G F D L

GEOPHYSICAL FLUID DYNAMICS LABORATORY

ACTIVITIES – FY89
PLANS – FY90

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
Environmental Research Laboratories

GEOPHYSICAL FLUID DYNAMICS LABORATORY

ACTIVITIES - FY89

PLANS - FY90

September 1989

Geophysical Fluid Dynamics Laboratory
Princeton, New Jersey

UNITED STATES DEPARTMENT OF COMMERCE
ROBERT A. MOSBACHER
SECRETARY OF COMMERCE

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
John A. Knauss
Under Secretary and Administrator

Environmental Research Laboratories
J. Fletcher
Director

NOTICE

Mention of a commercial company or product does not constitute an endorsement by NOAA Environmental Research Laboratories. Use for publicity or advertising purposes of information from this publication concerning proprietary products or the tests of such products is not authorized.

PREFACE

This document is intended to serve as a summary of the work accomplished at the Geophysical Fluid Dynamics Laboratory (GFDL) and to present a glimpse of the near future direction of its research plans.

It has been prepared within GFDL and its distribution is primarily limited to GFDL members, to interested offices of the National Oceanic and Atmospheric Administration, and to other relevant government agencies and national organizations.

The organization of the document encompasses an overview, project activities and plans for the current and next fiscal years, and appendices. The overview covers highlights of the five major research areas that correspond to NOAA's mission in oceanography and meteorology: Weather Service; Climate; Atmospheric Quality; Marine Quality; Ocean Service. These are five of the NOAA categories (bins) for research activities. The body of the text describes goals, specific recent achievements and future plans for the following major research categories: Climate Dynamics; Middle Atmosphere Dynamics and Chemistry; Experimental Prediction; Oceanic Circulation; Planetary Circulations; Observational Studies; Hurricane Dynamics; Mesoscale Dynamics; and Convection and Turbulence. These categories, which correspond to the internal organization of research groups, are different from the NOAA bins and are far from being mutually exclusive. Interaction occurs among the various groups and is strongly encouraged.

The appendices contain the following: a list of GFDL staff members and affiliates during Fiscal Year 1989; a bibliography of relatively recent research papers published by staff members and affiliates during their tenure with GFDL (these are referred to in the main body according to the appropriate reference number or letter); a description of the Laboratory's computational support and its plans for FY90; a listing of seminars presented at GFDL during Fiscal Year 1989; a list of seminars and talks presented during Fiscal Year 1989 by GFDL staff members and affiliates at other locations.

Although the specific names of individuals are not generally given in the overview, an entire listing of project participants can be found in Appendix A. Research staff personnel can normally be identified by consulting the cited Appendix B references or the names listed in the body of the text.

The 1989 Annual Report was co-edited by Robert E. Tuleya and Betty M. Williams.

September 1989

TABLE OF CONTENTS

APPENDICES

AN OVERVIEW

SCOPE OF THE LABORATORY'S WORK

The Geophysical Fluid Dynamics Laboratory is engaged in comprehensive long lead-time research fundamental to NOAA's mission.

The goal is to expand the scientific understanding of those physical processes which govern the behavior of the atmosphere and the oceans as complex fluid systems. These fluids can then be modeled mathematically and their phenomenology studied by computer simulation methods. In particular, research is conducted toward understanding:

- the predictability of weather, large and small scale;
- the particular nature of the Earth's atmospheric general circulation within the context of the family of planetary atmospheric types;
- the structure, variability, predictability, stability and sensitivity of climate, global and regional;
- the structure, variability and dynamics of the ocean over its many space and time scales;
- the interaction of the atmosphere and oceans with each other, and how they influence and are influenced by various trace constituents.

The scientific work of the Laboratory encompasses a variety of disciplines: meteorology; oceanography; hydrology; classical physics; fluid dynamics; chemistry; applied mathematics; high-speed digital computation; and experiment design and analysis. Research is facilitated by the Atmospheric and Oceanic Sciences Program which is conducted collaboratively with Princeton University. Under this program, regular Princeton faculty, research scientists, and graduate students participate in theoretical studies both analytical and numerical, and in observational experiments, both in the laboratory and in the field. The program, in part, is supported by NOAA funds. Research scientists visiting GFDL may also be involved through institutional or international agreements, or through temporary Civil Service appointments.

The following sections of the Annual Report describe the GFDL contribution to five major research areas that correspond to NOAA's mission in oceanography and meteorology.

HIGHLIGHTS OF FY89

and

IMMEDIATE OBJECTIVES

In this section, some research highlights are listed that may be of interest to those persons less concerned with the details of GFDL research. Selected are items that may be of special significance or interest to a wider audience.

Items in this section are placed in the NOAA emphasis categories of Weather Service, Climate, Atmospheric Quality, Marine Quality, and Ocean Service. These categories are organized rather differently than the GFDL research project areas presented in the main body of the report. References to more detailed discussions are given in parentheses.

I. WEATHER SERVICE

GOALS

During the past two decades synoptic-scale weather forecasts have improved considerably because of the development of numerical models that include more of the physical processes of the atmosphere, have high spatial resolution, and parameterize turbulent processes more accurately. Successful forecasts for periods up to 5 days are now routine, and the limits of atmospheric predictability have been extended to several weeks. However, quantitative forecasts of precipitation remain elusive. For smaller spatial scales, there has been considerable progress in determining the mechanisms that generate severe storms, in explaining how mesoscale phenomena interact with the large-scale flow, and in simulating the genesis, growth, and decay of hurricanes.

These successes in the extension of atmospheric predictability have encouraged GFDL to ask more challenging questions. For example, can the weather be predicted on time scales of months? Are mesoscale weather systems and regional-scale precipitation patterns predictable, and if so, to what extent is the accuracy dependent on the prediction of the ambient synoptic flow? Research to develop mathematical models for improved weather prediction will also contribute to the understanding of such fundamental meteorological phenomena as fronts, hurricanes, severe storms, and tropospheric blocking.

ACCOMPLISHMENTS OVER THE PAST YEAR (FY89)

* Using an air-sea coupled model, a seasonal forecast experiment was attempted for a second case, following the first successful case reported in FY89. The forecasts were started from January 1982, nine months before the observed El Niño emerged in September. A straightforward method and a method of systematic error correction were applied to the initial condition of the model-assimilated data set for the ocean and NMC analysis for the atmosphere. The forecast based on the former method showed only a slight tendency for sea temperature warming at the eastern Equatorial Pacific, while the forecast based on the latter method was somewhat more successful (3.4.4).

* It has been found that tropospheric blocking activity is manifested by a distinct subpolar peak in the meridional distribution of low-frequency eddy kinetic energy. The models which include the Mellor-Yamada turbulence parameterization tend to have a well-defined peak of this energy distribution. Based on the numerical experiment and other studies, a hypothesis has been postulated on a requirement for blocking: the westerly jet prior to the onset of blocking has to be displaced to a relatively lower latitude (3.2.4).

* The GFDL re-analysis of FGGE data from the Global Weather Experiment is finally near completion. The new analyses are quite good, compared with the original GFDL analyses or with the FGGE re-analyses of ECMWF. This implies, contrary to conventional notions, that continuous data assimilation works satisfactorily when compared with intermittent methods (3.3.1).

* An experimental 3-D prediction of Hurricane Gloria, 1985, was successfully performed in cooperation with NMC. The 72-hour time integration of the model after 00 UTC 25 September produced track prediction with significantly

accelerated movement after 48h, in good agreement with observation. The position error at 72h was 156 km. Also, the predicted distributions of the maximum surface wind and total precipitation during the passage of Gloria compared favorably with observations (7.1.2).

* Budget analyses of the vorticity and heat for two disturbances, one of which developed into Hurricane David, 1979, and another which did not develop, revealed sharp contrasts in the storm development above the surface depression between the two systems. Specifically, the sum of the effects due to vertical motion and latent heat release caused warm core formation only in the case of the developed system. Also, the non-developing system became detached from the easterly wave trough (7.2.1).

* Successful LAHM (Limited Area HIBU Model) cyclone development simulations have been completed for the period 25-28 January, 1986. During this time period, three cases occurred along the eastern coast of the United States that illustrate the different processes by which cyclones are generated. The results indicate that low-level baroclinic development without upper-level development is not conducive to explosive cyclogenesis. In the two explosive cases, an upper-level trough and low-level baroclinicity occurred, although the conditions by which the surface baroclinicity was established were different (8.2.2).

* A case of strong cyclonic development in the South Pacific has been successfully simulated. During the period of 4-6 September 1987, cyclogenesis developed as the subtropical branch of the jet stream near 40°S moved poleward and merged with the polar branch of the jet stream. Preliminary results using innovative diagnostics show that cyclone development occurred through a combination of barotropic and baroclinic processes (8.3.1).

* Two-dimensional African squall line simulations with/without the inclusion of a simplified ice bulk cloud physics have been extended to three dimensions. Both 3-D simulations show a typical squall line structure with two-dimensional features at low levels and increasing three dimensionality with height. The inclusion of the ice phase gave stronger vertical velocities in the anvil and a larger area with anvil rain than present in the model atmosphere without the ice phase (9.1.1).

SOME PLANS FOR FUTURE RESEARCH

* Numerical models for all scales of weather prediction will be improved with new physical packages such as SIB, simple biosphere, and a new vertical differencing scheme introduced for the HIBU model.

* Seasonal, mesocale, and tropical cyclone forecasts will be extended to additional cases and integrated with improved initial conditions.

* Diagnostic and theoretical studies involving atmospheric and oceanic phenomena, such as blocking, baroclinic waves, tropical storms, and squall lines, will be continued. The analysis of FGGE will continue as well as development of data assimilation techniques appropriate for the mesoscale.

* Cooperation with NMC involving exchange of physics packages, data bases, and new model development will continue.

II. CLIMATE

GOALS

The purpose of climate-related research at GFDL is twofold: to describe, explain, and simulate mean climate and climate variability on time scales from seasons to millenia; and to evaluate the effect on climate of human activities such as the release of CO_2 and other gases in the atmosphere. The phenomena that are studied include: large-scale wave disturbances and their role in the general circulation of the atmosphere; the seasonal cycle, which must be defined before departures from the seasonal cycle (interannual variability) can be understood; interannual variability associated with phenomena such as the Southern Oscillation-El Niño; very long-term variability associated with the ice ages; and the meteorologies of various planets, the study of which enhances our perspective on terrestrial meteorology and climate. To achieve these goals, both observational and theoretical studies are necessary. Available observations are analyzed to determine the physical processes by which the circulations of the oceans and atmospheres are maintained. Mathematical models are constructed to study and simulate the ocean, the atmosphere, the coupled ocean-atmosphere-cryosphere system, and various planetary atmospheres.

ACCOMPLISHMENTS OVER THE PAST YEAR (FY89)

* The response of a fully coupled ocean-atmosphere model to a gradual increase of atmospheric carbon dioxide exhibits a marked interhemispheric asymmetry. In the circumpolar ocean of the Southern Hemisphere of the model, the increase of surface air temperature is very slow due to the upwelling of deep water and efficient convection mixing. In the Northern Hemisphere of the model, the increase of surface air temperature is faster and increases with latitude. An exception is the North Atlantic region where the warming is relatively slow due to a weakening of the thermohaline circulation (1.1.1).

* A 100-year integration of a new version of a coupled atmosphere-ocean model with a global computational domain, realistic geography, seasonally varying insolation, and predicted cloudiness has been completed. Preliminary analysis shows that the temporal variability of annual-mean sea surface temperature resembles observed variability (1.2.1).

* Climate simulations with and without orography indicate that mountains play an important role in maintaining arid climates in the midlatitude Northern Hemisphere. General subsidence and relatively infrequent storm development upstream of orographically-induced stationary wave troughs contribute to the dryness of continental interiors. The relative wetness of these regions in the model experiment without orography agrees with paleoclimatic evidence of less aridity in the late Tertiary before the substantial uplift of the Rocky Mountains and Tibetan Plateau occurred (1.3.2).

* Results from an atmospheric GCM experiment incorporating near-global sea-surface temperature variations indicate the important role of oceanic changes in the extratropical North Pacific and North Atlantic on the overlying atmospheric flow pattern. The midlatitude storm tracks are seen to serve as an intermediary between the imposed SST forcing and the quasi-stationary response (6.2.2).

* Diagnosis of an 140-year integration of a low-resolution ocean-atmosphere coupled GCM reveals the existence of regular oscillations with 36-40 month time scales. The meteorological and oceanographic phenomena associated with these cyclical events bear a considerable resemblance to those observed during El Niño-Southern Oscillation episodes (6.2.3).

* A multi-year project to prepare global upper-air weather analyses for the period May 1958 - April 1988 was completed. This provides a unique opportunity to study global climate changes based on a 30-year, nearly homogeneous record (6.1.1). This data set indicates that, over the 1964-1985 period, there has been a general warming of the troposphere and cooling of the lower stratosphere, in general agreement with model projections of the effects of greenhouse gases (6.1.3).

* A study was made of recent claims that the Northern Hemisphere winter weather is significantly affected by a subtle combination of solar activity and the tropical stratospheric quasi-biennial oscillation (QBO). Analysis of historical meteorological and solar data for 1875-1936 was conducted using seven million different scenarios for the evolution of the QBO during this period. The results indicate that the claimed solar-QBO-weather relationship cannot be reproduced in historical data, and thus probably is not a real effect (2.2.8).

* Wavelike synoptic-scale disturbances with well defined structural and propagation characteristics have been identified in specific sectors of the tropical zone using observational data. The occurrence of such features is associated with prominent changes in the quasi-stationary, large-scale circulation (6.1.4).

* Midlatitude and tropical sea surface temperature anomaly experiments have been conducted with an idealized GCM in which the unperturbed climate is zonally symmetric. The significance of changes in the midlatitude storm tracks for the climatic response has been analyzed using a linear stationary wave model. In neither case is there strong positive feedback from the storm track eddies (1.4).

* An atmospheric GCM coupled to a mixed-layer ocean model has been used to study the climatic change due to variation in the obliquity of the earth's orbit and the longitude of the perihelion with respect to the equinoxes. For variations typical of those that have occurred in the past 200,000 years, temperature changes as large as 15K are found over North America in summer (1.3.1).

* Using line-by-line techniques, benchmark solutions for the interaction of solar radiation with water vapor and water drops have been obtained for the first time. Alternative techniques, which are computationally more efficient and whose accuracies range from good to excellent, have also been investigated; these have provided reference solutions to carry out several sensitivity tests related to cloud radiative properties. These calculations are already being used as a benchmark standard for solar radiation under cloudy conditions (1.6.3).

SOME PLANS FOR FUTURE RESEARCH

* Analysis and study of the transient response of climate to a gradual increase of atmospheric carbon dioxide will be continued. Other scenarios for gradual changes of the CO_2 amount in the atmosphere using the seasonal coupled ocean-atmosphere GCM will be evaluated.

* To investigate the role of oceans in climate variability, a detailed analysis will be conducted of the 100-year integration of a coupled ocean-atmosphere GCM with seasonal variation.

* Results from a new set of experiments will be analyzed to clarify the role of cloud feedback in CO_2-induced changes of tropical disturbances.

* The SKYHI GCM will be under development to enhance the simulation of a number of physical processes. Intensive diagnosis of the model will continue.

* Research to understand the role of aerosols in the climate of the stratosphere and upper troposphere will be intensified.

* Climatological analyses of the present observational 30-year data set will be actively pursued. Trend analyses and comparisons with other data sets will be done in joint projects with other institutions. The present 30-year data set will be extended.

* Further diagnoses of the North Pacific and Atlantic sea surface temperature anomaly experiments will be made. These will be conducted to understand the dynamical reasons for the different responses discovered in the perpetual and switch-on forcing experiments. The impact of sea-surface temperature anomalies located in regions other than the central North Pacific and Newfoundland sites will be examined.

* The series of sea surface temperature anomaly experiments with an idealized GCM will be continued. Experiments in which the unperturbed climate is zonally asymmetric will be compared against experiments with zonally symmetric control climates.

* Quasi-geostrophic turbulence integrations will be performed using a multi-level model with realistic atmospheric vertical structure. The model will be used to determine if eddy heat fluxes are more sensitive to low-level or to mean tropospheric temperature gradients.

* The solar radiative transfer techniques investigated during FY89 will be used to develop cloud radiative parameterizations that account for both water vapor absorption and water cloud extinction in overcast atmospheres.

III. ATMOSPHERIC QUALITY

GOALS

The main goal of atmospheric quality research at GFDL is to understand the formation, transport, and chemistry of atmospheric trace constituents on regional and global scales. Such understanding requires judicious combinations of theoretical models and specialized observations. The understanding gained will be applied toward evaluating the sensitivity of the atmospheric chemical system to human activities.

ACCOMPLISHMENTS OVER THE PAST YEAR (FY89)

* The GFDL Global Chemical Transport Model (GCTM) has been used to investigate the behavior of reactive nitrogen (NO_y) emitted by combustion processes. NO_y controls the chemical production of ozone (O_3) in the troposphere, indirectly controls the chemical reactivity of the troposphere, and is an important nutrient source for the oceans. No more than 1.4 tg of the 21.3 tg (nitrogen only) of reactive nitrogen is deposited in the Southern Hemisphere, less than 10% of background. The 4 tg exported from continents accounts well for most of the Northern Hemisphere oceanic deposition: local basin depositions are dominated by the upwind continental source regions (2.1.3).

* A new GFDL SKYHI model experiment has been started to investigate the chemical-transport-radiative-dynamical response of the stratosphere to the Antarctic "ozone-hole". The model shows substantial mixing of the ozone-depleted air into midlatitudes during Austral spring, but with relatively low memory of the low Antarctic values by the following winter. The ozone hole region produces spring polar vortex cooling of up to 10°C and zonal wind increases of up to 15 m sec^{-1} (2.4.1).

* Three-dimensional calculations for a boundary layer source of an insoluble tracer, a fully soluble tracer and a partially soluble tracer (SO_2 gas) have been carried out using the continental and tropical maritime squall line models. The only tracer to reach the upper atmosphere in significant amounts is the insoluble tracer. In contrast, virtually none of the fully soluble tracer is found at 10 km or above. Rainout is thus a very efficient mechanism for preventing boundary layer tracer from reaching the upper levels (9.3).

SOME PLANS FOR FUTURE RESEARCH

* Detailed analysis will continue on mechanisms governing regional chemical transport, including both stratospheric and surface sources.

* A new series of experiments will be underway to examine the various aspects of the tropospheric nitrogen budget. Emphasis will be placed upon differentiating natural and anthropogenic sources as well as the chemical behavior of the reactive nitrogen species.

* The long term effort to develop a fully consistent ozone chemistry for the SKYHI model will be accelerated.

* The SKYHI simulations of the doubled CO_2 and Antarctic "ozone hole" effects will be run to completion and analyzed.

* Using a 3-D convective model, studies will continue for both stratospheric and tropospheric tracers under various atmospheric conditions and for different chemical constituents.

IV. MARINE QUALITY

GOALS

Research at GFDL related to the quality of the marine environment has as its objectives the simulation of oceanic conditions in coastal zones and estuaries, the modeling of the dispersion of geochemical tracers (tritium, chlorofluorocarbons...) in the world oceans, and the modeling of the oceanic carbon cycle and trace metal geochemistry. For regional coastal studies two- and three-dimensional models of estuaries, basins, and western boundary regimes are being developed. The response of coastal zones to transient atmospheric storms, and the nature of upwelling processes (which are of great importance to fisheries), are being studied by means of a variety of models. Basin and global ocean circulation models are being developed for the study of the carbon cycle and trace metal cycling.

ACCOMPLISHMENTS OVER THE PAST YEAR (FY89)

* A first 3-D simulation of anthropogenically produced CO_2 uptake by the oceans has been carried out (4.3.1).

* Ocean biological processes are important to the ocean's carbon cycling. A simple ecosystem model of the euphotic zone of the upper ocean has been incorporated into a three-dimensional North Atlantic circulation model (4.3.2).

* An annual mean model of the global ocean general circulation has been used to study the effect of organic matter remineralization below the euphotic zone on the distribution of nutrients. An important role for dissolved organic matter in the carbon cycle is suggested by this work (4.3.2).

* The South Atlantic Ventilation Field Experiment (SAVE) has been completed in which measurements of radium-228 were collected. Laboratory measurements of a similar suite of ocean tracers in the North Atlantic have almost been completed (4.3.3).

SOME PLANS FOR FUTURE RESEARCH

* The fossil CO_2 experiments and related carbon cycle development studies will continue to be highest priority.

* The analysis of SAVE nutrient observations will begin. Oceanic tracers will be studied by both measurement analysis and modeling studies.

V. OCEAN SERVICE

GOALS

A variety of models that can be used for the prediction of oceanic conditions are being developed at GFDL. The simpler models are capable of predicting relatively few parameters. For example, one-dimensional models of the turbulent surface layer of the ocean predict the sea surface temperature and heat content of the upper ocean. More complex three-dimensional models are being developed to study many phenomena: the time-dependent development of Gulf Stream meanders and rings; generation of the Somali Current after onset of the southwest monsoons; response of coastal zones to atmospheric storms; and development of sea surface temperature anomalies such as those observed in the tropical Pacific Ocean during El Niño-Southern Oscillation (ENSO) phenomena.

ACCOMPLISHMENTS OVER THE PAST YEAR (FY89)

* To understand climate change it is critically important that ocean models have realistic pathways of CO_2. Transient tracers present the most realistic check of this property of models. The World Ocean Circulation model designed for climate studies has been used to predict the invasion of the ocean by chlorofluorocarbons (CFC's). A comparison with data shows that the model provides a good quantitative simulation of the downward pathways in the World Ocean (4.4).

* A hierarchy of coupled ocean models have been analyzed to provide an understanding of the El Niño phenomenon. Several types of equatorially trapped air-sea interactions take place, providing a partial explanation of the very large differences in individual El Niño events observed (4.1).

