Gates, 1981b). This experiment shows that the oceans act as an important source of heat and moisture for the atmosphere and are responsible for much of the climate's relatively moderate seasonal variations.

- When the ocean is represented by a "slab", or mixed layer of uniform and fixed depth (here taken as 60 m) whose mean temperature variation is determined by the net flux of heat at the surface, the simulated sea-surface temperature is generally lower than that observed in the North Pacific and Atlantic Oceans, and higher than that observed to the west of South America and Africa and near Antarctica (with less

sea ice). These temperature changes are accompanied by major changes in the pattern of precipitation, especially over the tropical oceans (Schlesinger and Gates, 1981b). This experiment suggests that the local variation of the sea-surface temperature, even as given by a highly-simplified mixed layer model, is an important determinant of the global climate distribution, and that oceanic processes such as advection and upwelling may be important factors in the ocean surface heat budget.

- When the ocean is represented by a mixed layer whose local depth may vary as a result of wind mixing, entrainment and convective overturning, and in which the effects of wind-driven currents and upwelling are taken into account (Pollard *et al.*, 1980), there is only a slight improvement in the simulation of the sea-surface temperature (Pollard, 1982). This experiment shows that wind-driven currents and variable heat capacity in the mixed layer are not sufficient to produce realistic seasonal patterns of sea-surface temperature.

- When the ocean is represented by a variable-depth mixed layer and an underlying layer of variable depth representing the seasonal thermocline, the errors in the simulation of the sea-surface temperature are significantly less than those made with either a slab or single mixed layer (Pollard, 1982). This experiment suggests that thermal communication with the seasonal thermocline is important in the variations of sea-surface temperature.

- When the atmosphere is coupled to a complete oceanic GCM (Han and Gates, 1982 a, b), there is little improvement in the simulation of the sea-surface temperature over that found with a variable mixed layer and thermocline (Gates *et al.*, 1983 (Appendix A of this report)). The similarity of these errors to those found in other coupled ocean-atmosphere GCM simulations (Manabe *et al.*, 1979; Washington *et al.*, 1980) suggests that the sea-surface temperature simulated by interactive atmosphere-ocean models is sensitive to the coarse resolution of the ocean model itself and to shortcomings in the atmospheric model's contribution to the surface heat flux.

b. Development of ocean models and solution methods.

The principal findings from this research are:

- An oceanic general circulation model with 1° latitude resolution can simulate many aspects of the observed three-dimensional structure and variation of the horizontal current, temperature and vertical motion in the equatorial ocean in response to variations in the large-scale surface wind stress and heating (Han *et al.*, 1980). This research suggests that such a model, in conjunction with an atmospheric GCM, might be able to simulate such events as the El Niño and Southern Oscillation.

- In the formulation of a coarse-grid oceanic GCM considerable care must be taken in the representation of the flow over bottom topography in the multiply-connected world ocean, and in the treatment of the integral properties of the numerical solution. When thermohaline effects are included in an extended simulation with realistic surface forcing, most of the observed large-scale features of the annual mean and seasonal variation of the temperature and circulation can be successfully simulated (Han and Gates, 1982 a, b). This research indicates that such a model would be suitable for coupling with an atmospheric GCM of comparable resolution (see Gates *et al.*, 1983 (Appendix A of this report)).

- In the numerical solution of a coarse grid ($>10^2$ km) oceanic GCM, the so-called B-scheme (in which the horizontal velocity is carried at the center and the pressure or geopotential is carried at each corner of a rectangular grid) is the most successful in the suppression of computational noise (Batteen and Han, 1980). In such models the choice of grid scheme is important for the representation of the meridional structure of the large-scale normal modes (Su *et al.*, 1980).

c. Development of diagnostic techniques and assembly of climatic data sets.

The principal results of this research are:

- Insight into the climate simulated by an atmospheric GCM is provided by the analysis of the balance of angular momentum in terms of the fluxes due to convection, background viscosity, the pressure force, vertical motion, and the relative transfers by the standing mean motion and by the stationary and transient eddies (Kim and Grady, 1980; Kim and Grady, 1982). This research shows that although the global mountain and frictional

torques balance, special attention should be given to the torques in the vicinity of mountains.

- Insight into the maintenance of the heat balance is provided by the analysis of the climate simulated by an atmospheric GCM in terms of the fluxes due to long- and shortwave radiation, convection, large-scale vertical motion, and the relative transfers and energy conversions by the mean motion and by the stationary and transient eddies (Kim and Wang, 1981). This research shows that the sensible and latent heat flux by cumulus-scale motions is an important part of the heat budget in both tropical and middle latitudes.