* A series of experiments in a model with simplified geometry provided a systematic exploration of the physical factors in the global distribution of heat and salinity of the World Ocean. The analysis allows a quantitative assessment of the relative source strength of deep and intermediate waters unobtainable using conventional water mass analysis. The experiments demonstrate the dominant role of the North Atlantic thermohaline circulation in the World Ocean circulation (4.5).

* A three-dimensional coupled ice-ocean model has been developed and applied to simulate deep convective regions near the ice edge including intense small scale (5-20 km) features called "chimneys", which ventilate the deep ocean (4.7).

* Using a regional orthogonal curvilinear model of the Gulf Stream, studies indicate that Gulf Stream separation is sensitive to the southeastward slope current and small changes in the inflow salinity. As part of an international program, a similar model is being created for the Mediterranean Sea and verification data is being collected (4.6, 4.8).

* A series of four studies describing the temporal variability of the thermohaline structure of the North Atlantic Ocean has been completed. Statistically significant changes on gyre and basin scales have been found which indicate that substantial redistribution of heat and salt took place between the 1955-59 and 1970-74 pentads (6.3.3).

SOME PLANS FOR FUTURE RESEARCH

* The invasion of CFC's will be studied through a coupled ocean-atmosphere model as a test of the model's ability to simulate downward pathways in the ocean important for the green house gas climate problem.

* Analyses of the various simulations of the El Niño will continue. Studies of the impact of the seasonal cycle on the Southern Oscillation will be initiated.

* The understanding of Gulf Stream dynamics and the enclosed basin of the Mediterranean will continue to be studied using the curvilinear model.

* The case of the 3-D coupled ice-ocean model will be extended to the main Arctic basin and other seas to study basin circulations and water mass modifications.

* All available data sets will be used in the study of temporal variability of the thermohaline structure of the world ocean as well as describing the climatological annual cycle.

PROJECT ACTIVITIES FY89

PROJECT PLANS FY90

1. CLIMATE DYNAMICS

GOALS

* To construct mathematical models of the atmosphere and of the joint ocean-atmosphere system which simulate the global large-scale features of climate.

* To study the dynamical interaction between large-scale wave disturbances and the general circulation of the atmosphere.

* To identify and elucidate the physical and dynamical mechanisms which maintain climate and cause its variation, and to examine their generality in the context of paleoclimate and the atmospheres of other planets.

* To evaluate the impact of human activities on climate.

1.1 CO_2 AND CLIMATE

1.1.1 Transient Response to Increasing CO_2

K. Bryan
K. Dixon
S. Manabe
M. Spelman
R. Stouffer

ACTIVITIES FY89

This project represents a close cooperation between the Ocean Dynamics and the Climate Dynamics groups at GFDL. In recent years the emphasis of this research has been placed upon the study of the transient response of the coupled ocean-atmosphere system to an increase of greenhouse gases in the atmosphere.

(a) Instantaneous Doubling of CO_2

The study of the transient response of climate to an abrupt increase of atmospheric CO_2 has been the subject of a long-term integration. During FY89 work was completed on the response of a global coupled ocean-atmosphere GCM (Global Circulation Model), which uses annual mean insolation, to an instantaneous doubling of CO_2 (mh). A large interhemispheric asymmetry appears in the transient response. During the first 40 years of integration, the surface air temperature over the Antarctic Continent and the Circumpolar Ocean rises more slowly than the Northern Hemisphere where the warming is particularly large in high latitudes. The presence of a deep, well-mixed column of water, which has a very large heat capacity, in the Circumpolar Ocean is partly responsible for this very slow rise in surface air temperature.

It is surprising that the warming of the surface air over the Circumpolar Ocean is reduced during the last 15 years of the 60-year integration. Because of the increased precipitation caused by enhanced penetration of relatively warm moisture-rich air aloft into high latitudes, the surface halocline of the Circumpolar Ocean intensifies, which suppresses the mixing between the surface layer and the warmer underlying water.

Very slow warming of the Circumpolar Ocean has occurred in other simulations of the transient response of climate to increasing CO_2, including one with a gradual increase of CO_2 which is described below.

(b) Gradual Increasing CO_2

A coupled global ocean-atmosphere GCM which uses seasonally varying insolation was used to study the transient response to a gradually increasing amount of CO_2 (1 percent per year)(mo). A large hemispheric asymmetry in the response to the gradually increasing CO_2 has been found. The asymmetry is qualitatively similar to that described above in the instantaneous doubling integration. In the Southern Hemisphere, the surface air temperature in the region surrounding Antarctica is very slow to increase. In the Northern Hemisphere, the surface air temperature increases in response to the increasing CO_2 with the largest increase in high latitudes except in the North Atlantic region.

Unlike the results from the instantaneous doubling experiment, the sea surface temperature in the northern North Atlantic Ocean is very slow to increase in response to the gradually increasing CO_2. The North Atlantic is also a region where there is a very deep, well mixed column of water. In the instantaneous doubling experiment, the water column in this region is unrealistically stably stratified. In the gradually increasing CO_2 experiment, the water column is very well mixed, in good agreement with the present observations.

The map of the difference in surface air temperature response averaged for the years 61-70 (just before doubling of the CO_2) is shown in Figure 1.1. The Northern Hemisphere warming is a maximum in high latitudes except in the North Atlantic region as described above. In contrast to general global warming, there are areas of cooling surrounding Antarctica.

PLANS FY90

The analysis and study of the transient response of climate to a gradual increase of atmospheric carbon dioxide will be continued. Other scenarios for the gradual change of the CO_2 amount in the atmosphere using the seasonal coupled ocean-atmosphere GCM will be evaluated. The effect of annual mean insolation on the model climate will be studied by comparing it with a model which has seasonal variation of insolation.

1.1.2 CO_2-Induced, Mid-Continental Summer Dryness

S. Manabe R. Wetherald

ACTIVITIES FY89

CO_2-induced change of hydrology has been the subject of long-term research (see for example, (795)). The results from climate models indicate that, over very extensive mid-continental regions of North America, Southern Europe and Siberia, soil becomes wetter during the winter season whereas it becomes considerably drier during summer in response to a doubling of atmospheric CO_2. Analysis of the various numerical experiments suggests that the entire summer dryness scenario may depend crucially upon how well the annual march of hydrologic quantities such as precipitation and evaporation over continental regions is simulated.

Recently, the CO_2-sensitivity investigation was repeated by a version of the model with twice as high a computational resolution (R30, spectral model truncated at wavenumber 30 corresponding to grid of 2.25° latitude by 3.75° longitude) as the models used in the previous studies. The model incorporates seasonal variation of insolation, cloud prediction and a static mixed-layer ocean. At the bottom of the oceanic mixed layer, a heat flux is prescribed such that the model reproduces the geographical and seasonal variation of observed sea surface temperatures and sea ice extents for the standard integration. It was found that the simulated distribution of precipitation over the major continental regions by this model was significantly more realistic than that produced by the models with lower resolution. Because of this improvement the CO_2-induced change of hydrology is reevaluated by comparing the climate generated from the standard integration with that produced by a doubling of atmospheric carbon dioxide.

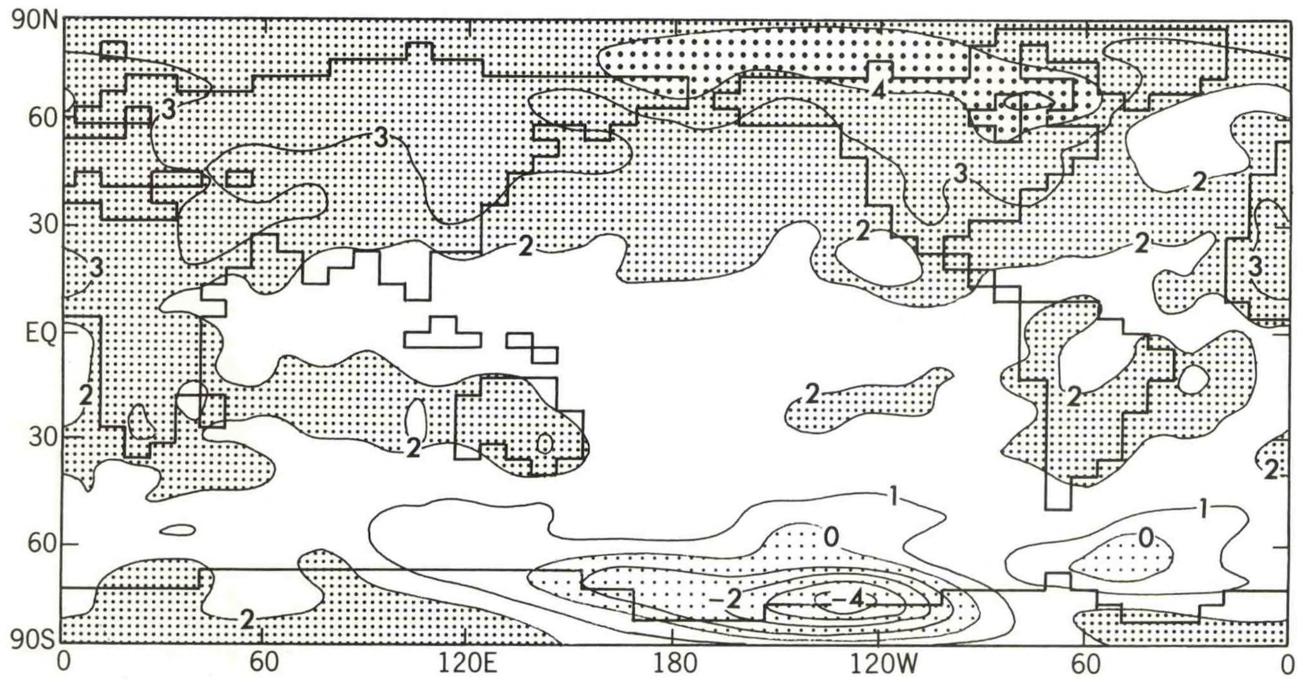


Fig. 1.1. The geographical distribution of surface air temperature response (°C) from the integration which has a gradually increasing amount of CO_2. The data are decadal means from the period just before doubling of the CO_2.

In general, the results from this latest experiment substantiate the main conclusions made in earlier studies, namely a tendency to produce warmer and wetter winters and hotter and drier summers over most of North America and Europe in response to the increase of CO_2. The latter feature is illustrated for North America in Figure 1.2 which shows the change of soil moisture over the continent for the months of April through September. In this figure, it may be seen that the region of soil moisture dryness which is confined to the lower portion of the United States in April spreads northward and becomes more intense as the months progress from spring to summer. The maximum dryness occurs during the months of July and August. Also of interest is a tendency for wetter soil conditions to occur in the extreme southern portion of the United States along the Gulf Coast and in the Southwest which appears to be related to the increased soil dryness in the interior of the continent.

PLANS FY90

The response to the climate of the higher resolution model to a doubling of atmospheric carbon dioxide will be continued. In particular, a detailed regional analysis of the control simulation as well as the corresponding CO_2-induced climate change will be performed and compared with that obtained for the lower resolution model. This will include an extensive evaluation of the features of mid-continental summer dryness and an increase of summer wetness over India.

1.1.3 CO_2 and Tropical Disturbances

A. Broccoli S. Manabe

ACTIVITIES FY89

During FY88, experiments were conducted using the R15 GCM to study the response of tropical storms to the doubling of atmospheric carbon dioxide. As discussed in GFDL A88/P89, the number of storm days (defined as the product of the number of individual tropical vortices and their duration) increases significantly in the R15 GCM without cloud feedback while it fails to increase in the R15 GCM with cloud feedback. The effort to understand the role of cloud feedback on CO_2-induced changes in tropical disturbances continued during the year. A pair of experiments was designed to better isolate the effects of interactive cloudiness from other differences between the models with and without cloud feedback. One of the experiments in this pair has been completed and the other is underway. In addition, the integrations of the R30 model with interactive cloudiness were completed. The results from these integrations were consistent with the results from the R15 model described in GFDL A88/P89.

While awaiting the completion of the new set of experiments, the completion of the R30 cloud feedback runs allowed a detailed analysis of the simulation of tropical disturbances for the present climate. The R15 and R30 experiments with the present concentration of greenhouse gases were used in this analysis. In both simulations, disturbances present in the model tropics resemble tropical cyclones in their thermodynamic structure. One such system is depicted in Figure 1.3a. These vortices develop over oceanic regions where tropical cyclones develop in the real atmosphere. Figure 1.3b illustrates the spatial distribution of these systems in the R30 experiment. With the

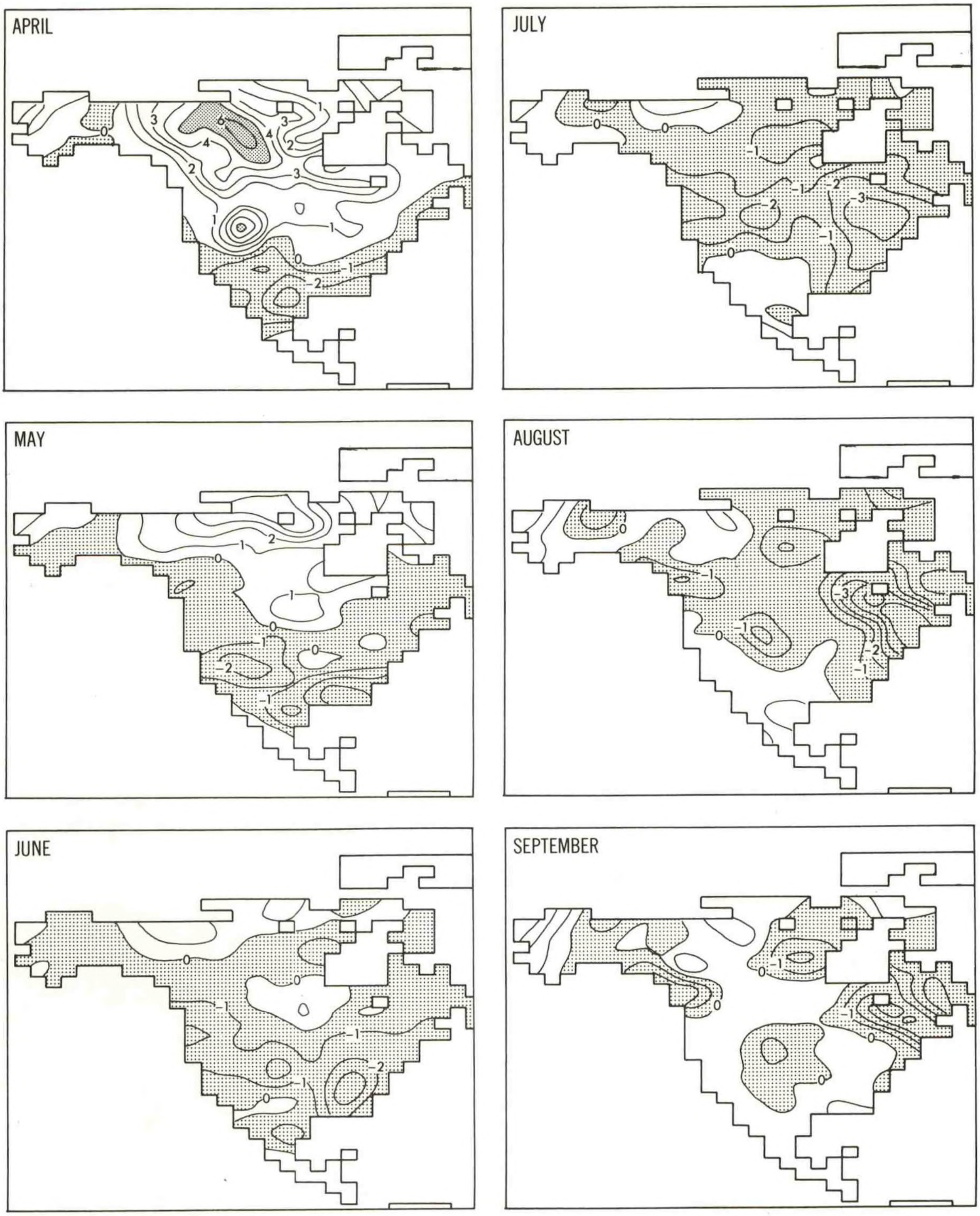
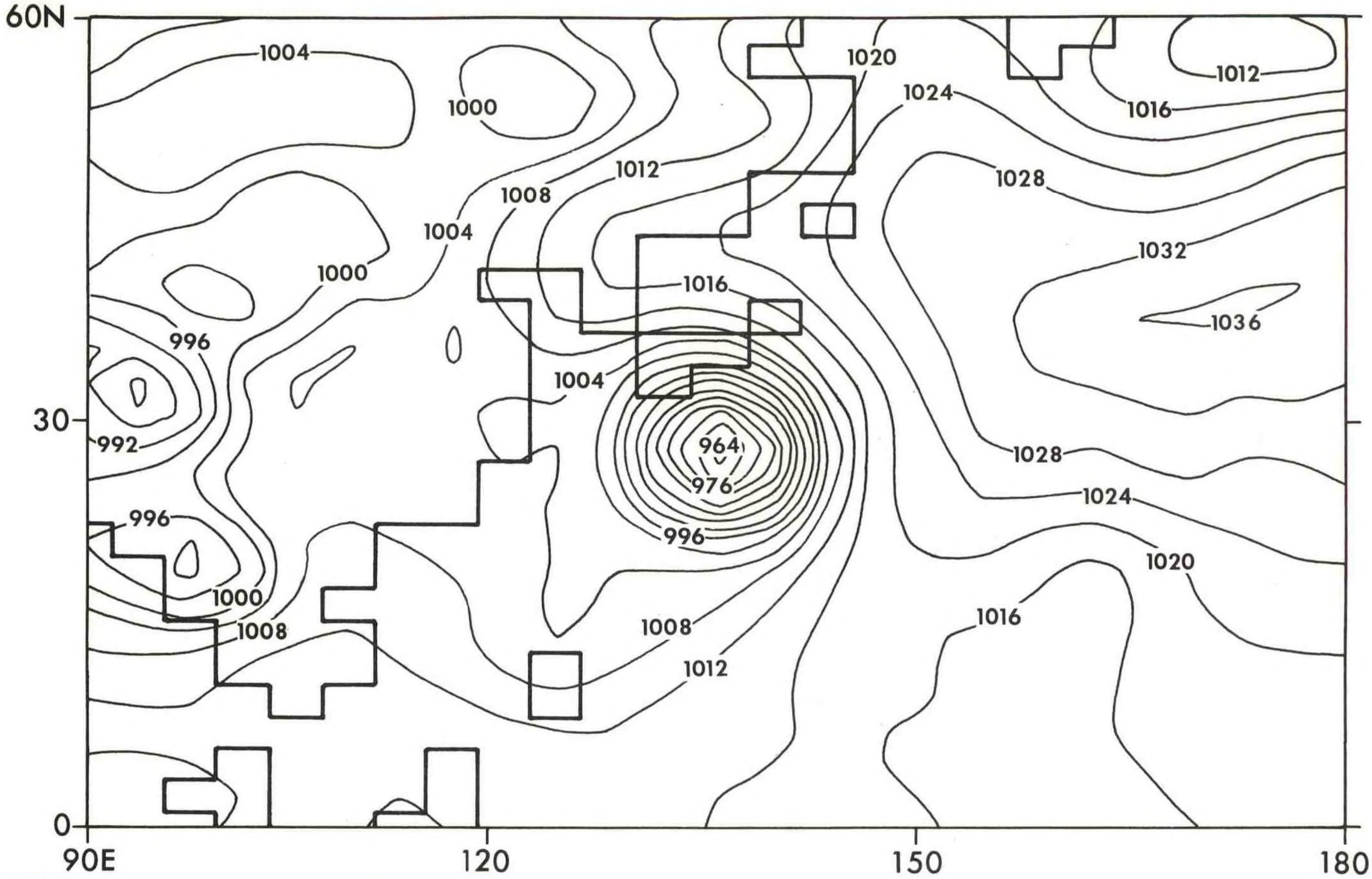


Fig. 1.2. Geographical distributions of the CO_2-induced change ($2xCO_2$-control) of monthly mean soil moisture (cm) over North America for six separate months from April to September. Results represent ten year averages. Negative values of soil moisture change are lightly shaded.



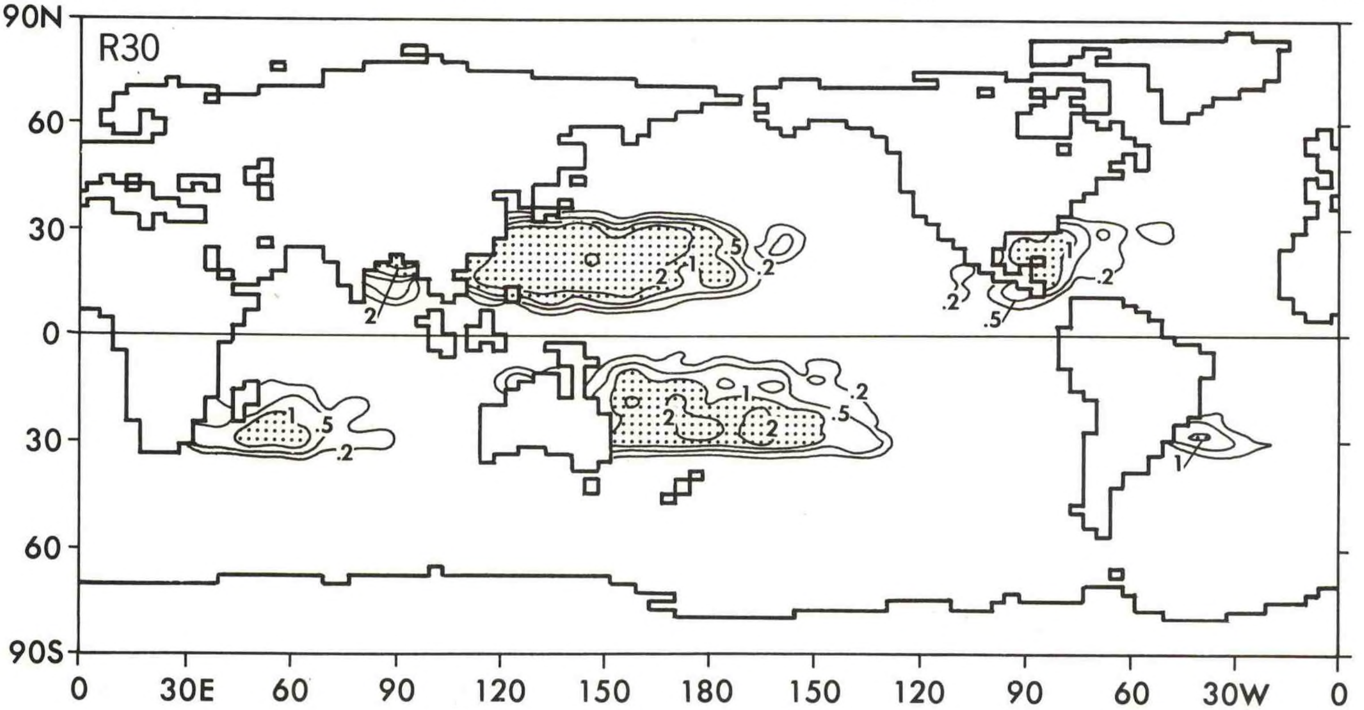


Fig. 1.3. (Top) Sea level pressure distribution in millibars for a mature cyclone from the R30 experiment. This system developed well east of the Phillipines then moved northwestward. (Bottom) Annual frequencies of tropical storm-strength cyclones (surface wind speed > 17 m/s) per unit grid box (approximately 450 km by 700 km) from the R30 experiment. [Note that the unit grid box is not the same size as the model grid.]

exception of the South Atlantic Ocean, where tropical cyclones are not found in reality, the simulation of the active regions for tropical disturbance activity is quite good. The average annual frequency of these systems producing surface winds of tropical storm strength (> 17 m/s) is similar to observed storm frequencies for many of the regions where tropical cyclones occur. Analysis of the ten-year R15 simulation indicates that the interannual variability is also similar to that of observed tropical cyclones.

PLANS FY90

Further effort will be devoted to understanding the role of cloud feedback in the CO_2-induced changes in tropical disturbances. This will involve analysis of the new experiments, and will begin once they are completed early in FY90.

1.2 CLIMATE VARIABILITY

1.2.1 Variability of a Coupled Ocean-Atmosphere GCM

K. Bryan S. Manabe
T. Delworth R. Stouffer

ACTIVITIES FY89

The study of the influence of the ocean on the variability of climate has been continued during the past year. A 100-year integration of a new version of a coupled atmosphere-ocean model was completed and analysis has just begun. The model has a global computational domain and realistic orography. Two substantial differences from previous experiments are that this model incorporates seasonally varying insolation and predicted cloudiness.

In order to assess the model's ability to reproduce the characteristics of oceanic variability, the standard deviations of annual mean sea surface temperature were computed for both the model output and for observed data from the COADS project (Comprehensive Ocean-Atmosphere Data Set), and are shown in Figure 1.4. The model sea surface temperatures are from the first 50 years of the integration, while the COADS data used is from 1950-79. The broad similarities between the two maps are very encouraging, suggesting that the model is able to simulate the large-scale features of sea surface temperature variability.

Quantitatively, the model's standard deviations are somewhat smaller than those from the COADS data set, although the coarse model resolution (4.5° latitude by 7.5° longitude) may be partially responsible for the differences. The maxima in the northwest Atlantic and Pacific are close to observed. There are zones of large variance in higher latitudes of the Southern Hemisphere for both the model and the observed data. In general, the degree of agreement between simulated and observed oceanic variability encourages use of this model for study of the influence of oceanic variability on the atmosphere.

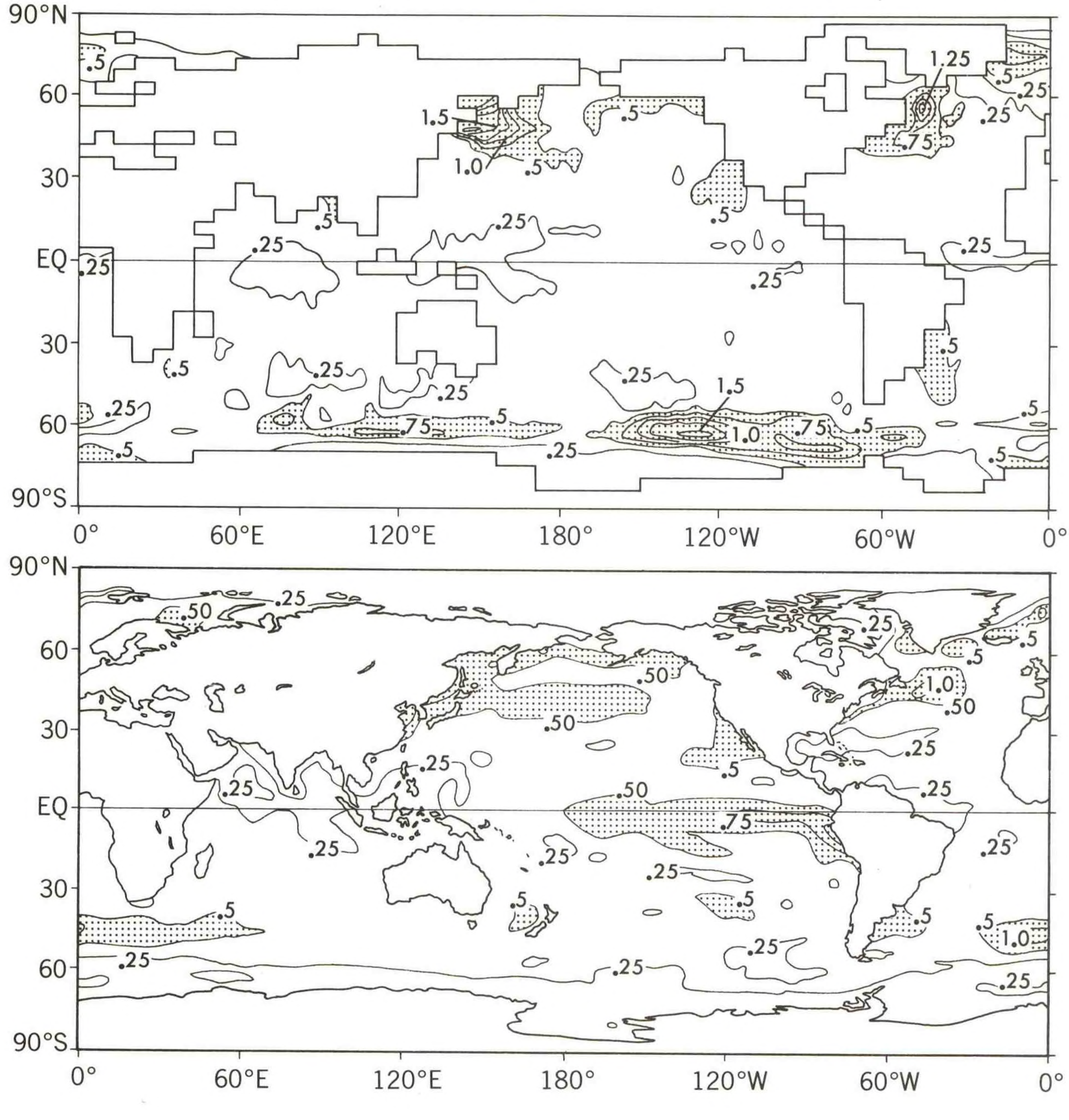


Fig. 1.4. Standard deviations of annual mean sea surface temperature (°C). Top: Computed from model output from the first 50 years of the integration. Bottom: Computed from observed (COADS) data from years 1950-79.

PLANS FY90

A detailed analysis of the variability of this model will be conducted. The impact of the temporal variability of the model ocean on the model atmosphere will be evaluated.

1.2.2 Land Surface-Atmosphere Interaction

T. Delworth S. Manabe

ACTIVITIES FY89

Investigations into the role of land surface processes in climate variability have been continued during the past year. The main data sets used for this analysis have been two extended integrations of an R15 GCM with seasonally varying insolation, a prescribed annual cycle of sea surface temperature, and fixed cloudiness. In the first integration of length 50 years, soil moisture was computed interactively while in the second integration, of length 25 years, the seasonal cycle of soil moisture was prescribed at each land point. Differences in atmospheric variability between the two integrations are attributable to land surface-atmosphere interactions.

Soil wetness interacts with the atmosphere by altering the latent and sensible heat fluxes at the surface. As shown previously (878), soil wetness is characterized by fluctuations on seasonal to interannual time scales. The persistence of soil wetness anomalies affects the surface fluxes of heat and moisture, thereby inducing persistent anomalies in the lower troposphere. As a measure of this persistence, one month lagged autocorrelations of a time series of an index of monthly mean relative humidity were computed at each grid point using data from June, July and August. The zonal means over land are shown in Figure 1.5. Relative humidity has substantial persistence up to 800 mb, with zonal mean autocorrelation values greater than 0.5 at some latitudes. In the integration with prescribed soil wetness, however, there is virtually no persistence of relative humidity anomalies, even very close to the surface. The persistence of relative humidity in the first integration is a direct result of interactions between the surface hydrologic balance and the atmosphere, which are not present in the second integration (mc).

PLANS FY90

Further analysis will be made of the atmospheric patterns associated with anomalous land surface conditions. In particular, a new integration of a GCM in which clouds are computed interactively will be used to study interactions between land surface processes and clouds.

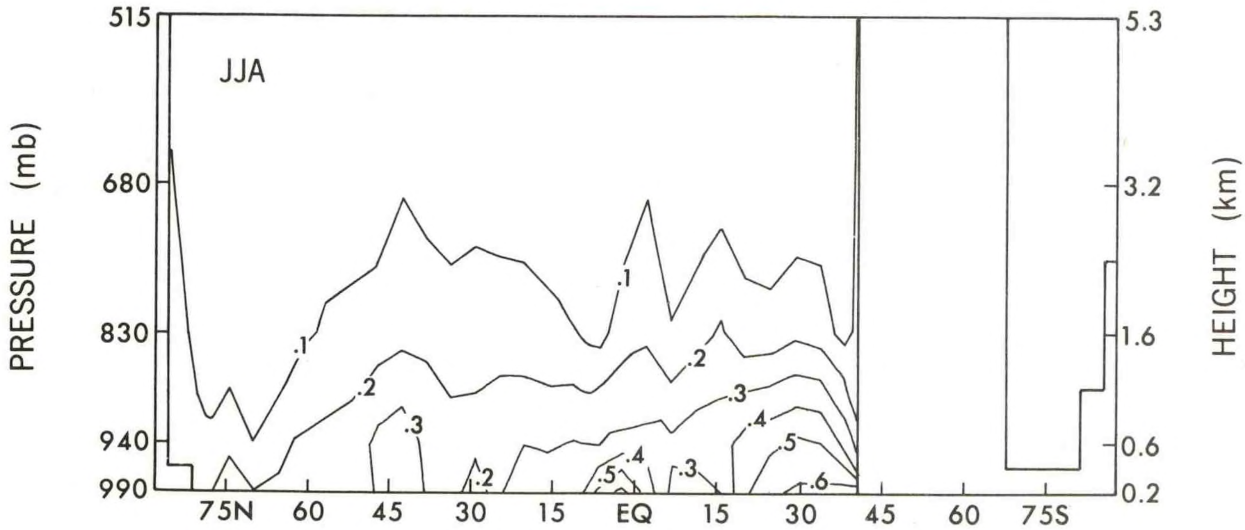


Fig. 1.5. Zonal means over land of autocorrelation values of an index of monthly mean relative humidity. At each grid point, values of this index were correlated with values of the same index one month later. Positive values denote a persistence of anomalies. The correlations were computed using data only from the months of June, July and August.

1.2.3 Tropical Intraseasonal Oscillations

D. Golder Y. Hayashi

ACTIVITIES FY89

Space-time spectral analysis of tropical intraseasonal oscillations has been made with the use of a 30-wavenumber spectral model integrated over 6 years and the ECMWF (European Centre for Medium Range Weather Forecasts) 4-dimensional analysis data set which was available over 9 years. It was shown that the model exhibited two eastward moving spectral peaks at 25-30 and 40-50 days, while the observed data indicated a major spectral peak, eastward moving, around 40-60 days. There was a substantial year-to-year variability in the spectra of both the observed and simulated data, even though the model's sea surface temperature does not have an interannual variability. Although a minor 25-30 day spectral peak appears in several years of the observed data, this peak did not stand out clearly in the 9-year average. This result suggests that the model atmosphere has some mechanism which artificially enhances the 25-30 day peak.

Using a spectral GCM with an all ocean surface, the effects of condensational heating and extratropical disturbances on tropical intra-seasonal oscillations have been studied. When condensational heating was removed, these oscillations were drastically reduced and their spectral peaks were hardly detectable against background noise. However, when extratropical disturbances were drastically reduced by removing the latitudinal gradient of the imposed sea surface temperature, these peaks became more clearly detectable in the vertical velocity. These results suggest that small amplitude tropical intraseasonal oscillations may exist even in the absence of condensational heating or extratropical disturbances.

PLANS FY90

The study of tropical intraseasonal oscillations with the use of a GCM will continue.

1.2.4 Energetics of Transient Waves

D. Golder J. Sheng
Y. Hayashi

ACTIVITIES FY89

Further analyses of spectral energetics in the frequency domain have been made of several observed data sets and those simulated by a GFDL general circulation model (ko, kp). The results indicate a good agreement on the direction of energy flows within both the observed and simulated atmospheres. The conversion of available potential energy to kinetic energy is the major source of transient kinetic energy for all the frequency bands discussed. The energy balance calculated for the tropics has quite different characteristics from those for the extratropics. Instead of an up-scale decascade as found in the results for the extratropics, kinetic energy in the tropics is transferred in an opposite sense, namely, from transients of longer time scales to those of shorter time scales. Using a 5-year data set from the ECMWF operational analysis, an energy cycle is obtained that is in general agreement with the one computed using the data of the FGGE year alone.

PLANS FY90

The atmospheric energetics in the frequency domain for observed and simulated data will be completed.

1.3 PALEOCLIMATE

1.3.1 Sensitivity to Orbital Parameter Variations

I. Held P. Phillipps

ACTIVITIES FY89

Two experiments have been performed with an R15 atmospheric GCM (with prescribed clouds) coupled to a mixed-layer ocean to test the sensitivity of the model to changes in orbital parameters. In both experiments the eccentricity of the earth's orbit was set at 0.04. In one experiment, the perihelion of the orbit was placed at summer solstice and the obliquity was set equal to 25°; in the other, the perihelion was at winter solstice and the obliquity equaled 22°. The latter set of parameters favors cool summers and is thought of as favorable for ice sheet growth.

Figure 1.6 shows the difference between the July mean surface temperatures and precipitation rates predicted by the model for these two sets of parameters. Temperature changes in central North America are larger than 15K. Despite this sensitivity, summertime temperatures are still too warm for the snow to persist in the "cool summer" case; in this sense the model fails to generate an embryonic Laurentide ice sheet over North America. A short experiment with "cool summer" parameters but with CO_2 lowered to 200 ppm indicated that the cooling resulting from this lower CO_2 value (comparable to the concentration at the last glacial maximum, as observed in ice cores) still does not prevent the snow from melting in summer.

Figure 1.6b shows dramatic changes in the hydrologic cycle, with wetter summertime conditions over Africa and monsoon Asia and drier conditions over much of central Asia and North America in the warm summer experiment. In order to analyze these precipitation and temperature changes, several perpetual July integrations were performed with the atmospheric model, using different combinations of the orbital parameters and the boundary conditions (SST, sea ice, ground wetness) generated by the seasonal integrations. This first demonstrated that the patterns in Figure 1.6 could be reproduced with surprising fidelity by comparing perpetual July integrations with orbital parameters and boundary conditions corresponding to the two seasonal integrations. Then, by comparing models which differed only in orbital parameters, or only in boundary conditions, one was able to demonstrate that:

1) roughly half the warming in North America was due to drying of the soil; the other half would have occurred with fixed soil wetness;

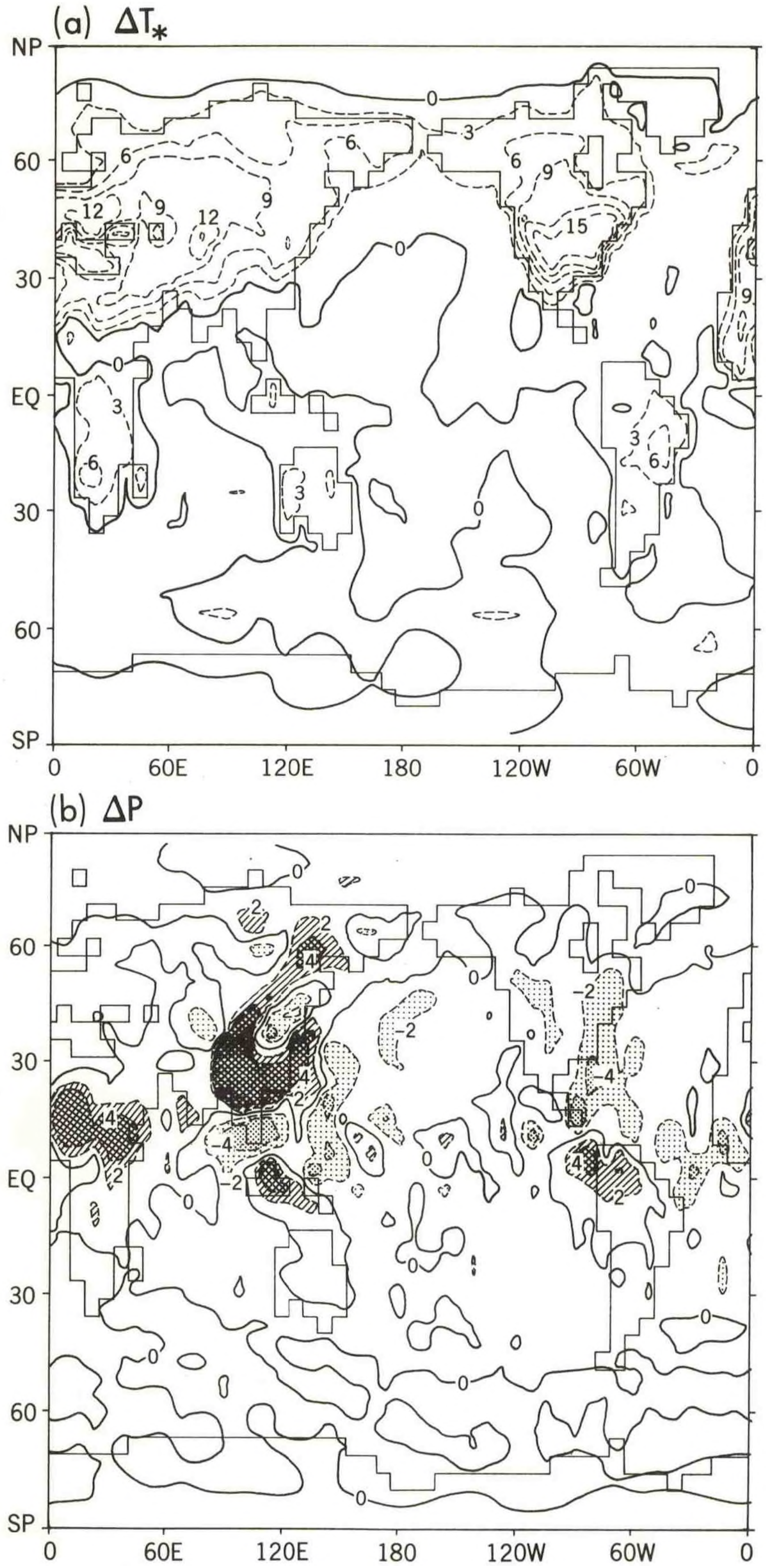


Fig. 1.6. Difference in a) July surface temperature and b) July precipitation rate between two orbital parameter GCM experiments ("warm" minus "cold" summer). The contour interval in a) is 3K; in b) it is 2mm/day.

2) the precipitation change over North America was almost entirely due to the change in soil wetness, emphasizing how strong the positive feedback is from ground hydrology in this region of the model;

3) the increase in rainfall over Africa is half due to insolation, half to a wetter soil, while the increase in Southeast Asia is almost entirely due to the insolation change.

PLANS FY90

Similarities and differences between the summer dryness over North America with "warm summer" orbital parameters and that predicted for a CO_2 rich climate will be examined in the context of the perpetual July integrations. Further seasonal experiments will be contemplated to study what happens as summertime temperatures are cooled further. A more complete parameter study of the sensitivity to orbital variations will await the advent of the next computer system at GFDL.

1.3.2 Climate and Orography

A. Broccoli S. Manabe

ACTIVITIES FY89

The study of the role of mountains in maintaining the extensive arid and semiarid climates in middle latitudes of the Northern Hemisphere continued during the past year. As discussed in GFDL A88/P89, two experiments were performed with the high resolution (R30) climate model. One of these (the M experiment) used realistic geography and orography while the other (the NM experiment) used realistic geography but flat continental surfaces. Examination of the large-scale patterns of soil moisture from these two experiments reveals little east-west variation in the NM experiment, while large departures from zonal symmetry occur in the M experiment. The substantial regions of low soil moisture present in the M experiment over central Asia and over the western interior of North America correspond quite well to observed steppe and desert regions.