- The meridional heat flux by the oceans may be estimated from a simulation with an atmospheric GCM, even when the sea-surface temperature is assigned its climatological values (Pollard and Gates, 1982). This research shows that the implied oceanic heat transports are sensitive to the surface heat fluxes simulated by the model, especially poleward of about 50° latitude in both hemispheres.

- A recalculation of the monthly mean wind stress over the global ocean using updated climatological data shows that the effect of the intramonthly variability of the wind is important in the depiction of the seasonal transitions of the wind stress, especially over the Indian and Southern oceans (Han and Lee, 1981). This research indicates that there are still extensive data-sparse regions of the ocean over which considerable caution should be used in the interpretation of GCM results.

- A recalculation of the monthly mean surface heat budget over the global ocean using updated climatological data shows that both the heat storage and the horizontal and vertical heat flux divergence play important roles in determining the local heat flux between the ocean and atmosphere (Esbensen and Kushnir, 1981). This research indicates that the oceanic surface heat budget may be successfully balanced with conventional flux parameterizations using monthly mean data.

- Analysis of the global balance of kinetic energy and total energy simulated by an atmospheric GCM in terms of the various mechanisms responsible for local energy changes shows that over much of the troposphere there is an approximate balance between the net kinetic energy flux and its production by

ageostrophic motions, and that there is a characteristically strong energy flux divergence in the tropics in both summer and winter (Wang *et al.*, 1983). This research also indicates that the apparent energy imbalance in the atmospheric GCM is about 2 Wm^{-2} due to the effects of data sampling.

- In the comparison of climatic data simulated by a model in sigma coordinates to observational data in pressure coordinates, it is important to use a mass-consistent scheme in the analysis and interpolation between surfaces (Ghan and Kim, 1983). When applied to the atmospheric energy cycle simulated by the OSU atmospheric GCM, this research shows that the estimates of the role of eddies is sensitive to such data analysis schemes.

3. Other Activities and Coordination

In the conduct of the research summarized here, the principal investigators have participated in a variety of other activities related to the general problem of the ocean's role in climate. Foremost among these is the research conducted concurrently under the sponsorship of the National Science Foundation on the development and application of atmospheric and oceanic GCMs for the purposes of climate simulation. A major focus of this program is the study of the likely climatic effects of increased atmospheric CO_2 , a problem in which the oceans play a critical role. A series of NSF grants has therefore co-sponsored the research with oceanic GCMs in particular, and has also contributed to the support of the research on diagnostic analysis. These research efforts have also been partially supported by a subcontract with the Lawrence Livermore National Laboratory.

In addition to the specific research achievements described here, NASA's support of this program has contributed significantly to the emerging scientific consensus that the oceans *must* be modelled more carefully than heretofore if an appreciation of their full role in climate is to be achieved. The principal investigator has thus been able to more effectively participate as a member of the Climate Research Committee of the National Academy of Sciences in the planning for major oceanographic research projects as part of the U. S. national climate program. This program has also enabled a greater contribution to be made to the development of international oceanographic research efforts as part of the World Climate Research Programme.

In summary, this NASA-supported project has enabled considerable progress to be made in both ocean modeling and in the diagnosis of the shorter-term response of the global ocean when coupled to the atmosphere in a variety of forms. This project has thereby significantly contributed to a fuller understanding of the ocean's role in climate and climate change. Building upon this base, it is hoped that subsequent research will address the many remaining questions involved in the ocean's long-term response as part of the coupled atmosphere-ocean climate system.

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APPENDIX A

PRELIMINARY RESULTS FROM THE OSU
COUPLED OCEAN-ATMOSPHERE GCM

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ABSTRACT

The OSU two-level atmospheric GCM has been successfully coupled to a version of the OSU six-level oceanic GCM in a preliminary simulation over 16 months during which the solar radiation at the top of the atmosphere underwent its normal seasonal cycle. The initial conditions for the atmosphere were taken from an interannual atmospheric control integration in which the ocean sea-surface temperature (and sea ice) was assigned its normal monthly climatological distribution; similarly, the initial conditions for the ocean were taken from an interannual oceanic control integration using prescribed climatological atmospheric conditions. When these GCMs were synchronously coupled (with fluxes at the air-sea interface computed each hour), the solution of the joint model was stable over the 16-month period but had not yet reached a climatological equilibrium.

The solution's principal transient adjustment occurred over the low-latitude oceans, and is most apparent in the sea-surface temperature. The climatological maximum January sea-surface temperature over the equatorial western Pacific and Indian oceans (used in the control) has cooled several degrees C in the coupled integration, and is accompanied by an eastward shift of the region of maximum tropical precipitation. In the North Pacific and North Atlantic oceans the coupled model produces a less intense meridional sea-surface temperature gradient than is observed in January, with temperatures several degrees C lower than observed in the western central oceans. At the same time the coupled GCM simulates sea-surface temperatures which are several degrees C above those observed off the west coasts of South America and Africa, and around Antarctica.