The geographical distribution of precipitation follows a similar pattern. In the NM experiment, a band of relatively large precipitation crosses the continents between 45N and 65N, with areas of light precipitation in the subtropics and polar regions. With mountains present, midlatitude precipitation has more east-west variability, with very light precipitation over the interior regions described above. Analysis of the atmospheric circulation in each experiment indicates that these interior regions are dry because general subsidence and infrequent storm development occur upstream of orographically-induced stationary wave troughs. Downstream of these troughs, precipitation-bearing storms develop frequently in association with strong polar jet streams. By contrast, the atmospheric circulation is more zonally symmetric in the NM experiment.

The transport of moisture into the continental interiors is also influenced by the presence of mountains. Figure 1.7 shows vertically-integrated moisture transport vectors from each experiment for the spring season. In the NM experiment, the North Pacific and North Atlantic are

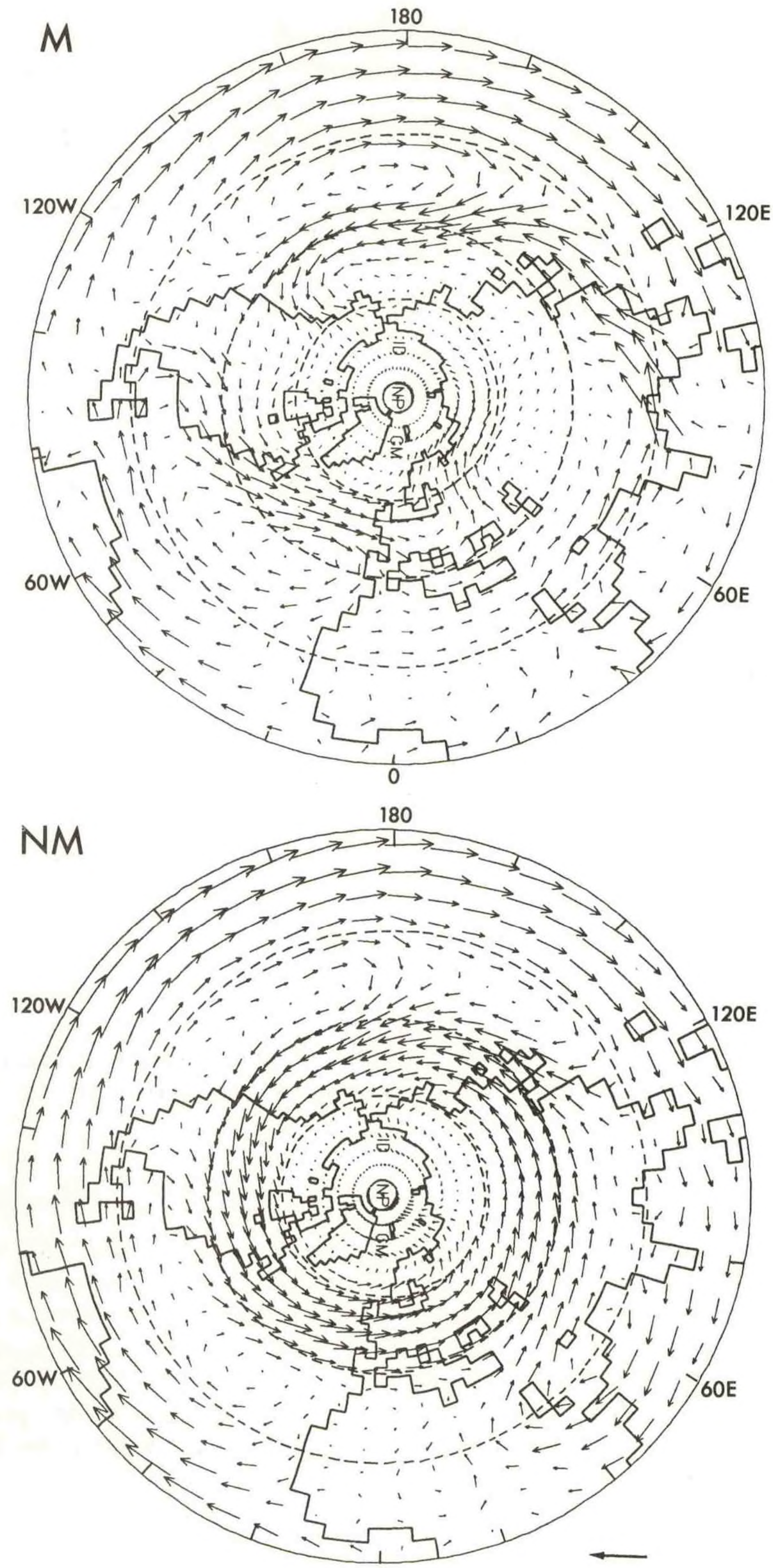


Fig. 1.7. Vertically integrated moisture transport vectors from (top) the M experiment and (bottom) the NM experiment for the March-April-May season. The arrow in the lower right corresponds to a transport of 30 g kg^{-1} m s^{-1}.

primary sources for the moisture that falls as precipitation over the continental interiors. In addition, the circulation carries moisture from the North Indian Ocean into the Asian interior. When mountains are present, the transport from the North Pacific and North Atlantic turns northward before reaching the continental interiors, reducing the availability of oceanic moisture for precipitation. To the south, Indian Ocean moisture undergoes a sharper anticyclonic turn around the Arabian Sea, then flows eastward across India and southeast Asia south of the Tibetan Plateau.

The results of these experiments are interesting in the light of evidence suggesting that much of the uplift in the Tibetan Plateau region and the western United States occurred in the last five to ten million years. In addition, paleoclimatic data suggest that winters became progressively drier over the northern Great Plains during the last 10 million years, and that a general drying of the Eurasian interior took place during a similar period. Assuming that the evidence of orographic uplift is correct, the changes in climate between the M and NM experiments are consistent with the paleoclimatic evidence from these regions.

PLANS FY90

The analysis of the effects of orography on the global distribution of arid and semiarid climates using the R30 M and NM experiments will be completed.

1.4 STATIONARY WAVES

K. H. Cook D. Karoly
I. M. Held M. Ting

ACTIVITIES FY89

Work has continued on both the theory of stationary eddies in the atmosphere and the comparison of stationary eddies produced in linear and nonlinear steady state models to those by GCMs.

1.4.1 The Relative Importance of Orographic and Thermal Forcing

Using a linear primitive equation model on the sphere, it was demonstrated that the stationary wave response to shallow extratropical heating tends to be inversely proportional to the strength of the low-level mean winds, and the response to orography proportional to these winds. As a consequence, the relative importance of thermal and orographic forcing is very sensitive to the strength of the low-level winds. An analysis using a linear quasi-geostrophic model of this problem on a beta-plane was performed to explain these results (mg).

1.4.2 Diagnosing Stationary Eddy Sources and Sinks

An earlier analysis of observed stationary and low-frequency eddies using Plumb's three-dimensional stationary eddy flux vector was extended by applying the same technique to solutions of the linear model forced by tropical heat sources. When applied to the linear model solutions, this technique gives a clear indication that the source is in fact in the tropics. This increases extratropically forced eddies. When applied to the observed waves, the same diagnostic gives little indication of a significant tropical source (ly).

1.4.3 Steady Nonlinear Response to Tropical Heating

A series of calculations have been performed starting with an idealized GCM over an all-ocean surface with prescribed zonally symmetric surface temperatures, and then perturbing this model with localized SST anomalies. The climatic responses to these anomalies have then been analyzed with a linear stationary wave model that is an exact linearization of the GCM equations about a zonally symmetric basic state. To extend these studies, an iterative, modified Newton-Raphson procedure has been developed to obtain steady nonlinear solutions of these same equations. To construct this nonlinear model, it was first necessary to develop a model that was linearized about a general zonally asymmetric flow. It is this asymmetric linear model that is iterated to obtain the nonlinear solution. Because of computational requirements, the nonlinear model is currently being used at less resolution than the GCMs it is mimicking. The meridional and vertical resolutions have been chosen to be identical to the R15 GCM, but the models have been truncated at zonal wavenumber four or five.

The nonlinear steady state model has been used to study the response of the idealized GCM to tropical SST anomalies. (Linear modeling studies of this response were described in GFDL A88/P89). The nonlinear analysis confirmed the main conclusion of the linear study: when the zonally symmetric climate is perturbed by a localized tropical anomaly, transients act to reduce the strength of the response; both the nonlinear and linear steady models overpredict the amplitude of the GCM's response. This result is in sharp contrast to the conclusions reached in a companion study (904) of the response to El-Niño SST anomalies in a realistic GCM. In the latter study, transients in the midlatitude storm tracks were clearly shown to enhance the amplitude of the steady extratropical response. Evidently, a zonally symmetric storm track responds very differently to a perturbation from the tropics than does a more realistic zonally asymmetric storm track. Apparently, a well defined "barotropic decay" region, such as the one that exists in the Eastern Pacific, is needed before positive feedback from the transients can be realized.

In this study, the linear model is reasonably successful in simulating the GCM, and the nonlinear and linear solutions are close to each other. The full value of the nonlinear steady state model will be realized when it is applied to cases for which the linear simulation fails badly, as in the topographic experiments described in 1.4.5.

1.4.4 Response of an Idealized GCM to a Midlatitude SST Anomaly

Several integrations have also been performed testing the sensitivity of this same idealized GCM (1.4.3) to midlatitude SST anomalies. Two experiments were analyzed in detail, one with a positive and the other with a negative Gaussian shaped anomaly centered at 45°N. The strength of the anomaly at its center was > 10K, much larger than any observed anomalies associated with interannual variability. However, the responses to the anomalies of opposite sign were similar (except for a sign change), as shown in Figure 1.8 suggesting that the response is quite linear and that one can interpolate to small forcing, for which the climatic signal would, in practice, be difficult

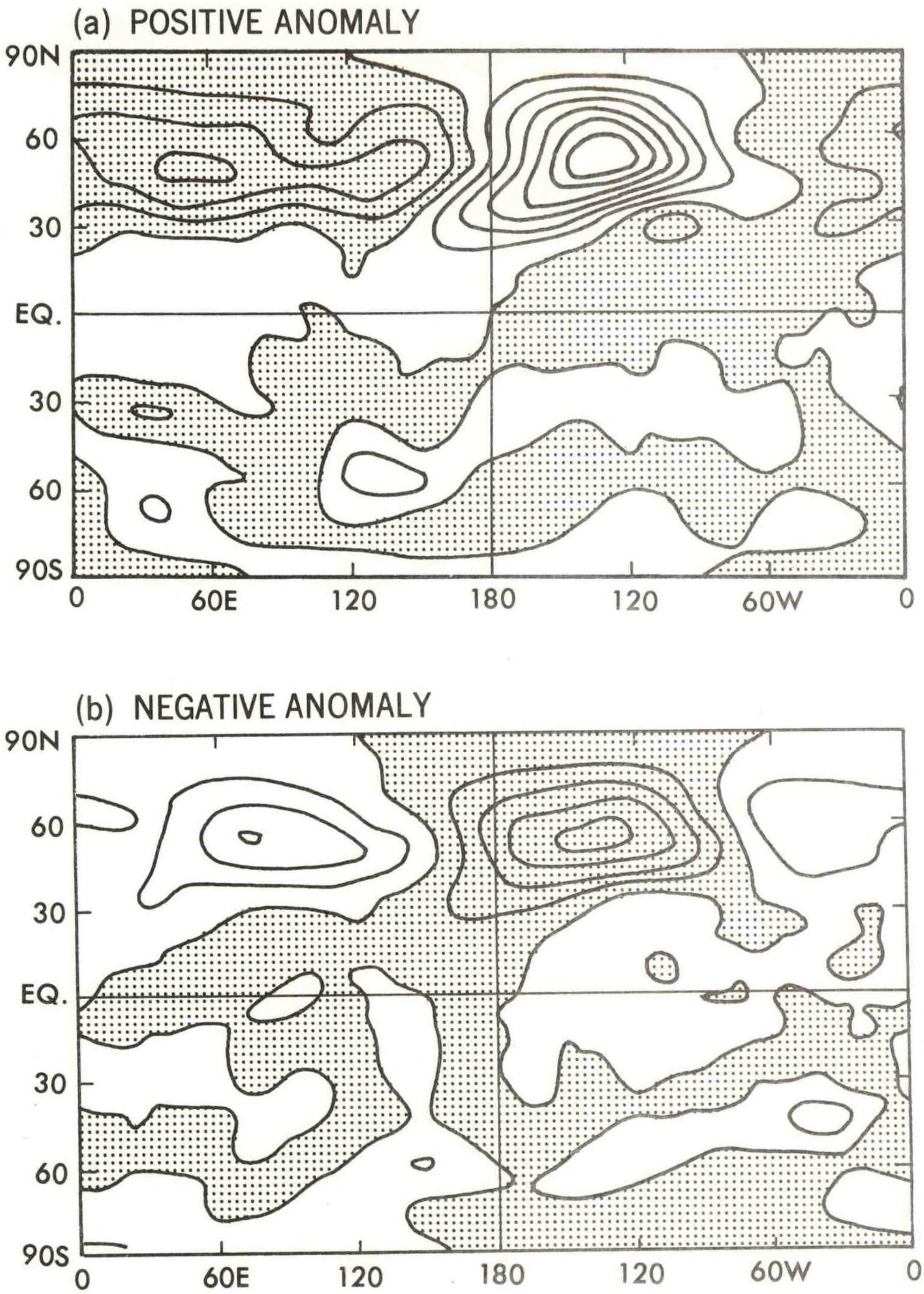


Fig. 1.8 Eddy potential at 300 mb resulting from a midlatitude SST anomaly of maximum strength a) + 10K, and b) -10K, in an idealized GCM. The anomaly is centered at 45°N and at the Dateline. The contour interval is 10m; negative values are shaded.

to isolate from the weather noise. Accepting the interpolation to small amplitudes, this model clearly would produce a very small (5-10 m) response to observed interannual anomalies (~1-2K).

Analysis of these results with a linear model has shown that the transients play two distinct roles in determining the responses: low level transient eddy heat fluxes act to damp the lower level temperature signal (one must include damping that crudely mimics this effect in order to produce useful results with the linear model); and the transient eddy flux of moisture displaces the heating anomaly polewards, where it forces a substantially different atmospheric response than it would if the heating occurred directly over the evaporation anomaly. The anomalies in upper tropospheric eddy momentum fluxes are relatively unimportant. There are indications from other work (ls) that the identical GCM, when integrated with realistic boundary conditions, is very sensitive to the observed interannual variability in the North Atlantic and Pacific. Once again, the working hypothesis is that there is positive feedback from transient eddies (particularly through the upper tropospheric momentum fluxes) in the realistic case and that this positive feedback is only realized when the unperturbed storm tracks are strongly zonally asymmetric.

1.4.5 Topographic Forcing in an Idealized GCM

The analysis of the response of an idealized GCM to isolated midlatitude topography has continued. In this case, the unperturbed model has a zonally symmetric climate once again, but utilizes a "swamp" (saturated, zero-heat capacity) lower boundary condition. Preliminary results were described in GFDL A88/P89. A series of integrations have been performed with different "mountain" heights. For the smallest height (0.7 km) a linear model that ignores the effects of transients provides a remarkably accurate simulation. This linear model breaks down rapidly as the mountain height increases. The dynamics of this breakdown are currently being examined. One important parameter appears to be the north-south slope of the boundary as compared to the mean isentropic slope in the basic state; when the topographic slope exceeds the isentropic slope, the mean low level flow forms closed contours and the Rossby wavetrain in the lee is forced to change dramatically.

An important property of the distortion of the flow by a mountain is the resulting force or drag exerted on the atmosphere by the surface. The drag exerted by an idealized mountain on the model atmosphere has been compared with the predictions of linear theory. The result is displayed in Figure 1.9. (The linear theory predicts that the drag is proportional to the square of the mountain height; in the figure, the drag is therefore normalized by the square of the height.) For small mountain heights linear theory is once again surprisingly accurate; for the more strongly forced cases, the linear prediction is a gross overestimate. Calculations are underway to determine whether the steady nonlinear model is capable of predicting some of the departures from linearity of the stationary wave pattern and the mountain drag.

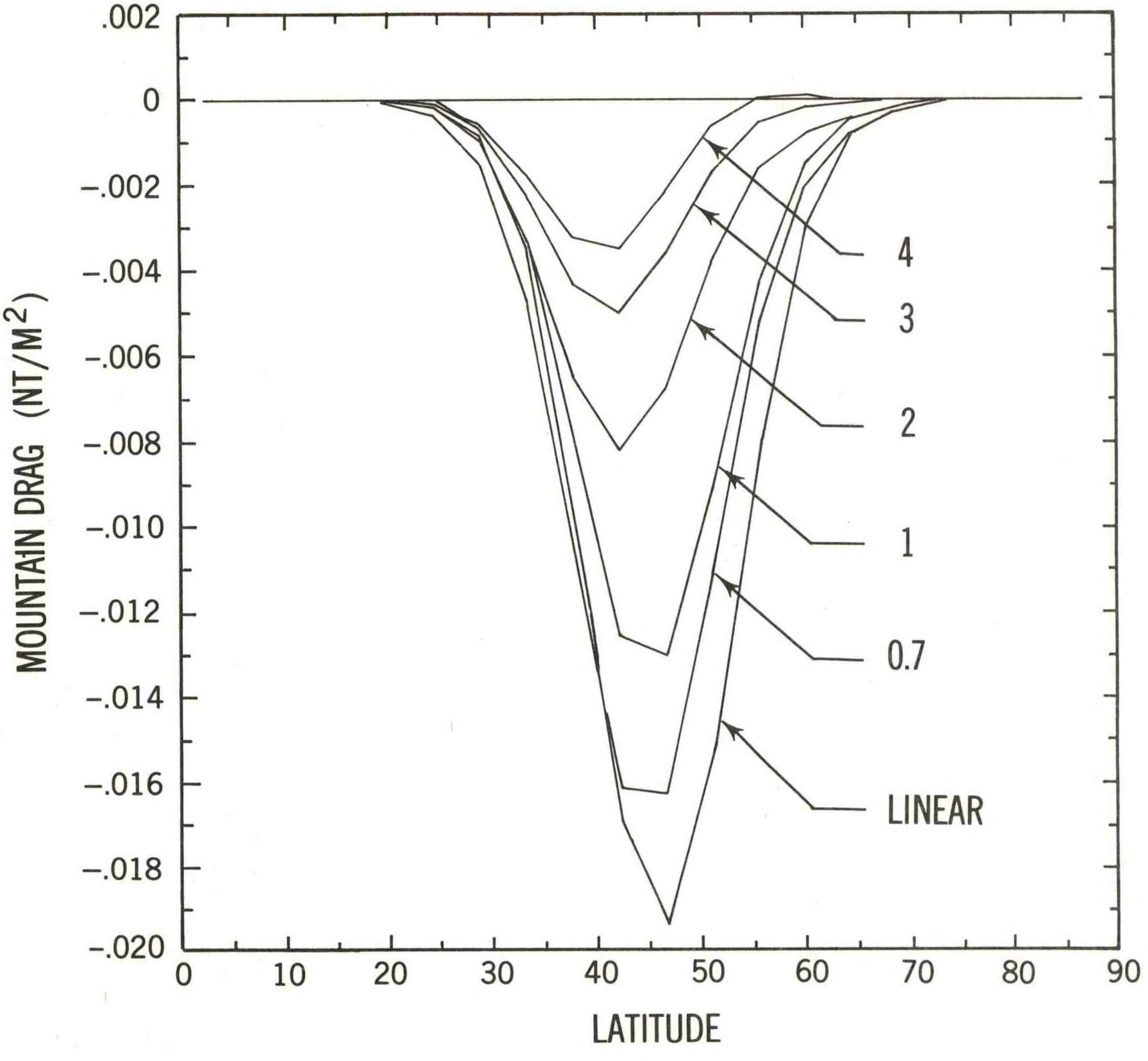


Fig. 1.9. The mountain drag resulting from the placement of a localized "mountain" at 45°N in a GCM with an otherwise zonally symmetric climate. Integrations with five different mountain heights, ranging from 0.7 to 4 km are shown. The drag is normalized by dividing it by the square of the mountain height. The prediction of a linear theory is also shown for comparison.

1.4.6 An Idealized Tropical Continent

An R15 GCM with simplified boundary conditions is being used to investigate the response of the tropical circulation to the presence of a continent and the relationship between the atmospheric circulation and the precipitation distribution over land. Two experiments with a large flat rectangular continent, of a size comparable to Africa, have been completed and compared with an all-ocean integration. In one experiment, the continent has an active surface (bucket) hydrology and in the other the surface is always saturated (a "swamp" boundary condition). Clouds are fixed and are zonally uniform, as are the sea surface temperatures. These temperatures and the insolation are held fixed at July conditions.

With an active surface hydrology, the land becomes very dry, even at the latitude of the oceanic ITCZ, and surface temperatures rise as much as 10-14K in the winter hemisphere subtropics and throughout the summer hemisphere. A classical desert circulation pattern is formed; moisture convergence occurs at low levels, but the upward flow is not deep and this convergence is balanced by divergence before the air is lifted sufficiently to cause condensation. When the surface is forced to remain moist, the low-level convergence is similar but the increased moisture content of the air results in condensation, and an ITCZ is maintained across the continent. Experiments are underway to assess the sensitivity of this idealized desert circulation to changes in the continental boundary conditions.

PLANS FY90

Analysis will continue of these idealized GCM experiments. The nonlinear steady state model will be used to analyze the responses to localized orography. Work will begin with more idealized quasi-geostrophic steady models of the orographic response to gain more insight into the breakdown of linearity as the amplitude of the orography increases.

A new series of calculations with the R15 model will be initiated to examine the importance of a zonally asymmetric control climate for the response to SST anomalies. The asymmetric control will be generated with idealized midlatitude orography. This climate will then be perturbed with tropical SST anomalies. The longitude of the anomaly with respect to the climatological midlatitude stationary wave will be varied and the results analyzed with linear and nonlinear steady state models. The goal will be to distinguish between the direct interaction of the climatological and anomalous stationary waves and the effects of anomalous transients. A. Plumb (MIT) will collaborate on this research.

1.5 PLANETARY WAVE DYNAMICS AND BAROCLINIC INSTABILITY

J. Fyfe
I. Held
S. Lee
N. Nakamura*
E. O'Brien
P. Phillipps
X. Tao

* University of Washington

ACTIVITIES FY89

1.5.1 Rossby Wave Breaking

Two simple rules that help determine if and how a barotropic Rossby wave will break as it propagates into a region of weaker mean winds have been developed (lv). This problem is central to any theory for the irreversible mixing and the zonal stresses generated by waves propagating from high to low latitudes within the troposphere. When a Rossby wave enters some previously undisturbed region, it decelerates the zonal mean flow. It has been shown, using the slowly varying (WKB) approximation, that if the mean flow is decelerated by more than 2/5ths of its original value in some region, an unstable wave-mean flow interaction will cause the wave amplitude to accumulate steadily and irreversible mixing will quickly result. If the deceleration is between 1/5 and 2/5ths of the original wind speed, the wave will still overturn, but in the absence of the unstable wave-mean flow interaction, the irreversible mixing that results is of a different character and takes longer to develop. Although these criteria were derived using the WKB approximation, numerical experiments show that they remain qualitatively valid when this approximation breaks down.

A multi-layer isentropic coordinate primitive equation spectral model has been developed and thoroughly tested. The model's lower boundary is an isentropic surface that is assumed never to intersect the earth's surface. Eddies are generated by specifying the motion of this lower boundary. This model will be used for studies of Rossby wave breaking in the upper troposphere and the middle atmosphere.

Research on the interaction between a breaking Rossby wave and the Hadley cell has now been completed (lr).

1.5.2 Equilibration of Baroclinic Instabilities

The manner in which baroclinic instabilities equilibrate when they are two-dimensional (independent of latitude) was analyzed using the classic Eady model (mj). In the two-dimensional case the usual mechanism for equilibration, the reduction of the mean meridional temperature gradient, is unavailable since the wave produces no convergence of the eddy heat flux and cannot change the zonal mean horizontal gradient. Quasi-geostrophic theory predicts no equilibration at all; the wave simply continues to grow exponentially. Semi-geostrophic theory predicts that the wave will generate a front in a finite time, at which point the theory breaks down. Careful experiments with the primitive equations have helped to identify the mechanism that halts the development of the wave. As the front forms and the warm sector pinches off the lower boundary, the reservoir of high potential vorticity at the boundary spreads into the interior; this stabilizes the wave by reducing the strength of the interaction between the upper and lower level disturbances. (Semi-geostrophic theory shows that the strength of this interaction is inversely proportional to the interior potential vorticity.) The behavior is analogous to that of a quasi-geostrophic model in which one arbitrarily allows the static stability to increase in response to the waves vertical eddy heat flux. Scaling arguments and numerical simulations show that this mechanism can be competitive with the reduction in the horizontal gradient for three-dimensional disturbances if Richardson's number is of order unity. This can be the case for cyclones forming at low levels over the oceans in winter.

1.5.3 Quasi-Geostrophic Turbulence

A multi-layer doubly periodic quasi-geostrophic model has been developed and fully optimized for the Cyber 205. By imposing a time-mean vertical shear, one can study the dependence of the heat and potential vorticity fluxes on the shear, static stability, and surface friction in a system with horizontally homogeneous statistics. Such a homogeneous system is useful since, on the one hand, one can try to make contact with developments in the theory of homogeneous turbulence to explain the results and, on the other hand, the statistics in an unstable region are known (at least in the two-layer model (894)) to approach those predicted by such a homogeneous model as the width of this region becomes much larger than a Rossby radius. In an initial series of calculations, a ten-layer Boussinesq model on a beta-plane was used to test scaling arguments that suggest that the poleward heat flux is proportional to the fifth power of the vertical shear when the shear is sufficiently small. Preliminary results are broadly consistent with this prediction. The vertical structure of the potential vorticity flux and eddy kinetic energy obtained from this turbulence model are surprisingly similar to that of the most unstable wave on the time mean flow.

1.5.4 Storm Tracks in a Two-Layer Channel Model

A fully nonlinear quasi-geostrophic two-layer model in a channel has been developed to study storm track dynamics and the interaction between the storm track and planetary scale waves in a simple dynamic setting. Preliminary calculations have explored the behavior of the system with zonally symmetric forcing as a function of the temperature gradient to which the flow relaxes radiatively and the strength of the surface friction. At large values of the friction, hysteresis was observed of a kind that has not previously been documented in such a model: for the same set of parameters the model can relax either to a purely zonally symmetric flow or into an unsteady, chaotic flow with large eddy kinetic energy.

PLANS FY90

Calculations with the doubly periodic quasi-geostrophic model will be performed with vertical structures more typical of the atmosphere (non-Boussinesq, static stability increasing into the stratosphere) and the ocean (Boussinesq, most of the stratification confined to a thermocline, weak damping). In the atmospheric case, the lower and upper tropospheric mean temperature gradients will be varied separately to determine if the poleward heat flux and eddy energy levels are primarily sensitive to a mean tropospheric gradient or to low level gradients.

The parameter study with the quasi-geostrophic channel model will be continued. Zonally asymmetric storm tracks will be generated with orographic and/or thermal forcing and the interaction between the storm tracks and stationary waves in this relatively simple system will be compared with that observed in GCMs.

A series of Rossby wave breaking calculations will be performed with the multi-layer isentropic spectral model to study the factors that control the mean flow modification resulting from the associated irreversible mixing.

1.6 MODEL DEVELOPMENT

1.6.1 Continental Hydrology in Atmospheric GCMs

C. Milly

ACTIVITIES FY89

A study of the sensitivity of climate to the hydrologic behavior of continental land surfaces has been initiated. The objectives of this work are to analyze and to improve the parameterization of land hydrology used in atmospheric GCMs and to study the role of continental hydrology in climate dynamics. This research is a cooperative effort between GFDL and the U.S. Geological Survey.

The first phase of this study has focussed on the seasonal response, evaporation in particular, of simple land hydrology models subjected to prescribed atmospheric forcing. The effects of sub-freezing temperatures on water storage and movement have not been considered. The standard GFDL bucket model was compared to several other similar parameterizations. In the evaluation of potential evaporation, the GFDL model employs the actual surface temperature to evaluate the surface humidity; comparisons were made with a model that employs the surface temperature resulting from an energy balance that assumes a wet surface. The GFDL model produces runoff only when the soil water storage is at field capacity; this was compared to an approach that allows a moisture-dependent fraction of precipitation to run off under unsaturated conditions. The sensitivity of evaporation to field capacity and critical soil moisture was also assessed.

The use of actual surface temperature in the calculation of potential evaporation produces a significant bias upward in the actual evaporation rate. Under non-potential conditions, the surface is hotter than under potential conditions, leading to a potential evaporation rate that may be elevated several times over. This leads to more rapid drying of the soil during periods of the year when infiltration rates fall below equivalent net radiation rates. The neglect of dry season runoff in the GFDL model overestimates the rate of recharge to soil moisture, and most of this excess goes immediately toward further evaporation. The monthly evaporation is only mildly sensitive to the choice of values for field capacity and critical soil moisture. Overall it appears that the GFDL bucket method overestimates total evaporation (for given atmospheric forcing) in the common situation where neither annual water supply nor annual energy supply provides an absolute upper limit on annual evaporation.

PLANS FY90

The analysis will be extended to include snowpack accumulation, snowmelt, and frozen soil, and to examine sensitivities of hydrologic changes associated with doubling of atmospheric carbon dioxide. A similar analysis will be initiated using a GCM to evaluate the effects of atmospheric feedbacks on the sensitivities already identified, and to examine the sensitivities of other climatic variables to the parameterization of land hydrology.

1.6.2 Vertical Mixing in Planetary Boundary Layer

S. Manabe R. Wetherald

ACTIVITIES FY89

A R15 spectral model with 30 vertical finite difference levels has been developed in order to obtain a more realistic vertical distribution of atmospheric variables. It incorporates seasonal variation of insolation, a simple method of cloud prediction, and a planetary boundary layer formulation proposed by Mellor and Yamada.

It has been noted that various atmospheric models developed at GFDL, and elsewhere, tend to develop a very intense and shallow inversion layer over continental surfaces during winter. This is because no vertical subgrid-scale mixing is predicted by these models in a stable boundary layer where the Richardson number is larger than a certain critical value. One can speculate that other mechanisms, such as breaking gravity waves, exist in the actual planetary boundary layer which weaken the inversion layer. It has been found that the simulation of the height and magnitude of the inversion layer is considerably improved by inserting an additional background mixing for the vertical diffusion of momentum, heat and moisture which is applied regardless of the magnitude of the Richardson number. This study suggests that, in the stable planetary boundary layer, there exist additional important mechanisms of vertical mixing which are not included in the Mellor-Yamada parameterization.

PLANS FY90

Investigation of the climate obtained by the 30-level model will continue. In particular, an extensive analysis will be performed with regard to the simulation of the vertical cloud distribution, polar and trade wind inversions and continental hydrology. Ultimately, this model will be used to repeat the cloud feedback study previously conducted with the 9-level general circulation model in response to a doubling of atmospheric carbon dioxide.

1.6.3 Computation of Radiative Transfer

S. B. Fels   V. Ramaswamy
S. Freidenreich   M. Schwarzkopf

ACTIVITIES FY89

Investigation of the shortwave radiative transfer in the atmosphere continued as part of the second phase of the ICRCCM-related (International Comparison of Radiative Codes for Climate Models) activities at GFDL. Three categories of problems have been addressed: absorption by water vapor only, extinction by cloud drops only, and simultaneous water vapor absorption and cloud extinction (cloud confined to a single model layer) in inhomogeneous atmospheres (md). Exact numerical solutions over the entire solar spectrum for all three classes of problems have been made possible through extensive optimization of the radiative transfer algorithms. The 'exact' (line-by-line + doubling - adding) method for the water vapor and cloud problem is computationally expensive (about 100 CYBER 205 hours) so that it has been possible to examine only four different cloud cases using this technique. Results for the vertical profile of the heating rate due to water vapor absorption only in five model atmospheres are shown in Figure 1.10a while the midlatitude summer atmosphere results for all 3 classes of problems are shown in Figure 1.10b for a CL model (optical depth = 1.0) cloud located in the 800-820 mb layer. The solutions obtained during FY89 constitute ICRCCM benchmark results and these have been archived along with those mentioned in GFDL A88/P89.

Various other techniques that are more economical, were also studied and their accuracy assessed. One of them ('binning' method) is extremely accurate for use as a benchmark. Since this method is about 25 times more efficient than the exact method, it will be used henceforth to generate benchmark results for overcast atmospheres containing cloud in a single layer.

Radiative transfer computations in clouds which span more than one model layer were initiated. Calculations over a limited number of frequency intervals (4400-6200 cm^{-1}) show that the 'binning' method is also accurate for the transfer in multiple layer clouds. For the entire solar spectrum, at present even the 'binning' method is computationally expensive (about 70 hours for a 5-layer cloud); further research is necessary to obtain benchmark solutions efficiently for multiple layer cloud cases.

The line-by-line + delta-Eddington method for the transfer in an overcast atmosphere is a good approximation to the 'exact' solutions but is less accurate than the 'binning' method. Since it is 8 times more efficient than the 'binning' method, it has been possible to obtain the transfer solutions using this method for a large number of cloud cases (different optical depths, cloud altitudes and solar zenith angles). Assuming these to be the reference solutions has enabled the testing of parameterizations that combine a Lacis-Hansen type water vapor absorption formulation with a two-stream type approximation for clouds; such simplified computational approaches have been or are beginning to be adopted in several climate models. The comparisons with the reference solutions reveal a deficiency in the amount of radiation absorbed by cloud: There is an overestimate by the above-mentioned approximate approach which becomes significant for thick clouds located in the lower troposphere. Efforts to rectify this shortcoming are underway.

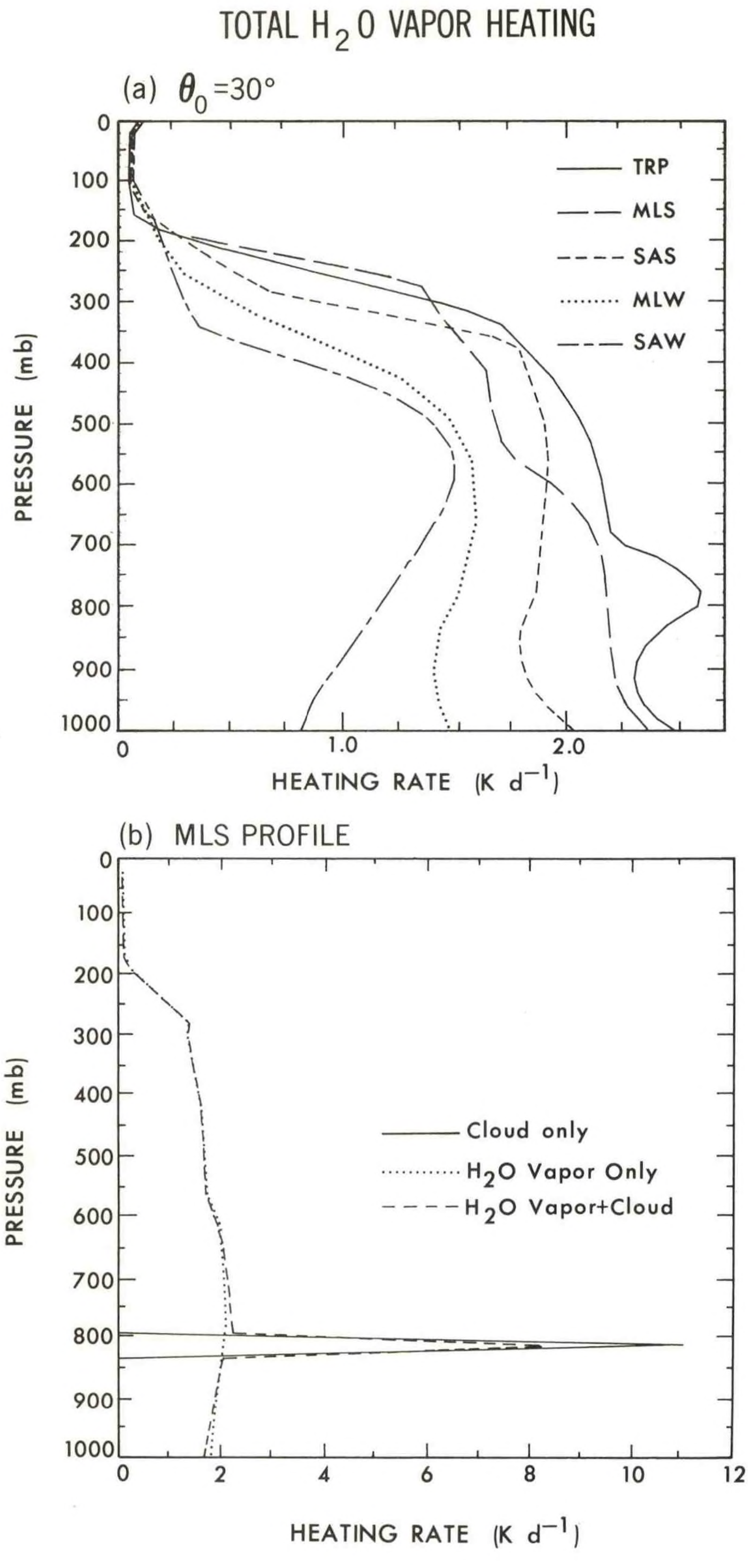


Fig. 1.10. Vertical profile of the exact solar heating rate in a) 5 model atmospheres containing water vapor (surface albedo = 0.2); TRP-tropical, MLS-midlatitude summer, MLW-midlatitude winter, SAS-subarctic summer; and SAW-subarctic winter and b) a MLS atmosphere containing, respectively, water vapor only, cloud only and water vapor + cloud. The CL cloud (optical depth= 1.0) is located between 800 and 820 mb.

PLANS FY90

Reference transfer calculations accounting for CO_2 will be performed. The general problem of computing the exact radiation transfer when scatterers are present in more than one layer will be investigated; the solutions will constitute additional reference results in the ICRCCM framework. Parameterizations will be developed for overcast atmospheres that account simultaneously for both water vapor absorption (already developed in FY88) and cloud extinction.

2. MIDDLE ATMOSPHERE DYNAMICS AND CHEMISTRY

GOALS

* To understand the interactive three-dimensional radiative-chemical-dynamical structure of the middle atmosphere (10-100 km), and how it influences and is influenced by the regions above and below.

* To understand the dispersion and chemistry of atmospheric trace gases.

* To evaluate the sensitivity of the atmospheric system to human activities.

2.1 ATMOSPHERIC TRACE CONSTITUENT STUDIES

W. Chameides*
P. Kasibhatla*
H. Levy II
S. C. Liu**
J. D. Mahlman
W. J. Moxim

* Georgia Institute of Technology
** Aeronomy Laboratory/NOAA

ACTIVITIES FY89

2.1.1 Model Development

There is a continuous effort to improve and expand the existing global chemical transport model (GCTM), while developing the next generation model. Particular emphasis is placed on improving parameterizations of sub-grid transport, surface exchange processes, cloud transport and removal, and chemistry.

A stratospheric source data base for total reactive nitrogen (NO_y) has been developed, using an assumed distribution for O_3, a distribution for N_2O that was simulated by the SKYHI model, and detailed calculations of photolysis rates for O_3. The resulting source strength is 0.8 tg N/yr, as compared to a tropospheric combustion source of 21.3 tg N/yr.

A more physically realistic wet removal scheme has been developed. Instead of removing soluble tracers from all tropospheric model levels (990-315 mb) during a rain event in the grid column, a check is first made to determine if the precipitation is stable or convective. Wet removal is then allowed to occur at 315 mb and 500 mb only when the scaled moist Richardson number at that level is less than 0.25; tracer is removed from lower levels regardless of the local stability.

A highly parameterized chemical reaction scheme was developed to calculate OH profiles, which will then be used to partition NO_y into soluble and insoluble species. The OH field was scaled to give a global methyl-chloroform lifetime of 6.2 years. The calculated global average OH concentration is approximately 6.5×10^5 molecules/cm^3.

In preparation for the inclusion of chemical reactions in studies of the global nitrogen budget, the multiple-species GCTM has been upgraded to utilize the new removal parameterization and physics. In addition, new off-line analysis code has been written to examine the results of future multiple-species simulations.

As a first step in the development of the next generation of chemical transport models, the SKYHI model was modified to simulate the distribution and removal of multiple species. Computer code was added to monitor the tracer mass balances and to calculate running sums of wet and dry deposition on-line, as well as to incorporate a sink term for surface removal. Initial simulations have been started to study the impact of resolution on the model's simulation of stratospheric injection, as well as the relative contributions of stratospheric and tropospheric sources to observed values of NO_y.

2.1.2 Transport Studies

Atmospheric transport is as important as chemistry in determining the impact of both natural and anthropogenic emissions on the global chemical structure of the atmosphere.

The role of GCTM's in assessing the global impact of local and regional pollution on tropospheric chemistry has been addressed. The three major components of such models are: an effective regional source that includes not only the actual emissions, but their chemical reactions and the meteorology responsible for mixing the surface emissions into the free troposphere; long-range advection by the ensemble of three-dimensional meteorological events that comprise the transport climatology; and effective removal processes that include the individual processes of wet and dry deposition, the chemical conversion among species of varying surface reactivity and solubility, and their transport into the boundary layer and to the ground.

A collaborative effort on the vertical transport of trace chemicals by convective clouds has begun with the Convection Project. A number of idealized tracer experiments as well as the simulated transport of CO, NO_y and O_3 are planned. Further details are given in 9.3.1.

An examination of observed ^{222}Rn at Amsterdam Island, a remote island in the South Indian Ocean, revealed episodes of elevated levels of ^{222}Rn with the highest values occurring during the Austral winter (July-August-September). Since both ^{222}Rn and reactive nitrogen have surface sources and relatively short atmospheric lifetimes, the Amsterdam Island time series from the global combustion simulation were compared with the ^{222}Rn observations. The model's results agree well with observation, properly depicting both the infrequent episodes and the winter maximum. Further investigation revealed that the large values are the result of winter storms sweeping high concentrations of surface tracer from South Africa out over the remote South Indian Ocean.

2.1.3 Tropospheric Reactive Nitrogen

The global distribution of NO_y compounds is the key to understanding the global biogeochemical cycle of nitrogen. Moreover, NO_y controls the chemical production of O_3 in most of the troposphere and indirectly controls the chemical reactivity of the atmosphere. Therefore, the relative contributions of anthropogenic and natural sources of NO_y determine the role of anthropogenic activities in modifying the chemical behavior of the lower atmosphere (926, 929).

Atmospheric deposition of trace chemicals is thought to be an important source of nutrient for the world's oceans. The simulated oceanic deposition of NO_y emitted by fossil fuel combustion has been calculated for the major source regions (916). No more than 1.4 tg of the 21.3 tg of NO_y emitted by fossil fuel combustion is deposited in the Southern Hemisphere; this can account for less than 10% of the apparent background deposition. The 4 tg of NO_y exported from the 3 major source regions (US/Canada, Europe and Asia) account for most of the deposition to the oceans of the Northern Hemisphere. The simulated deposition to the North Pacific, which is in good agreement with recent estimates, is dominated by emissions from Asia, while US/Canadian emissions dominate deposition to the North Atlantic and Northern European emissions control deposition to the Arctic.

The nitrogen component of acid deposition was simulated over North America for both US and Canadian emissions. Preliminary analysis shows that at least 80% of the acid deposition over eastern Canada results from US emissions. The one exception is along the Ontario border where Canada has significant emissions that account for up to half of the local deposition. In western Canada, acid deposition is much less, but Canadian emissions account for a much larger fraction.