1. Introduction and model description

In spite of the generally acknowledged important climatic role of the oceans, there have been no long-term integrations of a coupled ocean-atmosphere GCM which includes realistic global geography, seasonally-varying insolation, and resolution of the large-scale synoptic and seasonal interactions between the atmosphere and ocean. The pioneering work of Manabe and Bryan (1969), Manabe *et al.* (1975) and Bryan *et al.* (1975) contained none of these features, although it did establish that an oceanic GCM with relatively coarse horizontal resolution was capable of satisfactorily portraying major portions of the average large-scale structure and circulation of the ocean. The more recent work of Manabe *et al.* (1979) and of Washington *et al.* (1980) contain the first two of these features, but do not resolve the synoptic and seasonal-scale interactions. In the interests of accelerating the solution toward an equilibrium climate, they have employed asynchronous coupling schemes in which the ocean model is integrated for several years with fixed atmospheric forcing, after which the atmosphere is integrated for a relatively short period with the updated ocean now providing new sea-surface temperatures.

In the present 16-month simulation the OSU two-level atmospheric GCM has been coupled with the OSU six-level oceanic GCM on a one-to-one basis, i.e., time proceeds at the same rate in both ocean and atmosphere, and the surface fluxes of heat, momentum and moisture are exchanged every hour. Although it includes realistic global geography and seasonally-varying insolation (together with internally-predicted cloudiness and surface hydrology), the coupled model version used here has prescribed (climatological) sea-ice. In spite of this approximation, the present integration is evidently the first to be successfully undertaken for a fully coupled ocean-atmosphere GCM for a period longer than a single annual cycle. This integration also serves as the most general of a series of 16-month simulations which has been undertaken to explore the role of the ocean in climate. Previous members of this series include (aside from the control case with climatologically-prescribed monthly sea-surface temperature) the cases of a mixed layer of fixed depth (Schlesinger and Gates, 1981), a mixed layer of variable depth (Pollard *et al.*, 1980) and a variable depth mixed layer overlying a variable depth thermocline layer (Pollard, 1982).

The initial conditions for the coupled integration were furnished by independent seasonal control runs of the separate atmospheric and oceanic GCMs. For the atmosphere, these initial data were those for 1 November of "year 1" of the interannual control simulation as described by Schlesinger and Gates (1981). In this integration of the sea-surface temperature (and sea ice) was prescribed from monthly climatological distributions. The initial conditions for the oceanic model were similarly taken as those for 1 November at the end of a 210-year spin-up calculation, in which the seasonal forcing was derived from climatological atmospheric data as described by Han and Gates (1982b).

In their separate control runs both the atmosphere and at least the upper ocean were in reasonably complete equilibrium with their respective seasonal boundary conditions or forcing at the sea surface, and the atmospheric and oceanic climates simulated in these controls are in reasonable agreement with observations. Among the major errors of the atmospheric model are the simulation of excessive amplitude (and southward displacement) of the semi-permanent Icelandic and Aleutian lows, and the simulation of apparently excessive precipitation over the western North Atlantic, Pacific and equatorial Indian oceans. A characteristic error of the ocean model is its failure to simulate the observed strength and structure of the relatively narrow boundary and equatorial currents found in various basins of the world ocean; this error is likely due to the oceanic GCM's use of the same 4° latitude and 5° latitude horizontal grid used by the atmospheric GCM, and its consequent failure to resolve the effects of mesoscale oceanic processes. Nevertheless, the oceanic GCM simulates the large-scale distribution of the sea-surface temperature and surface heat flux reasonably well (Han and Gates, 1982b).

Once the models are coupled, however, the initial surface fluxes will in general not be in adjustment with the initial conditions as determined by the separate (and observationally-driven) atmospheric and oceanic control runs. The coupled model may therefore be expected to exhibit a transient adjustment from the imposed initial state, especially over the tropical oceans where the atmosphere's response to oceanic conditions appears to be strongest. A summary of this transient response is given in the following section, followed by a preliminary description of the climate simulated by the coupled GCM near the end of the 16-month integration.

2. Summary of the transient response

Since neither the atmospheric nor oceanic portions of the model will be error-free, the performance of the coupled model cannot be expected to be the same as that found in the separate atmospheric and oceanic GCM control runs in which observed climatological data were used at the ocean surface. The transient response of the coupled model will therefore begin immediately upon coupling, and persist until *both* the sea-surface temperature and the surface fluxes (principally of heat and momentum (wind stress)) are internally consistent with the evolving solutions of the model which determine them.