The injection of combustion NO_y into the troposphere has been simulated in the current GCTM for both the old (929) and new (2.1.1) wet removal schemes. Preliminary analysis finds that the new wet removal scheme allows much more combustion NO_y in the upper troposphere. However, the stratospheric source of NO_y, while significant, cannot explain the background levels of deposition and surface concentration observed in remote regions. Transport from the stratosphere does make an important contribution to the levels of NO_y in the middle and upper levels of the troposphere.

The simulation of global deposition and distribution of NO_y emitted by combustion of fossil fuel has also been re-run with the new stability-dependent wet removal parameterization. Preliminary analysis finds that, while the major conclusions reported in (929) are not changed, the lifetime and mixing ratio of NO_y in the middle and upper troposphere increase, as do the surface mixing ratios in remote regions.

PLANS FY90

Utilizing new observations of NO_y and trace gases, work will continue on detailed analysis of the mechanisms of regional synoptic transport. In addition, examination will begin on the transport differences between synoptic events operating on stratospheric sources and those events operating on surface sources.

The final analysis of simulations of the relative contribution of the United States and Canadian emissions to acid deposition in North America will be completed.

A series of idealized tracer studies will be initiated in collaboration with the Convection Project. These results will be used to explore a possible 1-D parameterization for convective removal and transport in the GCTM.

The distribution of reactive nitrogen in the troposphere resulting from stratospheric injection will be simulated with a 2-species GCTM after incorporating the chemical partitioning between insoluble and soluble species. These results will be compared with earlier simulations using single species and parameterized wet removal, both old and new. A multiple-year integration of the SKYHI model will be carried out for the stratospheric source of reactive nitrogen. Both its transport to the troposphere and its evolution in the stratosphere will be studied.

Data bases for biomass burning and for lightning will be developed for use in the GCTM as part of the on-going effort to quantify the relative contributions of natural and anthropogenic sources to the nitrogen budget.

The highly parameterized chemical scheme (2.1.1) will be evaluated by comparing it with more complete chemical models. Also, the chemical module will be expanded to include a more complete suite of NO_y subspecies.

2.2 MODELS OF THE TROPOSPHERE-STRATOSPHERE-MESOSPHERE

S. B. Fels
K. P. Hamilton
C.-C. Ma
J. D. Mahlman
N. Nakamura***
R. Saravanan
M. D. Schwarzkopf
L. J. Umscheid

*** University of Washington

ACTIVITIES FY89

2.2.1 Model Improvements

Continuing enhancements were added to the SKYHI GCM concerning model structure and documentation. A version of the model has been converted to standard FORTRAN 77 in preparation for the Class VII computer.

A number of changes in the model code and diagnostic packages have been added to accommodate the family of trace gases required to include self consistent ozone. The ozone model is now undergoing checkout and evaluation.

New versions of the shortwave and longwave radiation codes have been incorporated into the GCM. The new algorithms produce a one-third speedup in execution time. A description of the changes in the physics of the longwave code is contained in (1h). The new shortwave algorithm includes the effects of diurnal variation of the solar zenith angle. Offline calculations indicate that the resulting change in shortwave heating rates is up to 10 percent at latitudes near the solar terminator, and about 5 percent at the tropical stratopause.

A minor error in the moist convection parameterization has been identified and repaired. Sea-surface temperature climatology with increased accuracy and temporal resolution has been incorporated. Model changes have been made to incorporate time-dependent, multiple-level soil conditions. These changes should make it possible to address an array of research questions involving the role of the diurnal cycle in radiation, chemistry, and dynamics.

2.2.2 Higher Resolution Seasonal Cycle Experiments

The seasonal cycle of the middle atmosphere is being investigated with 3° and 1° latitude versions of the 40-level SKYHI model. The 3° version has been integrated for nearly 6 years, while the 1° version has completed about two-thirds of one year.

The 6-year integration of the 3° latitude model is being used as a control climate for sensitivity experiments on reduced Antarctic ozone (2.4.1) and doubled carbon dioxide (2.4.2). The 1° latitude grid integration is being lowered in priority due to its intensive computer requirements and severe difficulties in analyzing its huge data files. Both difficulties should be reduced after installation of the Class VII computer.

2.2.3 Sources of Systematic Errors in SKYHI Climatology

Comparison of the 3° and 1° latitude versions of the SKYHI seasonal cycle experiments with an earlier 5° latitude version reveals some remarkable sensitivities to horizontal resolution. For example, the wintertime zonal mean subtropical jet stream is at the right strength and properly located near 30°N in the 1° latitude version, while it is too strong and is located progressively equatorward in lower resolution versions. Preliminary analysis suggests that the lower-resolution versions artificially overdamp the midlatitude planetary waves before they can propagate into the subtropics. This produces too much wave-induced deceleration north of 30°N and too little deceleration south of 30°N. This apparent overdamping at lower resolutions is due to the model's use of non-linear viscosity. In the 1° latitude version, the use of non-linear viscosity as a subscale closure appears to be physically reasonable because the major damping is now within the mesoscale subrange.

2.2.4 Observational Study of Gravity Waves

The historical archive of soundings by meteorological rockets represents a unique source of information about inertia-gravity (IG) waves in the middle atmosphere. Studies by earlier investigators have utilized rocketsonde measurements of the horizontal wind to make inferences about the dominant frequencies of the IG wave field. Unfortunately, such analysis cannot determine reliably the dominant direction of phase propagation for the waves. In the present project, the analysis of IG wave variability was extended through the simultaneous use of temperature and wind soundings. This allowed the unambiguous determination of dominant propagation directions. Systematic climatologies of dominant amplitudes, frequencies and propagation directions have been computed for 10 years of rocket data at 12 stations worldwide. The results reveal a great deal of systematic behavior in the IG wave field. Particularly notable is a strong seasonal cycle in the dominant direction of propagation. This seems to be fairly consistent with expectations of how the mean flow might filter the IG wave spectrum.

2.2.5 Evaluation of the Simulated Inertia-Gravity Waves in SKYHI

The procedures used in the analysis of rocket observations (see section 2.4) are now being applied to collections of individual instantaneous soundings from the SKYHI model. Preliminary indications (917) are that the general circulation model simulation will compare rather well with the statistics obtained from the rocketsondes.

Efforts are underway to characterize the high-frequency wave field in the SKYHI model in other ways. High density sampling tapes have been created allowing detailed analysis of the time and spatial structure of high-frequency variability in the model. Preliminary results suggest a very low horizontal coherence in the high frequency wave field.

2.2.6 Equatorial Waves in the SKYHI Model

Analysis of both observations and general circulation model output suggests that large-scale waves in both the tropical and extratropical stratosphere are strongly dissipated as they propagate vertically. The dissipation due to radiative and photochemical processes is well understood, but appears to be too weak to account for the observed decrease of wave activity with height.

A number of experiments are now being conducted in an attempt to determine the dominant causes of dissipation for tropical waves in a general circulation model. In these experiments a monochromatic Kelvin wave was forced by the inclusion of a tropical heat source. Each experiment involves a 144 day integration of the 5° latitude version of the model. The initial experiments have concentrated on relatively weak waves that have minimal influence on the mean flow evolution. Analysis of the results has now commenced.

2.2.7 Mechanisms for Stratosphere-Troposphere Mass Exchange

The 1° latitude SKYHI model is being used to evaluate the mechanisms responsible for detailed mass exchange events between the stratosphere and troposphere. The 1° latitude model provides, for the first time, nearly sufficient horizontal and vertical resolution to address these phenomena in a credible manner.

Theories of upper-troposphere cyclogenesis are being combined with SKYHI isentropic-coordinate diagnostics to address these problems. Model potential vorticity fields and the inert tracer N_2O are both being used for diagnostic interpretation of the exchange mechanisms.

2.2.8 An Examination of the Proposed Sun/QBO/Weather (SQW) Relationship

Recently much attention has been focussed on claims by some researchers that the Northern Hemisphere winter weather is significantly affected by a subtle combination of the tropical stratospheric quasi-biennial oscillation (QBO) and the 11-year solar cycle. These claims are based on analysis of data since 1952. The extension of the analysis to earlier periods is hampered by ignorance of the QBO phase. The present project tried to determine if historical records of meteorological and solar data could be reconciled with the proposed SQW relationship for a plausible sequence of QBO phases. The first step of this approach was the generation of about 7 million sequences of easterly and westerly phases that seem possible in any 40 year period. Then historical records of surface temperature and pressure from several stations for two 40-year periods (1875-1914 and 1897-1936) were examined. For each of the 7 million possibilities the meteorological data was stratified by QBO phase and then correlated with sunspot number. None of the QBO time series seem to allow a good reproduction of the results obtained with post-1952 data. This problem became even more severe when the QBO possibilities were constrained using limited wind observations from the tropical stratosphere during 1909-1918. Thus it seems reasonable to conclude that either, the QBO behaved very differently in the 1875-1936 period than it now does, or the SQW relationship is not a stable feature of the data record. In the latter case one would expect to see the proposed SQW relationships break down as more data are collected over the next few decades.

PLANS FY90

A new version of the 3° latitude model will be under development to include: increased vertical resolution; improved radiative transfer; time-dependent soil temperature physics; condensed water; more correct convection parameterization; chemical processes; and subgrid-scale parameterizations. This development phase should require several years.

The 1° latitude version will be integrated further and the generalized SKYHI code will be converted to the Class VII computer. Topics of research analysis will include tropospheric phenomena, stratosphere-troposphere exchange, potential vorticity diagnostics, gravity wave dynamics, and wave-mean flow interaction on time scales of days to the quasi-biennial oscillation.

2.3 PHYSICAL PROCESSES IN THE MIDDLE ATMOSPHERE

S. B. Fels	V. Ramaswamy
P. Kasibhatla*	M. D. Schwarzkopf
S. C. Liu**	L. J. Umscheid
J. D. Mahlman	X. Zhu

* Georgia Inst. of Technology
** Aeronomy Laboratory/NOAA

ACTIVITIES FY89

2.3.1 Modeling of Ice Phase and Associated Effects in the Polar Stratosphere

The one-dimensional ice microphysics model described in GFDL A88/P89 was coupled with a detailed radiative transfer model to assess the radiative effects associated with the evolution of the Polar Stratospheric Clouds (PSC's) during the Antarctic winter. Temperatures in the Antarctic suggest that the potential for forming ice condensates may exist from July onwards.

At temperatures below the frost point near 190K, ice particles consisting of H_2O are formed; continued temperature decreases enables sustained growth, the particles grow bigger and fall, depleting the cross-section of the atmospheric constituents interacting with the infrared radiation. This reduces the outgoing longwave flux at the top of the atmosphere. The ice crystal sizes and the vertical thickness of the cloud formed also perturb the radiative cooling rates from the clear sky values.

The sign (i.e., heating/cooling) and magnitude of the perturbations in the lower stratosphere are governed by the temperature profile in the troposphere and the presence or absence of tropospheric clouds. Different temperature profiles that are based on observations were employed to assess the sensitivity to the tropospheric state. Warm tropospheric temperatures (e.g., the sub Arctic winter profile with a surface temperature of 257K) yield a warming effect due to the PSCs. The presence of a high cloud lowers this effect. On the other hand, extremely cold tropospheric temperatures (such as those measured over the South Pole in 1986 and 1987) yield a cooling effect due to the PSC's. Loss of water vapor also influences the radiative interactions, that is, a warming effect is induced. This effect is negligible compared to the effects due to the particulates. The effect of steadily decreasing stratospheric temperatures causes an ever-changing trend in the radiative heating/cooling rates in response to particle growth, water vapor depletion and sedimentation. For temperature decreases below the frost point in the 50 mb region, there can be a substantial change in the heating/cooling rates. In the sensitivity studies performed, the departures from clear sky values, averaged over 10 days, ranged between 20 and 85%. This suggests the possibility of significant radiative perturbations due to the PSC's during the Antarctic winter.

2.3.2 Ozone Photochemistry

The chemistry and transport of ozone and its relevant family members are now incorporated into SKYHI in its "non-chlorine" version which includes reactive hydrogen (HO_x), reactive nitrogen (NO_y), and nitric acid (HNO_3) as fully transported model variables. Longer-lived gases such as N_2O and CH_4 are prescribed in accordance with previous SKYHI transport experiments and previous research insights (716). Faster parts of the chemical system are included diagnostically (no time dependence) or semi-prognostically (no advection or diffusion of the individual species). These include O, O'(D), H,OH, HO_2, H_2O_2, NO, NO_2, NO_3, N_2O_5, HO_2NO_2. The code is configured so that adding chlorine reactions and any of the three types of dependent variables is straightforward.

The ozone chemistry now appears to be working acceptably well and is undergoing further evaluation. The SKYHI model version is now completely consistent with a GFDL off-line one-dimensional version, which in turn is consistent with the version being maintained at the Aeronomy Laboratory/NOAA.

2.3.3 Radiative Modeling of the Middle Atmosphere

Random band models with more general distributions of line intensity are proposed for both the Lorentz line profile and an approximate Voigt line profile (874, 925). This work presents an unification of, and some improvements in the classical theories concerning Goody and Malkmus models.

A new algorithm for calculating the CO_2 15μm cooling has been suggested (mp) which follows earlier work (441). Preliminary results show some advantages in using this scheme to calculate the cooling rates in the upper stratosphere and mesosphere.

PLANS FY90

The long-term project to develop a fully self consistent ozone chemistry for SKYHI will be accelerated. This work will be coupled with a longer-term effort to prepare a new generation tracer model out of the SKYHI framework.

Further studies of the radiative-microphysical interactions will continue by employing the radiative equilibrium and fixed dynamical heating assumptions. The potential for feedbacks due to the PSC's on the temperature field will be examined. These exploratory studies with the one-dimensional model will serve as a guide to three-dimensional simulations with the SKYHI GCM in the future.

2.4 EFFECTS OF ANTHROPOGENIC CHANGES IN ATMOSPHERIC COMPOSITION

S. B. Fels
J. D. Mahlman
J. Pinto
V. Ramaswamy
M. D. Schwarzkopf
L. J. Umscheid

ACTIVITIES FY89

2.4.1 Antarctic Ozone Depletion

Recent research has made it evident that substantial chemical depletion of ozone is occurring inside the Antarctic spring polar vortex, but with significant modulation by seasonal and interannual dynamical processes. In response to this, the 3° latitude SKYHI model has been set up to explore the chemical-radiative-transport-dynamical response to a parameterized polar vortex ozone destruction that approximately mimics the observed "ozone hole". The model criteria for turning on the polar vortex destruction chemistry depends upon 3 independent requirements being satisfied simultaneously: (1) presence of sunlight; (2) the local absolute vorticity magnitude being greater than the magnitude of the polar Coriolis parameter; and (3) local memory of significant freezeout of model water vapor due to sufficiently low temperatures. These conditions allow air peeling off the polar vortex into midlatitudes to maintain ozone-destroying properties, at least until "outside air" is mixed in. A simplified chemistry for restoration of the reduced amounts in the ozone hole is also included.

At the present time, 2½ years of model integration have been completed following a 1 September startup. The results show substantial November and December mixing of the low Antarctic ozone values into midlatitudes. The model indicates relatively small memory of the low Antarctic values by the time of onset of the following polar night.

By comparing the three available model Austral springs to the 6-year control climatology, a number of important effects are indicated. The polar vortex temperatures near 25 mb are up to 10°C colder than the control, accompanied by westerly wind increases of more than 15 m sec^{-1}.

There are early indications of important non-local dynamical effects, particularly in late spring and early summer. Confident insight about these effects requires further integration of the experiment and careful statistical and mechanistic analysis of the model results.

2.4.2 Seasonal Doubled CO_2 Experiment

Integrations of the SKYHI model have continued to assess the stratospheric radiative and dynamical responses to a doubling of CO_2. The earlier discovery of apparently unexpected dynamical responses that seem to resist the radiative changes has made the diagnostic interpretation more complex than anticipated earlier. The number of runs is being increasd to improve the statistical confidence in the interpretation of the dynamical response to doubled CO_2.

2.4.3 Climatic Effects Following a Nuclear War

Work on simulations of the climatic effects following a nuclear war in the Northern Hemisphere winter season were begun. Analysis of these runs are still in progress. Long-term simulation (> 30 days) performed at GFDL and elsewhere reveal that some of the injected smoke is lofted into the upper troposphere and stratosphere where it has a long residence time; this has been termed as the "residual" smoke. To compliment the GCM studies, experiments were carried out for 50 days with a time-dependent, one-dimensional, radiative-convective model. The initial forcing for this model on Day 0 is a smoke layer with a prescribed optical depth at altitudes above 7 km. Various smoke optical depths were considered at 3 different altitudes: between 7 and 12 km, between 10 and 20 km, and between 21 and 24 km. The temperatures in the smoke layer and the downward longwave flux at the surface increase with time. For optical depths of 1 or greater, this increase does not offset the solar flux depletion at the surface and the surface cools by 38K (Day 50). For an optical depth of 0.1, the altitude of location makes a significant difference on the evolution of the surface temperature. For the case when the smoke is confined between 21 and 24 km, the surface cooling by Day 50 (7K) is hardly affected by the increase in the stratospheric temperatures. If the smoke is between 10 and 20 km, there is a turnaround in the surface temperature evolution and, on Day 50, the cooling is only 4K. If the smoke is between 7 and 12 km, the convective coupling between this layer and the surface further ameliorates the cooling; in this case, on Day 50, the surface temperature is warmer than the unperturbed value by 4K. These studies demonstrate that the amount of the "residual" smoke and its location are important factors in determining the surface response over long time periods; in fact, the long-term perturbations can be considerably different from those over a short-term period (< 2 weeks) that have been reported in some earlier GCM studies.

2.4.4 Assessment of Anthropogenic Changes in Atmospheric Composition

The explosion in public awareness of serious possibilities of ozone reduction and climate warming has led to major demands upon GFDL scientists to provide analysis and assessment of what may happen. In response to these demands, preliminary evaluations have been completed on: changes in Antarctic ozone (886); stratosphere chemical/climate change (897); and greenhouse warming (mk). In each case, the analysis is necessarily preliminary and tentative due to the incomplete status of current research.

2.4.5 Radiative Forcing by Halocarbons and Other Tracer Gases

Model studies have pointed out the potential of the chlorofluorocarbon compounds (CFC's, i.e., CFC11, CFC12, CFC113, CFC115, currently used in the refrigeration and electronics industries) for destroying stratospheric ozone. This characteristic has been highlighted dramatically by the observations made in the Antarctic "ozone hole" during the winter/spring of 1986 and 1987. There is now a worldwide concerted effort to tackle this problem by replacing the CFC's with alternative compounds - termed as hydrofluorocarbons (HFC's) and hydrochlorofluorocarbons (HCFC's). The HFC's and the HCFC's appear to be less effective in destroying ozone because they are themselves removed in the troposphere and, thus, lesser amounts reach the stratosphere.

Laboratory measurements of the spectra of a number of the halocarbon molecules indicate clusters of closely spaced absorption lines, yielding an appearance of a smeared-out continuum structure. The absorption bands of all the halocarbons occur mostly in the infrared 'window' frequencies. The absorption cross-sections of the HFC's and HCFC's occur in approximately the same frequency regimes as do those of the CFC's.

A line-by-line longwave algorithm (lh) was used in conjunction with the high resolution (0.25 cm^{-1}) laboratory spectra to evaluate the radiative effects due to the CFC, HFC and the HCFC compounds. The changes in the net surface-troposphere radiative fluxes of a clear midlatitude atmosphere due to the presence of each of these compounds (assumed mixing ratio of 1 ppbv) is listed in Table 2.1. Also listed for comparisons are the contributions due to the effects of methane and nitrous oxide (current concentrations) as well as that due to doubling of carbon dioxide concentrations. Note that all gases reduce the net longwave flux at the tropopause, implying a net gain of energy by the surface-troposphere system.

The radiative forcing by any of the halocarbons is smaller than that due to doubled carbon dioxide or the current total methane + nitrous oxide radiative forcing. The CFC's exert stronger forcings than do the HFC's and the HCFC's. When viewed as a ratio to the effects due to CFC11, the rest of the CFC's possess similar potentials (per ppbv) for greenhouse warming. The HFC's and the HCFC's have potentials that are 50-80% of the CFC11 values. These results are serving as reference calculations for the evaluation of the alternative halocarbons (Alternative Fluorocarbon Environment Assessment Study) and for trace gas climate impact assessments (WMO-UNEP).

PLANS FY90

The SKYHI simulations of the doubled CO_2 and Antarctic "ozone hole" effects will be run to completion. Mechanistic and statistical analysis will be continued in both experiments with particular emphasis placed upon separation of dynamical and radiative responses to altered trace gases.

Analysis of the climatic effects of a nuclear war scenario will be completed. Updates of chemical/climate change assessments will be continued on a demand basis.

The line-by-line results will be used to develop radiative parameterizations for use in climate models; simulations will be initially performed in the context of a one-dimensional radiative-convective model.

Table 2.1: Clear sky radiative forcing due to 1 ppb of various trace gases. The reference atmosphere is the midlatitude summer profile of McClatchey et al. (1972). Net tropopause flux for the unperturbed atmosphere consisting of H_2O, CO_2, and O_3 is 273.92 W/m^2.

Gas	Change in the net flux at tropopause (W/m^2)
CFC11	-0.35
CFC12	-0.42
CFC113	-0.42
CFC115	-0.44
HCFC22	-0.29
HCFC123	-0.28
HCFC141b	-0.22
HCFC142b	-0.27
HCFC152a	-0.17
HFC134a	-0.26
2X CO_2	-5.68
CH_4 + N_2O (current values)	-4.60

3. EXPERIMENTAL PREDICTION

GOALS

* To develop more accurate and efficient atmospheric and upper oceanic GCM's suitable for monthly as well as seasonal forecasting.

* To identify upper ocean-atmosphere interaction and land surface-atmosphere interaction mechanisms important for the forecast range of several weeks to several seasons.

* To develop means of accurately specifying the initial states of atmosphere, ocean, soil moisture and snow/ice cover.

* To investigate the influence of processes such as orographic forcing, cloud-radiation interaction, cumulus convection, and soil moisture anomalies on atmospheric variability.

3.1 MODEL IMPROVEMENT

J. Derber
C. T. Gordon
J. Kinter*
K. Miyakoda
A. Rosati
M. D. Schwarzkopf
J. Sirutis
R. Smith
W. Stern
B. Wyman

*COLA (Center for Ocean-Land-Atmosphere Interaction), University of Maryland

ACTIVITIES FY89

3.1.1 Spectral Model

A version of the spectral model which uses triangular truncation has been developed. Preliminary tests at resolutions T30L9, T30L18 and T42L18, indicate satisfactory results where T30L9, for example, denotes the triangular truncation at zonal wavenumber 30, and 9 vertical levels. The capability to extend to higher horizontal resolutions (i.e., T63L18 and T80L18) has been incorporated. Beyond the conventional physics (E-type, see 3.1.5), this model includes: cloud-radiation interaction (801), orographic gravity wave drag (828, 919, 934), the 1988-89 version of the Fels-Schwarzkopf radiation (3.1.2) currently implemented at NMC, shallow convection, a modified turbulent mixing length-scale (mu), and a mixed ice-water scheme for the treatment of Antarctic circumpolar pack ice (919).

3.1.2 Improvements to Radiation Code

A new operational longwave radiation algorithm has been completed and installed in the spectral model and the global HIBU model, as well as in other operational models at GFDL. The improvements in physics included in the new model are described in (938) and (lh). The operational code has been written to permit efficient computations for all grid points along a latitude circle ("slab" version) in addition to the standard method of computations for one grid point at a time ("column" version). The "slab" version greatly improves computation speed, particularly when half-precision arithmetic is employed.

A revision of the shortwave radiation algorithm has also been completed and installed into GFDL operational models. The revision is designed for the purpose of increased computation speed.

Table 3.1 indicates computation speeds of the new longwave and shortwave radiation algorithms for various GFDL models, as compared to the previous versions.

TABLE 3.1

	LONGWAVE				SHORTWAVE	
Model Type	L40F	L40H	L18F	L18H	L40H	L18H
prev. code	6.49	5.54	2.98		.498	.412
new, "column"	5.73	4.89	2.72	2.54		
new, "slab"	4.11	2.78	1.01	0.66	.239	.147

Table 3.1: L40 refers to a radiation code with 40 vertical levels, used in the SKYHI model; L18 to a code with 18 vertical levels, used in the Experimental Prediction Group model; F and H refer to full and half-precision arithmetic, respectively. Timings are given in 10^{-3} sec/grid point.

3.1.3 Cloud-Radiation Interaction and Shallow Convection

A parameterization of shallow convection has been developed, in the spirit of Tiedtke et al.[1] and is being tested. Increased eviction of water vapor out of the planetary boundary layer is achieved by augmenting the vertical diffusion for water vapor only in the Mellor-Yamada turbulence closure scheme. Shallow convection may occur above the lifting condensation level, provided a buoyancy criterion is satisfied. A lid, e.g., at 750 hPa has to be imposed, however. The parameterized shallow convection layer defines the top and base of the empirically predicted shallow convection clouds.

3.1.4 Global HIBU Model

A rationalized one-dimensional coding has replaced the conventional inefficient code of the HIBU model, and the step-mountain eta coordinate of Mesinger et al. (881) has been introduced. It appears that the eta coordinate model is advantageous in maintaining the local intensity of vorticity. This is the most outstanding feature of the current HIBU model. In addition, a new horizontal advection scheme of Janjic[2] has been incorporated with polar boundary conditions of Rancic and Nickovic[3] and appears beneficial for the

---

[1]Tiedtke, M., W. A. Heckler, and J. Slingo, 1988: Tropical Forecasting at ECMWF: The Influence of Physical Parameterization on the Mean Structure of Forecasts and Analysis, Quart. J. Royal Meteor. Soc. 144, 639-664.

[2]Janjic, Z.I., 1984: Nonlinear Advection Schemes and Energy Cascade on Semi-Staggered Grids, Mon. Wea. Rev., 112, 1234-1245.

[3]Rancic, M., and S. Nickovic, 1988: Numerical Testing of E-Grid Horizontal Advection Schemes on the Hemisphere. Contri. to Atmos. Phys., 61, 265-273.

calculations in the polar regions. Extensive tests have been carried out on the polar filtering. The 30-day integration with N45L9 resolution and the conventional physics gives promising results.

3.1.5 Comparison of Various SGS (subgrid-scale) Parameterizations

Final analysis has been completed on four packages of SGS physics parameterization for one-month forecasts (mt). As was mentioned in the previous reports, the four models, i.e., A, E, F, and FM parameterization packages (627), are formulated by cumulatively increasing the sophistication of the physics. One-month integrations were performed for 8 January cases with each case consisting of three different forecasts. Originally, the forecast performance was expected to improve with the increased sophistication of the SGS physics from the A to the FM. However, the results do not turn out to be that simple. The impact of these processes on the one-month integration is subtle and yet significant. The superiority of the F model over the A and the E models is evident in the last 10 days of the one-month forecasts, though the performance of the E model is consistently good in terms of root-mean-square (rms) error of geopotential height. The FM model gives the lowest rms error, but the predicted transient eddy energy is extremely low.

3.1.6 Land Surface Processes

The Simple Biosphere (SiB) model[4] has been incorporated in the R21L9 GCM, and the performance of the 30-day prediction is being investigated and compared with the results of the conventional bucket model. As a second step, a "Simplified SIB" package is being incorporated; this version has been developed in the COLA of University of Maryland. The computing time is substantially reduced by the new model, without sacrificing the original contents of SIB hydrology.

3.1.7 Upper Ocean Model

Improvements to the ocean model (898) still continue. These improvements include the deceleration of the circumpolar flow in the Southern Ocean, the separation of the Gulf Stream in the Atlantic Bight, and adequate vertical mixing. It has been suggested (529) that the specification of the Deep Western Boundary Current as a lateral boundary condition is important in determining the mean path of the Gulf Stream. Utilizing this idea the net transport through the Labrador Sea is specified in the ocean model to see if the mean flow can be altered, so as to improve the location of the Gulf Stream separation.

---

[4] Sellers, P. J., Y. Mintz, Y. Sud, A. D. Dalcher, 1986: A Simple Biosphere Model (SiB) for Use Within General Circulation Models, Journal of the Atmospheric Sciences, 43, 505-531.

PLANS FY90

A triangular spectral model of T63L18 resolution will be developed. A one-month integration will be conducted employing a higher resolution version of the GCM, e.g., R42, with cloud-radiation interaction and shallow convection. Some ISCCP (International Satellite Cloud Climatology Project) and/or ERBE (Earth Radiation Budget Experiment) satellite-derived cloud and radiation data will be processed and used as verification data for the above integrations.

The development of the global HIBU of N60L18 resolution with adequate physics will continue. The simplified SIB model will be further investigated. Comparison between the bucket and SIB hydrology will be performed. The improved Arakawa-Schubert cumulus parameterization will be examined. Improvement of the ocean model will continue.

3.2 THEORETICAL AND DIAGNOSTIC STUDIES

J. Anderson	E. Manzini
M. Dahleh*	K. Miyakoda
A. da Silva	F. Parham*
K. Lamb*	R. T. Pierrehumbert
S. J. Lin	A. Rosati

*Applied and Computational Mathematics Program
Princeton University

ACTIVITIES FY89

3.2.1 Theoretical Studies of Dynamic Meteorology

Progress has been made in a number of studies relating to baroclinic instability, nonlinear planetary waves, storm track structure, low frequency variability, and nonlinear gravity waves. The effect of Ekman friction on baroclinic instability of realistic flows, and the wave packet stability analysis for such flows, has been carried to completion; it reveals that the atmosphere is not normally absolutely unstable, or at best only weakly so (942). The results have implications for the fundamental nature of the storm tracks. A theory for nonlinear and linear Rossby wave critical levels in a vertically sheared atmosphere has been developed, and consequences for equatorial wave absorption and Rossby wave normal mode structure have been identified. An extensive study of nonlinear gravity wave critical levels has been completed with the conclusion that the steady states for the gravity wave case can exhibit a richer variety of behavior than the more constrained Rossby wave case. A novel method has been developed for large eigenvalue problems and used to perform high resolution calculations of barotropic instabilities connected with low frequency variability. Calculations have been carried out on evolution of coherent atmospheric vortices using a novel Lagrangian numerical method based on discrete vortex elements. The methods have been extended to the atmospheric case, an efficient algorithm has been implemented, and several test cases have been run. Besides these subjects, a program of research on chaotic mixing of tracers by geometrically simple large-scale velocity fields was carried out. This revealed that efficient mixing does not require small scale turbulence.

3.2.2 Effect of Orographic Gravity Waves

Using a high resolution, two-dimensional (2 km for Δx and 320 m for Δz) anelastic model, the character of orographic gravity wave breaking and the effect of deceleration of basic flow are investigated. The numerical experiments indicate that wave breaking takes place at multiple levels and that the levels are determined by the horizontal width of the dominant subgrid-scale mountain (934). It is also found that the deposition of momentum flux associated with the gravity waves is well represented by the "saturation momentum flux" approach, as far as the breaking in the lower stratosphere and the upper troposphere is concerned. However, wave breaking in the lower troposphere has not yet been studied.

3.2.3 Ten-Year Run of the Ocean GCM

To study the characteristics of the upper ocean GCM, a 10-year run from 1979 to 1988 using observed atmospheric forcings is being carried out. The period includes two El Niños. One of the current studies is to compare the simulations with their available observational counterparts, and thereby, to identify the strengths and biases of the model. An understanding of the overall behavior of the upper ocean circulation (above about 200 m) and the evolution of ocean heat content in the Equatorial belt are other important subjects.

3.2.4 Systematic Error and Blocking Forecasts

The capability of predicting blocking has been investigated for four different models, distinguished by their respective subgrid-scale parameterization packages (i.e., A, E, F, and FM models--see 3.1.5), using a dataset of one-month forecasts for 8 January cases (mu).

One of the major issues is whether the model's systematic bias is generated by the failure to adequately forecast blocking. This study overall supports this assertion, despite the different definitions of blocking. The study also reveals that the A model is inferior to the other three models, such as the E model, with regard to forecasting blocking.

It is also pointed out that the blocking activity in the winter northern hemisphere is manifested by a distinct subpolar peak in the meridional distribution of standing (low-frequency) eddy kinetic energy (Figure 3.1). The E model tends to generate a well-defined peak of this energy distribution. All models are deficient in that they expand the zonal mean westerlies to higher latitudes, particularly the A model. In this connection, a hypothesis is postulated on the condition of blocking: the westerly jet prior to the onset has to be displaced to a relatively lower latitude.

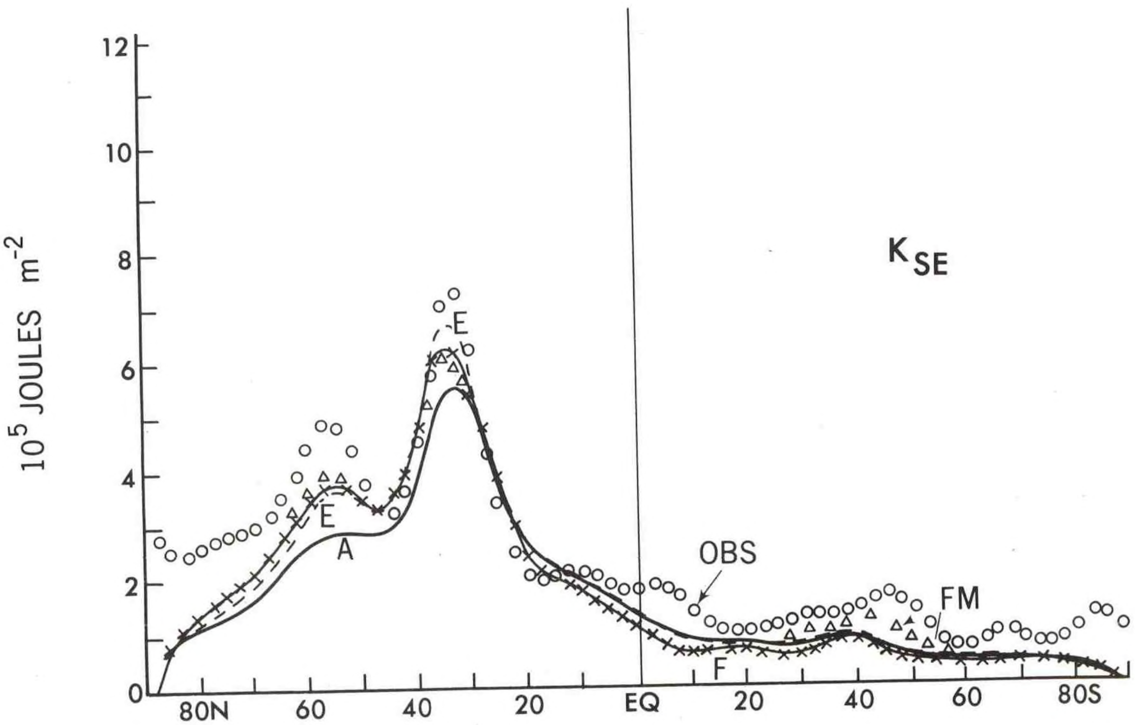


Fig. 3.1 Latitudinal distribution of standing (low- frequency) eddy kinetic energy, K_{SE}, which are averaged vertically over a month for 8 January cases. Small circles are observations. The A-model is indicated by thick solid line (——); the E-model by dash line (- - -); and the F-model by thin solid line connected by crosses (—x—x—); and the FM-model by triangles.

PLANS FY90

Theoretical studies of blocking will be carried out.

The two-dimensional study on the orographically induced wave-breaking will be expanded to include the condensational effects.

The 10-year ocean GCM run will be diagnosed to investigate the causes for systematic errors in the ocean model.

Brazilian drought will be investigated using information of SST and a simple dynamical model.

3.3 DATA ASSIMILATION

J. Derber
R. Gudgel
K. Miyakoda
J. Ploshay
A. Rosati
R. Smith
W. Stern

ACTIVITIES FY89

3.3.1 Re-analysis of Atmospheric FGGE Data

Finally the re-analysis is nearing completion; SOP-I (Special Observing Period I) has been completed, and half of the SOP-II has been finished. The routine processing aspect of the FGGE re-analysis will be completed before September, 1989, although the diagnostic analysis of the results will continue.

A preliminary study indicates that the new analyses are quite good, implying that continuous data assimilation works satisfactorily, and is at least comparable with the intermittent method. Perhaps the key elements of success are that first, a 6-hour forecast is used for the initial guess, instead of a 6-hour persistence, and secondly, the collection range of observed data for producing insertion data were extended from 250 km to 550 km (Figure 3.2). For the purpose of smoothness of analyzed fields, a weak geostrophic balancing technique of Daley and Puri[5] is adopted; it is indeed effective and useful for eliminating the noisiness present in GFDL's original FGGE analysis. Because of this procedure, the non-linear normal mode initialization is not necessary, and has been entirely removed from the analysis system.

The re-analysis results are now being compared with the original GFDL FGGE analyses and the re-analyses from ECMWF. Verification with radiosonde data reveals that the new analyses are generally superior to the original GFDL analyses, and is competitive with the re-analyses of ECMWF.

---

[5]Daley, R., and K. Puri, 1980: Four-Dimensional Data Assimilation and the Slow Manifold, Mon. Wea. Rev., 108, 85-99.

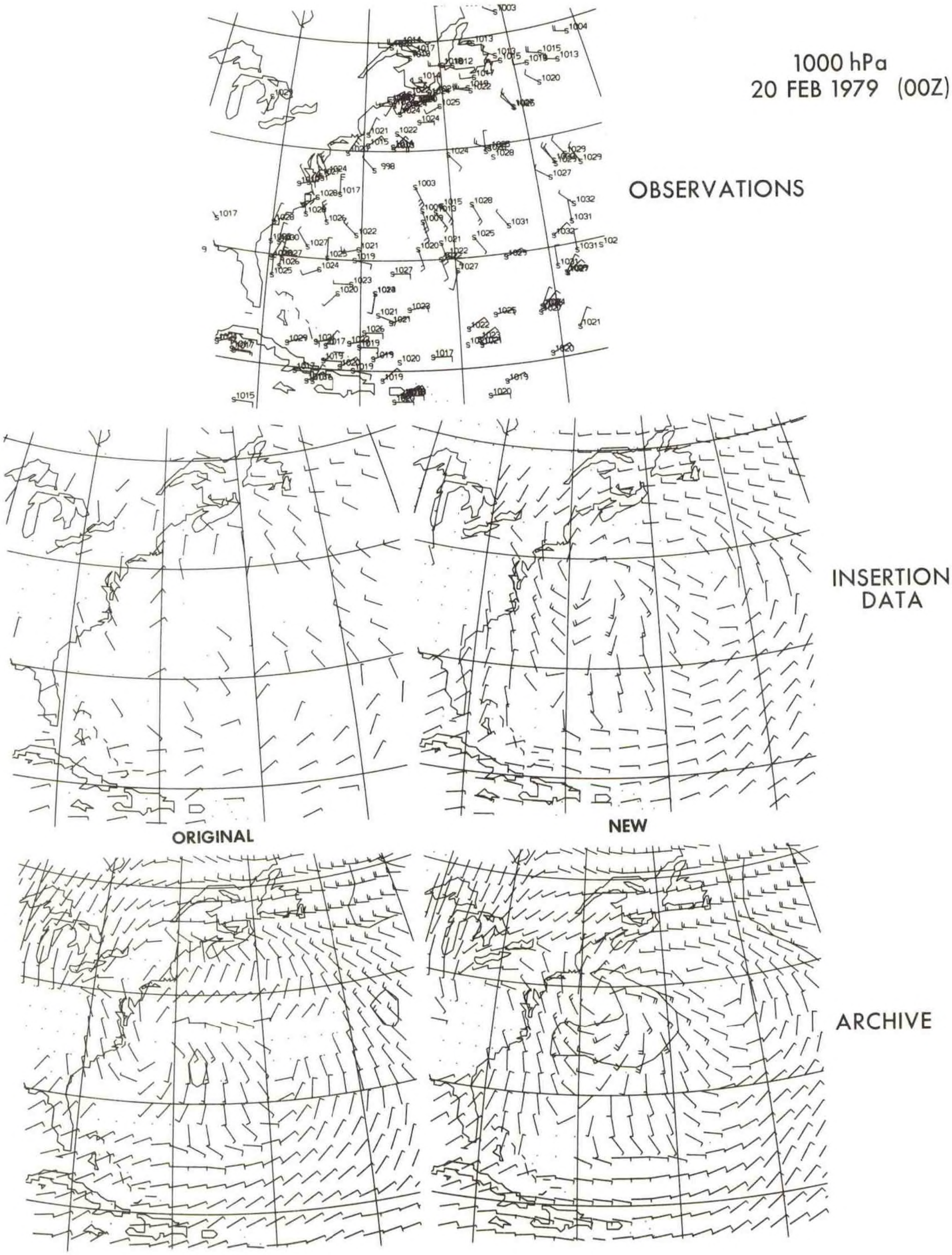


Fig. 3.2 FGGE re-analysis is shown by an example of 1000 hPa observations (top) for the period of Presidents' Day storm. 1000 hPa insertion data for GFDL old system (mid-left), new system (mid-right); Level III-B archive for GFDL old system (bottom-left) and new system (bottom-right).

3.3.2 Ocean Data Assimilation

The global ocean data assimilation system (iq) was made computationally more efficient; the speed is now two and a half times faster without affecting the accuracy. This efficient scheme is being applied to the period from 1979 to 1983, using the data of COADS and MOODS (Master Oceanographic Observations Data Set), and NMC atmospheric data. This oceanic analysis dataset will provide not only a useful time series of the sea surface temperature (SST) and the ocean heat content, but also a means for studying various features of the upper ocean circulation.

3.3.3 A New Atmospheric Data Assimilation System

The new assimilation system is based on variational principles, aided by the concept of an adjoint method. In the meantime, a variational nudging technique which distributes corrections to the model solution over the assimilation interval has been developed and examined (lj). This project has been transferred to NMC.

PLANS FY90

Diagnostic studies involving the FGGE re-analysis will be continued and papers will be written.

The ocean data assimilation will be extended.

The atmospheric data assimilation system will be applied to the triangular truncation spectral model, as well as to the HIBU model.

3.4 LONG-RANGE FORECAST EXPERIMENTS

A. da Silva	A. Rosati
T. Gordon	J. Sirutis
R. Gudgel	R. Smith
K. Miyakoda	W. Stern

ACTIVITIES F89

3.4.1 Monthly Forecast Study--Without Cloud-Radiation Interaction

The 1988 standard model with R42L18 was applied to one-month integrations for six cases, as specified by the WGNE (Working Group on Numerical Experimentation) of WMO. The model includes an orographic gravity wave drag parameterization, a correction to the extension of orography over the ocean due to the Gibbs phenomenon, and a parameterization of the Antarctic circumpolar pack-ice.

The results were presented at the WGNE conference in Toronto (919) and have been subsequently submitted to WGNE for intercomparison purposes.

3.4.2 Monthly Forecast Study--Cloud-Radiation Interaction and Shallow Convection

The model's 30 day mean thermodynamical and dynamical responses have been analyzed. With cloud-radiation interaction, the systematic zonal mean temperature error is reduced in the upper troposphere during northern hemisphere winter. The zonal-mean zonal wind error is also reduced in portions of the southern hemisphere summer, but increased westerlies occur in the tropical upper troposphere and lower stratosphere. The impact on the time-mean geopotential height prediction in the southern hemisphere extratropics is modestly favorable. Recent experiments indicate that cloud-radiation interaction significantly increases the sensitivity of model predictions of monthly means to the formulations of the mountain gravity wave drag parameterization.