This transient adjustment of the coupled GCM is most pronounced over the tropical oceans, and is illustrated in Fig. 1 for the sea-surface temperature in the equatorial Pacific Ocean. Relative to the atmospheric control (in which monthly climatological sea-surface temperatures were prescribed) the coupled GCM simulates mostly lower temperatures between 80°W and 120°E at 2°N during most of the 16-month integration, with a maximum warming between 6 and 7°C occurring near 110°W after about five months' integration (March). The physical cause of this behavior has not yet been completely diagnosed, but it appears to be due to the model's excessive cold water advection and/or upwelling rather than to an excessive surface heat loss. This behavior may in turn be related to the coupled model's simulation of relatively strong trade winds in this region.

Although the coupled GCM has not been run long enough to establish either the average or the mean seasonal variation of the sea-surface temperature, the initial transient response shown in Fig. 1 provides interesting evidence of the model's adjustment to anomalous forcing (in this case imposed via the initial conditions). Between November (of year 1) and March, the sea-surface temperature anomaly at 2°N may be viewed (albeit roughly) as an eastward-propagating wave which moves from about 140°W to about 110°W. This corresponds to a speed of approximately 0.4ms^{-1} , and may represent the model's simulation of an eastward-propagating equatorial Kelvin wave.

An even clearer example of wave propagation, however, may be seen in Fig. 1 between March and January (of year 2), during which time the maximum sea-surface temperature anomaly appears to move westward from about 110°W

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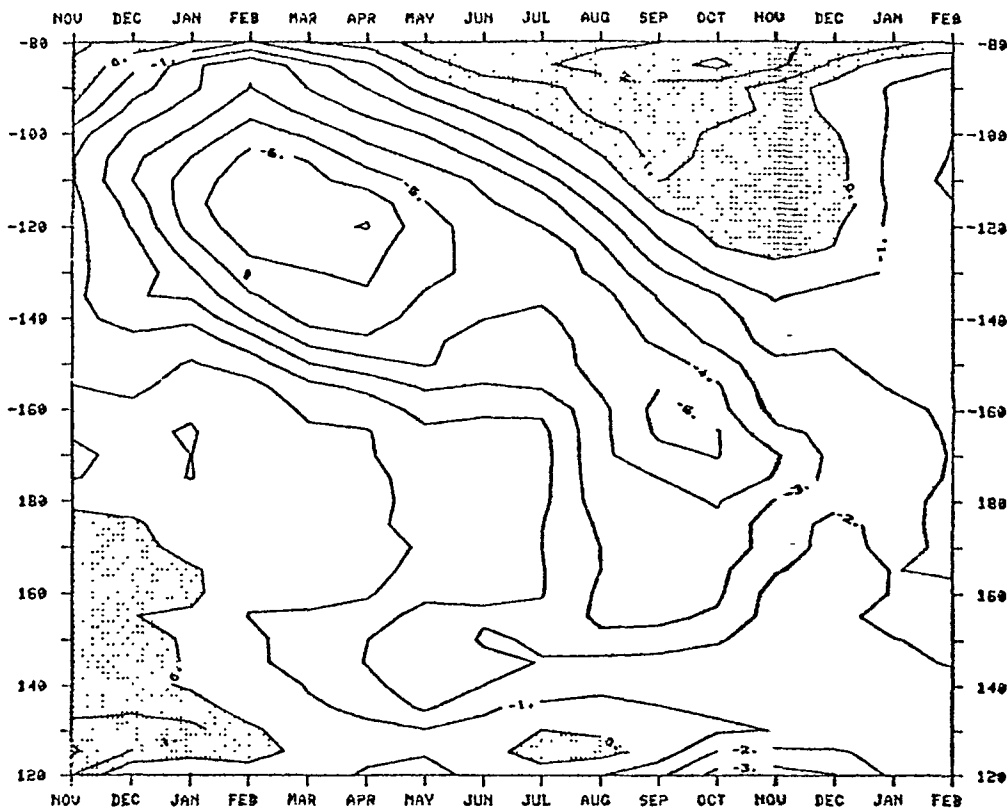


Fig. 1. A time-longitude plot (Hövmöller diagram) of the difference between the sea-surface temperature ($^{\circ}\text{C}$) simulated by the coupled ocean-atmosphere GCM and the observed climatological value (used in the atmospheric GCM control) as a function of simulation month and longitude across the Pacific Ocean at 2 N latitude. Shading indicates values greater than zero (coupled model warm anomaly).

to 180°W. This propagation corresponds to a speed of approximately 0.25 ms^{-1} , and may represent the model's simulation of a westward-propagating internal Rossby wave. That this speed is somewhat less than the $0.5\text{-}1.0 \text{ ms}^{-1}$ reported by Rasmusson and Carpenter (1982) as the average westward speed of (warm) sea-surface temperature anomalies observed in the equatorial western Pacific Ocean, may be due to the model's distortion of the effective internal baroclinic Rossby modes and/or its simulation of relatively low mean current speeds.

This interpretation of the coupled GCM's transient response as wave propagation along the equator is supported by the fact that the propagating temperature anomaly pattern seen in Fig. 1 is also found at 2°S, and is seen at 6°N and 6°S with the same zonal propagation characteristics but with smaller amplitude anomalies. This behavior is *not* seen, however, at 10°N or 10°S (or higher latitudes) in the Pacific, and does not occur in the equatorial Atlantic or Indian oceans.

Although the time required for the essential completion of the model's transient response has not been determined, it appears that several years' simulation would be required before at least the low-latitude sea-surface temperature exhibits only the 1 or 2°C changes which are characteristic of observed seasonal fluctuations. At this time presumably the other climatic variables would also exhibit realistic seasonal and interannual variations, even though their mean values may be systematically in error as is evidently the case for the sea-surface temperature.

3. Preliminary description of the simulated climate

Even though the present 16-month integration is too short to establish either the coupled model's mean climate or its natural seasonal and interannual variability, it is still of interest to examine some of the emerging differences between this simulation and that of the corresponding uncoupled atmospheric GCM.

Certainly a key variable in the coupled ocean-atmosphere system is the sea-surface temperature, whose transient response in the equatorial Pacific has just been examined. In Fig. 2 the complete global distribution of the sea-surface temperature simulated for January (of year 2) by the coupled GCM

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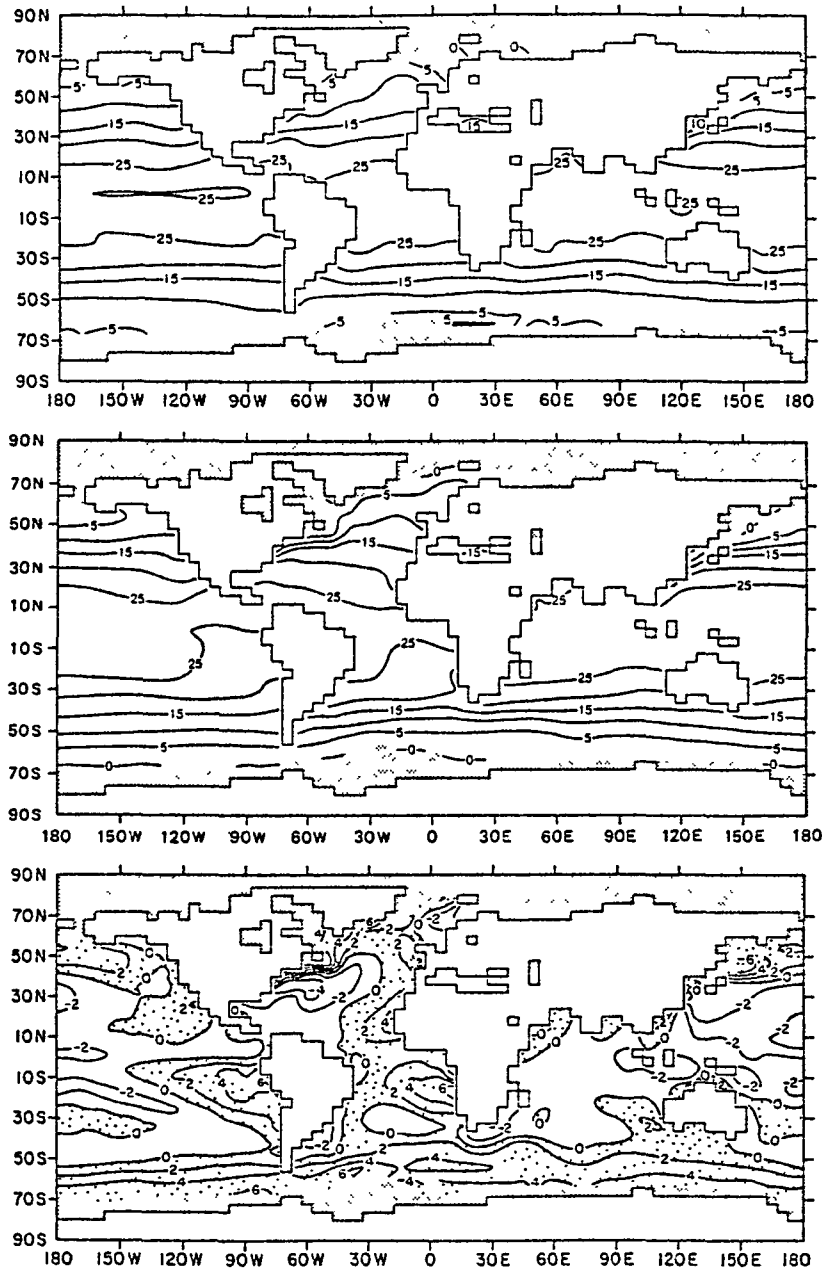


Fig. 2. The sea-surface temperature ($^{\circ}\text{C}$) simulated for January of "year 2" in the coupled ocean-atmosphere GCM (top) and the observed January climatological sea-surface temperature ($^{\circ}\text{C}$) used in the atmospheric GCM control (middle). The bottom panel shows the difference between the sea-surface temperature ($^{\circ}\text{C}$) simulated in the coupled GCM and that observed. Dotted pattern denotes values greater than zero (coupled model warm anomaly), while shading denotes the prescribed locations of sea ice.

is shown, along with the observed climatological January distribution as used in the atmospheric GCM's control integration. From an inspection of these data it is clear that the coupled model has not been able to maintain the relatively large temperature gradients in the North Atlantic and Pacific oceans associated with the Gulf Stream and Kuroshio, and has simulated a warming and general weakening of the meridional temperature gradient south of about 50°S in the Southern Ocean. In the tropical oceans the coupled model has simulated widespread cooling as noted earlier and here shown in the lower part of Fig. 2, while substantial warming has been simulated at subtropical latitudes off the west coasts of South America and Africa. Although a diagnosis of the ocean surface heat budget has not yet been made, these features are probably related to errors in the model's surface wind field and to associated errors in the simulation of upwelling and surface heating. We may also note that the general pattern of the coupled model's sea-surface temperature errors shown in Fig. 2 after only 15 months' simulation is similar to that found in the more extended integrations of asynchronously coupled models by Manabe *et al.* (1979) and Washington *et al.* (1980).

One of the more important climatic effects of the tropical sea-surface temperature is its close relationship with tropical precipitation. It is therefore of interest to examine the precipitation distribution in the coupled model compared with that in the atmospheric control. These data are shown in Fig. 3 for January, where we note a major decrease in the rainfall over the equatorial Indian Ocean in the coupled model relative to that in the uncoupled control. We also find increased precipitation in the coupled case off the west coasts of South America and Africa near 10°S, corresponding to the warmer sea-surface temperatures in these areas. Outside the tropics, however, it is difficult to identify major large-scale differences of precipitation between the coupled and atmospheric simulations.

It is interesting to note that the January precipitation simulated by the coupled GCM given in Fig. 3 is in somewhat better agreement with the observed average January precipitation as given by Jaeger (1976), for example, than is the precipitation simulated by the atmosphere-only GCM with the observed average sea-surface temperature. This indicates that the present model atmosphere cannot accurately simulate the deep tropical convection

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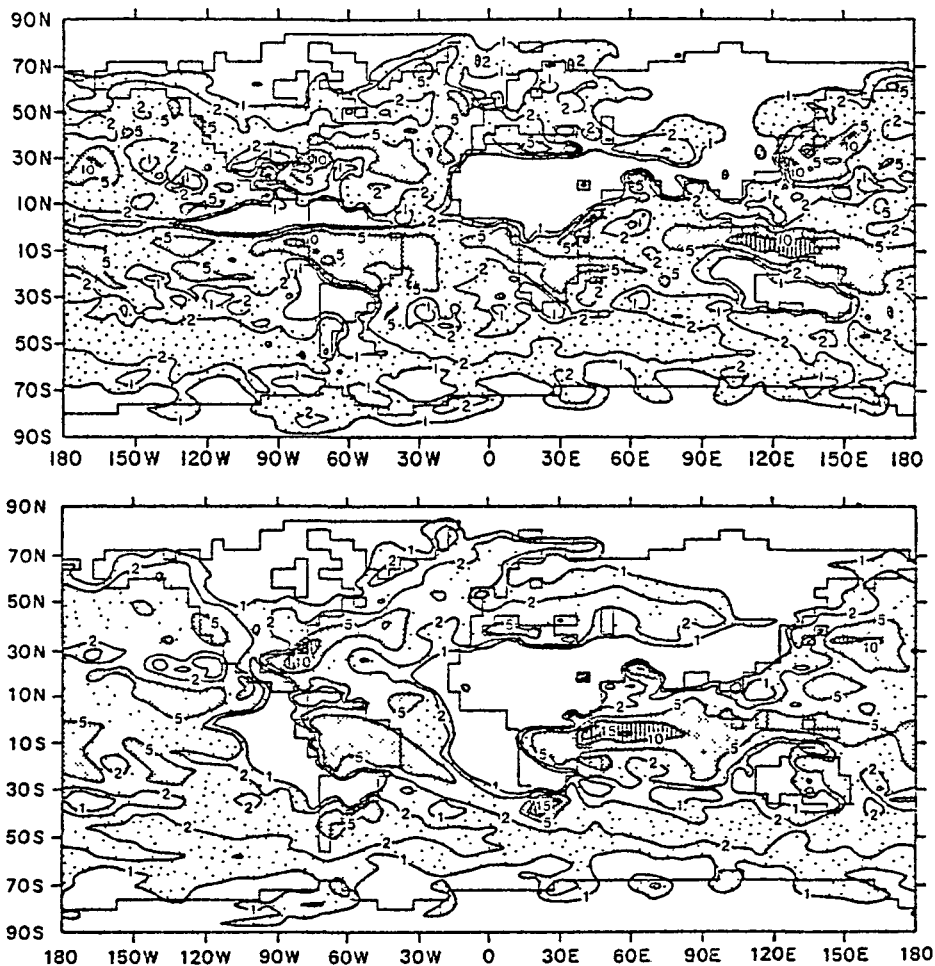


Fig. 3. The precipitation rate (mm day^{-1}) simulated for January of "year 2" in the coupled ocean-atmosphere GCM (above) and that simulated in the atmospheric GCM control (below). The areas of heavier precipitation are more densely shaded.

and associated latent heating and precipitation if the sea-surface temperature is not allowed to respond to the surface heat flux. When the sea-surface temperature is free to interact, however, we obtain a markedly improved simulation of the tropical atmosphere at the expense of a degradation of the accuracy of the sea-surface temperature itself. If this behavior is characteristic of coupled GCMs of relatively coarse resolution, it may not be too high a price to pay for the convenience of such models. This error or climatic drift of the sea-surface temperature could presumably be reduced with the use of higher resolution and/or improved parameterizations of the surface fluxes.

4. Further research

As a follow-on to the present research, it is planned to perform an extended interannual simulation with an improved version of the coupled ocean-atmosphere model, including an imbedded submodel of the oceanic surface mixed layer and sea ice. This integration will allow us to examine the stability of the shifts in such features as the sea-surface temperature and precipitation noted here in association with the model's transient adjustment, and will permit the first systematic analysis of the global climate simulated by a fully-coupled ocean-atmosphere GCM.

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We wish to thank R. L. Mobley and W. R. McKie for their production of the coupled model integrations, and Elizabeth Webb and Naomi Zielinski for their assistance in preparing the manuscript. This research was supported by the National Aeronautics and Space Administration under Grant NSF 5353, and by the National Science Foundation under Grant ATM-8305992. The computations were performed at the National Center for Atmospheric Research (under the sponsorship of the NSF) and at the OSU Climatic Research Institute.

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APPENDIX B

TITLE PAGES AND ABSTRACTS
OF REPORTS PREPARED WITH WHOLE OR PARTIAL
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(17 Reports)

CLIMATIC RESEARCH INSTITUTE

Report No. 12

ON THE COMPUTATIONAL NOISE OF FINITE-DIFFERENCE
SCHEMES USED IN OCEAN MODELS

Mary L. Batteen and Y.-J. Han

Climatic Research Institute
and
Department of Atmospheric Sciences
Oregon State University
Corvallis, Oregon

May 1980

OREGON STATE UNIVERSITY, CORVALLIS, OREGON 97331

CLIMATIC RESEARCH INSTITUTE

Report No. 13

THEORETICAL STUDIES OF FINITE-DIFFERENCE
GRIDS USED IN GENERAL CIRCULATION MODELS

PART I

ASYMPTOTIC EXPANSION OF THE NORMAL MODES
OF THE LINEARIZED SHALLOW WATER EQUATIONS
FOR SMALL LAMB'S PARAMETER

Chang-Chun Su

Michael E. Schlesinger

Jeong-Woo Kim

Department of Atmospheric Sciences

and

Climatic Research Institute

Oregon State University

July 1980

OREGON STATE UNIVERSITY, CORVALLIS, OREGON 97331

CLIMATIC RESEARCH INSTITUTE

Report No. 18

PRELIMINARY ANALYSIS OF THE ANGULAR MOMENTUM BALANCE IN THE OSU
TWO-LEVEL ATMOSPHERIC GENERAL CIRCULATION MODEL

J.-W. Kim and W. Grady

Climatic Research Institute
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Department of Atmospheric Sciences
Oregon State University
Corvallis, Oregon

September 1980

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NO. 14, 15, 16, 17

OREGON STATE UNIVERSITY, CORVALLIS, OREGON 97331

CLIMATIC RESEARCH INSTITUTE

Report No. 20

A NUMERICAL INVESTIGATION OF EQUATORIAL OCEAN
DYNAMICS WITH REFERENCE TO EL NIÑO

Y.-J. Han, W. L. Gates and J.-W. Kim

Climatic Research Institute
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Department of Atmospheric Sciences
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December 1980

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CLIMATIC RESEARCH INSTITUTE

Report No. 21

DEVELOPMENT OF A SIMPLE OCEANIC MIXED-LAYER AND
SEA-ICE MODEL FOR USE WITH AN ATMOSPHERIC GCM

David Pollard, Mary L. Batteen and Young-June Han

Climatic Research Institute
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Oregon State University
Corvallis, Oregon

December 1980

OREGON STATE UNIVERSITY, CORVALLIS, OREGON 97331

CLIMATIC RESEARCH INSTITUTE

Report No. 23

PRELIMINARY ANALYSIS OF THE MEAN ANNUAL CYCLE AND INTER-
ANNUAL VARIABILITY SIMULATED BY THE OSU TWO-LEVEL
ATMOSPHERIC GENERAL CIRCULATION MODEL

M. E. Schlesinger and W. L. Gates

Climatic Research Institute
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February 1981

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CLIMATIC RESEARCH INSTITUTE

Report No. 25

PRELIMINARY ANALYSIS OF FOUR GENERAL CIRCULATION MODEL
EXPERIMENTS ON THE ROLE OF THE OCEAN IN CLIMATE

M. E. Schlesinger and W. L. Gates

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June 1981

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CLIMATIC RESEARCH INSTITUTE

Report No. 26

A NEW ANALYSIS OF MONTHLY MEAN WIND
STRESS OVER THE GLOBAL OCEAN

Y.-J. Han and S.-W. Lee

Climatic Research Institute
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Department of Atmospheric Sciences
Oregon State University

June 1981

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CLIMATIC RESEARCH INSTITUTE

Report No. 28

THE JANUARY AND JULY HEAT BALANCE
SIMULATED BY THE OSU TWO-LEVEL ATMOSPHERIC
GENERAL CIRCULATION MODEL

J.-W. Kim and J.-T. Wang

Climatic Research Institute
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Department of Atmospheric Sciences
Oregon State University

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Report No. 29

THE HEAT BUDGET OF THE GLOBAL OCEAN:
AN ATLAS BASED ON ESTIMATES
FROM SURFACE MARINE OBSERVATIONS

S. K. Esbensen and Y. Kushnir

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Oregon State University
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December 1981

OREGON STATE UNIVERSITY, CORVALLIS, OREGON 97331

CLIMATIC RESEARCH INSTITUTE

Report No. 30

PRELIMINARY ANALYSIS OF THE PERFORMANCE OF
THE OSU SIX-LEVEL OCEANIC GENERAL CIRCULATION MODEL
PART I. BASIC DESIGN AND BAROTROPIC EXPERIMENT

Y.-J. Han and W.L. Gates

Climatic Research Institute
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January 1982

OREGON STATE UNIVERSITY, CORVALLIS, OREGON 97331

CLIMATIC RESEARCH INSTITUTE

Report No. 31

THE PERFORMANCE OF AN UPPER-OCEAN MODEL COUPLED TO AN
ATMOSPHERIC GCM: PRELIMINARY RESULTS

David Pollard

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February 1982

OREGON STATE UNIVERSITY, CORVALLIS, OREGON 97331

CLIMATIC RESEARCH INSTITUTE

Report No. 32

DIAGNOSIS OF THE OCEANIC HEAT TRANSPORT IMPLIED

IN AN ATMOSPHERIC GCM SIMULATION

D. Pollard and W.L. Gates

Climatic Research Institute
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Oregon State University

February 1982

OREGON STATE UNIVERSITY, CORVALLIS, OREGON 97331

CLIMATIC RESEARCH INSTITUTE

Report No. 34

PRELIMINARY ANALYSIS OF THE PERFORMANCE OF
THE OSU SIX-LEVEL OCEANIC GENERAL CIRCULATION MODEL
PART II. A BAROCLINIC EXPERIMENT

Y.-J. Han and W. L. Gates

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April 1982

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CLIMATIC RESEARCH INSTITUTE

Report No. 38

THE ANGULAR MOMENTUM BALANCE SIMULATED BY
THE OSU TWO-LEVEL ATMOSPHERIC GENERAL CIRCULATION MODEL
FOR JANUARY AND JULY

J.-W. Kim and W. Grady

Climatic Research Institute
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Department of Atmospheric Sciences
Oregon State University

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NO. 35, 36, 37

October 1982

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CLIMATIC RESEARCH INSTITUTE

Report No. 42

THE BALANCE OF KINETIC AND TOTAL ENERGY
SIMULATED BY THE OSU TWO-LEVEL ATMOSPHERIC GENERAL CIRCULATION MODEL
FOR JANUARY AND JULY

J.-T. Wang, J.-W. Kim and W. L. Gates

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February 1983

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Report No. 43

A MASS-CONSISTENT SCHEME
FOR THE ANALYSIS OF MODEL-SIMULATED DATA,
WITH APPLICATION TO THE ATMOSPHERIC
ENERGY CYCLE

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