3.4.3 The Systematic Bias in the Air-Sea Model Experiment

As was reported in GFDL A88/P89, the current air-sea model exhibits large systematic errors. The errors are amplified in the air-sea coupled mode, compared with each of the uncoupled modes.

In order to estimate the bias in terms of compensating surface heat flux, the method of Newtonian nudging to the observed SST has been applied to the air-sea model run from 1979 to 1984. Based on this run, geographical distributions of the requisite heat flux for the specified observed SST have been obtained (914).

The largest SST biases found are associated with the high-latitude confluence zones of the northward tropical flows at the western boundaries and the southward polar flows, e.g., between the Gulf Stream and the Labrador current. The Southern Ocean has a large bias for excessive heating. Most of the domains, including the equatorial zone, have a tendency toward excessive cooling. Possible reasons for these biases are: deficiencies in condensational heating; the lack of the southward protrusion of cold water along western boundaries; and other systematic biases of the atmospheric and oceanic GCMs.

3.4.4 Seasonal Forecast Experiment Using an Air-Sea Model

Two 12-month forecasts were performed from 1 January 1982, one using a straightforward method in which no heat flux correction is made, and the other adopting a heat flux correction (see 3.4.3). The ocean initial conditions are taken from the data assimilation of SST nudging, and the atmospheric conditions are taken from the NMC analysis. In the former run, excessive SST cooling occurred, as was described in 3.4.3, and as a result, the El Niño was not well simulated, while in the latter run, an El Niño-like signal has emerged in the eastern Equatorial Pacific from September, 1982. Figure 3.3 compares the SST anomaly fields from the latter forecast, i.e., the prediction using the correction heat flux, with Reynold's observation for November, 1982. The model's warming in the eastern Pacific is not sufficiently strong, but at least the El Niño signature is present; this is due to the eastward propagation of the cumulus convective systems along the equator (585).

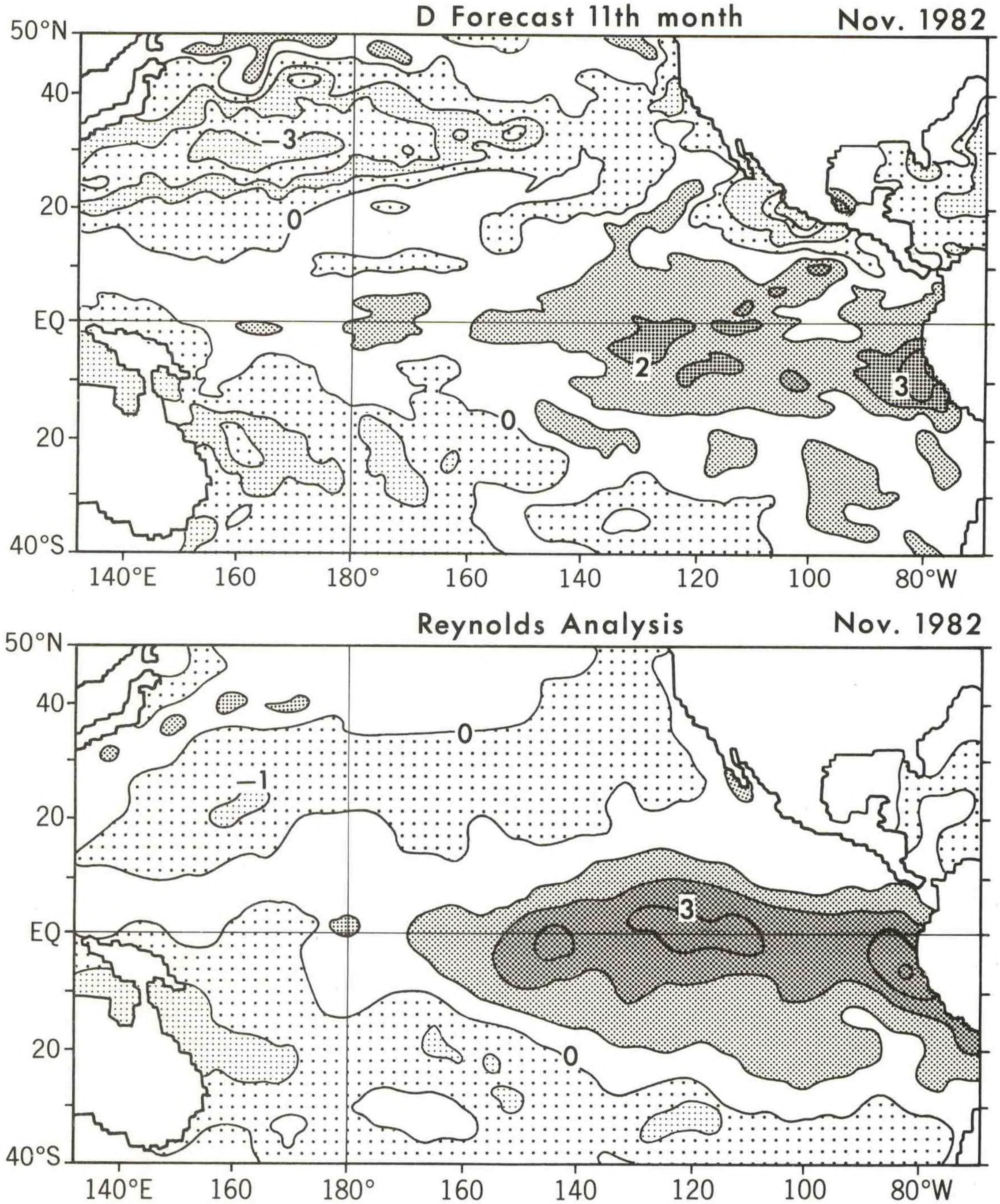


Fig. 3.3 The monthly mean sea surface temperature anomalies over the Pacific in the eleventh month (November, 1982) of forecast with heat flux correction (upper), compared with the NMC analysis (lower). Contour interval is 1°C.

Thus it may be safely stated that this seasonal forecast has achieved some success in predicting the El Niño 9 months ahead. However, this forecast has many flaws. Possible reasons may be due to initial imbalances in the surface winds and slightly deficient initialization of the Equatorial Ocean thermal structure. A third run is now being carried out, in which the initial imbalance in surface winds is alleviated.

PLAN FY90

A Newtonian nudging to the observed SST will be continued from 1984 to 1987. This study will provide detailed information on the seasonal variability of the systematic deficiency of the heat flux. The causes of the biases in the atmospheric and oceanic GCM will be further investigated. The forecast experiment will be extended to other cases. A fourth version of the forecasts will include seasonal variation of the heat flux correction. The air-sea model will be applied to the simplified assimilation, in which the nudging method is used for observed SST as well as observed surface winds.

4. OCEANIC CIRCULATION

GOALS

* To develop a capability to predict the large-scale behavior of the World Ocean in response to changing atmospheric conditions through detailed, three-dimensional models of the World Ocean.

* To identify practical applications of oceanic models to man's marine activities by the development of a coastal ocean model which has a detailed surface layer and bottom boundary layer.

* To incorporate biological effects in a coupled carbon cycle/ocean GCM.

* To study the dynamical structure of the ocean through detailed analyses of tracer data.

4.1 OCEAN-ATMOSPHERE INTERACTIONS

I. Held
N.-C. Lau
M. J. Nath
D. Neelin*
R. C. Pacanowski
S. G. H. Philander

*UCLA

ACTIVITIES FY89

Studies of interactions between the tropical oceans and global atmosphere are being pursued with several coupled ocean-atmosphere models: the R15 atmospheric GCM coupled to a coarse-resolution, global oceanic GCM; the R15 atmospheric GCM coupled to a higher resolution oceanic GCM of the tropical Pacific Ocean (681); and a relatively simple atmospheric model that describes steady wind conditions in response to sea surface temperature patterns (787) coupled to a higher resolution oceanic GCM of the tropical Pacific. Each of these models simulates a Southern Oscillation, with a reasonable time interval between realistic warm El Niño and cold La Niña states (lo). The manner in which El Niño (and La Niña) evolves is different in each model. Modest El Niño conditions gradually migrate and expand (1) westward in the model with the coarse resolution ocean, (2) eastward in the model with the higher resolution ocean coupled to the R15 atmospheric GCM and (3) grow in place in the model with the simple atmosphere. This happens because the evolution of El Niño depends on the processes that determine sea surface temperature changes. In the higher resolution ocean model, oceanic waves are very prominent, especially near the equator, and strongly influence sea surface temperature changes. Differences between the winds in the R15 model and the simple atmospheric model cause the oceanic waves to have different roles in the two models. In the coarse resolution ocean model diffusive processes are so strong that waves are practically absent so that advection controls sea surface temperatures.

The coupled model with the simple atmosphere has been used to study how the character of the interannual oscillations changes as the strength of the coupling between the ocean and atmosphere changes. In Figure 4.1 interactions are made weak (left), stronger (middle), and strongest (right). A perturbation of westerly winds that persist for a month in the west initiates a damped oscillation (left), a more energetic self-sustaining oscillation (middle), and an oscillation that is subject to secondary instabilities (right). Further increases in the strength of the interactions between the ocean and atmosphere result in chaotic fluctuations. Such a parameter range is not believed to be relevant to reality. Rather, the observed Southern Oscillation, and those simulated with the coupled GCM's correspond to modestly unstable ocean-atmosphere modes that would be perfectly regular and predictable, as in Figure 4.1(b), were it not for the disruptive effect of random atmospheric disturbances or "weather" (mq).

PLANS FY90

Analyses of the simulations will continue. Studies of the seasonal cycle will be initiated. The response of the coupled ocean-atmosphere to the annual variations in solar radiation is affected by interactions between the ocean and atmosphere similar to those that cause the Southern Oscillation. The close relationship between seasonal cycle and the Southern Oscillation is poorly understood at present.

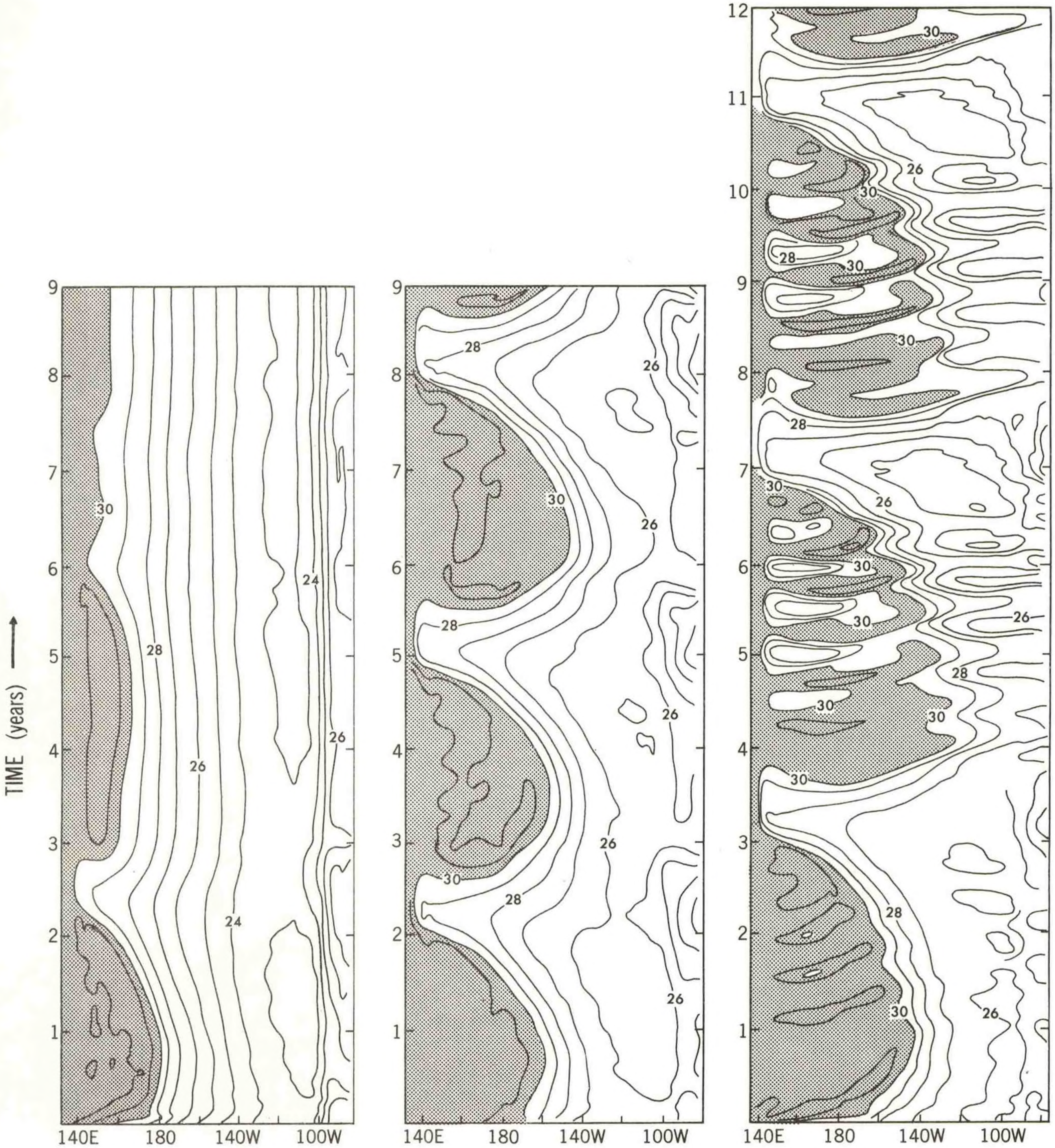


Fig. 4.1. Isotherms (°C) along the equator over a period of years in a coupled ocean-atmosphere model in which the atmosphere is the relatively simple one proposed by Neelin and Held (1987) and the ocean is a GCM of the tropical Pacific. Westerly winds are imposed over the western side of the basin for a month whereafter ocean-atmosphere interactions, which are weak (left), moderately strong (middle), and very strong (right), control further developments. The strength of the interactions is increased by increasing the drag coefficient that converts wind speed to stress.

4.2 OCEANIC RESPONSE STUDIES

Y. Chao R. C. Pacanowski
W. J. Hurlin S. G. H. Philander
R. Matano

ACTIVITIES FY89

4.2.1 The Circulation of the Southern Atlantic Ocean

The Antarctic Circumpolar Current, the cold northward Malvinas Current, along the coast of Argentina, that meets the warm southward Brazil Current near 35°S where both veer eastward and start to meander, and the Agulhas Current along southeastern Africa that sheds warm eddies in the Atlantic are all features of the oceanic circulation of the southern Atlantic. A high resolution GCM of that region that captures these features has been constructed and is now being analyzed to determine how the curl of the wind over the region, the inflow at the Drake Passage and outflow to the south of Africa, and the topography of the ocean floor, influence the circulation.

4.2.2 Low Frequency Variability of the Tropical Pacific

A GCM of the tropical Pacific has been forced with the winds that prevailed during the period 1968 to 1978. The simulation reproduces the various El Niño and La Niña episodes observed during that period and permits a detailed study of the similarity and differences between the various episodes. Of special interest is the heat budget during a complete Southern Oscillation: the equatorial region loses heat during El Niño because of an enhanced poleward export of heat and increased loss of latent heat. It recovers this heat during La Niña (879).

The seasonal cycle below the thermocline is being analyzed to determine whether it can be explained primarily in terms of free waves and to find out whether equatorially trapped waves are of special importance even though forcing at a period of one year will excite waves with turning latitudes far from the equator.

4.2.3 Simulation of the Tropical Atlantic Ocean

An improved model of the tropical Atlantic, and an accurate surface wind field for the tropical Atlantic Ocean have been used to simulate conditions in that ocean during the years 1982, 1983 and 1984. The model reproduces the unusually warm El Niño-type event that occurred in the Atlantic in 1984. The results are now being analyzed to determine how the oceanic circulation changed to effect a redistribution of warm surface waters, and to determine whether the warm event could have been anticipated.

PLANS FY90

Studies of the seasonal cycle below the tropical thermocline in each of the three ocean basins are being planned. In the Atlantic this should shed light on seasonal changes in the southward transport of deep cold water across the equator.

A GCM of the tropical Atlantic Ocean will be used to simulate variability over a ten-year period, 1960 to 1970, in order to describe the climatological seasonal cycle and to discuss how representative that cycle is of conditions in any one year. This information will permit a better assessment of discrepancies between the model and measurements which are adequate only for a description of climatological conditions.

4.3 MARINE GEOCHEMISTRY

L. Anderson	S. Rintoul
R. Key	R. Rotter
G. McDonald	J. Sarmiento
T. McGrath*	Rochelle D. Slater
R. Murnane	Richard D. Slater
R. Najjar	J. R. Toggweiler
J. Oor	R. Wong

* Geology Department
Princeton University

ACTIVITIES FY89

4.3.1 Fossil CO_2 Uptake Models

A key role to understanding the greenhouse effect is played by the oceans with their capacity to absorb anthropogenically produced CO_2. This uptake capacity is studied using a 3-D global circulation model of the ocean and histories of atmospheric CO_2 and fossil fuel production. A first simulation using the history of atmospheric CO_2 gives an airborne fraction of 0.638, compared with an observed airborne fraction, relative to the fossil CO_2 input only, of 0.568. Gas exchange has a minimal impact. An increase of 20% in gas exchange rate gives only a 2.5% increase in CO_2 uptake, while a doubling of the gas exchange gives only a 9.2% increase in CO_2 uptake. The experiment in which fossil fuel production is specified gives an airborne fraction of 0.671.

4.3.2 Carbon Cycle Modeling

Oceanic biological processes are important to the ocean's carbon cycling and its ability to take up atmospheric CO_2 (872). A simple ecosystem model of the euphotic zone has been incorporated into a three-dimensional North Atlantic circulation model (741). A parameter set to best fit oceanic observations is being tested for this model. A qualitative comparison between model and satellite chlorophyll is good, but does indicate some deficiencies in both the biological and physical models.

An annual mean model of the global ocean general circulation (kn,kq) has been used to study the effect of organic matter remineralization below the euphotic zone on the distribution of nutrients and new production. A fixed fraction of the new production is put into large, fast-sinking particles which are remineralized below at all depths without being laterally advected. The remainder of the new production goes into dissolved organic phosphorus (DOP), which is carried by the circulation and remineralized at a rate proportional to its concentration. When all of the new production is put into particles that are remineralized according to these rates, nutrient trapping occurs in various upwelling regions of the model, such as the eastern equatorial Pacific and the Bay of Bengal. When one-half of the new production is in the form of DOP, nutrient trapping is eliminated, suggesting an important role for dissolved organic matter in the marine carbon cycle.

4.3.3 Models of Trace Metal Cycling in the Oceans

Trace metal distributions are a major source of information on the recycling of organic particulate matter in the water column. A model of particle and trace metal cycling has been fit to thorium observations and suggestions for revisions to the model have been made (mv). Sampling strategies for improving the model require measurement of all thorium isotopes and their parents in dissolved and particulate form over a period of time long enough to average out any temporal variability.

4.3.4 Paleoceanography

Simple box models continue to be developed to understand how ocean chemistry may have changed in the past as a guide to how it might change in the future. Work has abeen completed on possible model scenarios for global episodes of anoxia that occurred during the Cretaceous, and for more recent episodes of anoxia in the Mediterranean (880, 901). A new one-dimensional advection/diffusion model with a high latitude outcrop has been developed to obtain better vertical resolution in the ocean interior. This model does a very good job of fitting modern observations and is being used to explore scenarios of past ocean chemistry. A model of sediment diagenesis is being developed to add to the 1-D model.

4.3.5 Observational and Tracer Studies

Research describing the advantages and disadvantages of using tracer derived ages for circulation studies have been completed (lc). Observations are being compared to estimate the rate of metabolism in the North Atlantic main thermocline. The rates appear to be higher than the supply of organic matter from the surface can support, suggesting a major role for lateral impact of dissolved organic matter.

A field experiment SAVE (South Atlantic Ventilation Experiment) has been recently completed in collaboration with several other institutions, during which samples were collected for measurement of radium-228.

Laboratory measurements of a similar suite of samples collected in the North Atlantic have almost been completed. Some modeling and descriptive studies using these data have begun.

A reanalysis of GEOSECS, (Geochemical Ocean Sections Study) nutrient data is taking place in order to determine the ratio of nutrients to each other in remineralized organic matter.

PLANS FY90

The fossil CO_2 experiments and related carbon cycle development studies will continue to be highest priority. The group plans to incorporate trace metal particle cycling models into a 3-D model of ocean circulation and to expand collaborations with groups making trace metal measurements through an exchange of visits. The sediment diagenesis models will be incorporated into the 1-D advection/diffusion model. The group plans to begin an analysis of SAVE nutrient observations using inverse modeling techniques.

4.4 WORLD OCEAN STUDIES

K. Bryan
M. D. Cox
K. Dixon
R. Gammon*
B. Samuels
J. R. Toggweiler

**Pacific Marine Environmental Laboratory/NOAA

ACTIVITIES FY89

Climate change depends critically on the ability of the ocean to absorb a large fraction of the excess heat produced by greenhouse warming. It is very important that the ocean component of models used to project global climate have realistic vertical pathways. Transient tracers present the most realistic check of this property of the models. A study of the penetration of carbon-14 into the World Ocean (kn, kq) was completed in FY88 through use of a 12 level model. In order to test a more detailed, 44-level model of the World Ocean including seasonal variations and isopycnal mixing, a new series of experiments have been performed in which anthropogenic chlorofluorocarbons (CFC's) were used as tracers in global ocean model simulations of the period 1932 to 1990. The principle purpose of the experiments is to develop the techniques needed to use the CFC's as aids in quantitatively analyzing aspects of ocean model simulations. The CFC's are particularly well suited for examining oceanic ventilation processes on decadal timescales.

Analysis of model results via comparisons with observations is being done in cooperation with the staff of PMEL/NOAA, who have collected numerous Pacific and Indian Ocean CFC measurements. Figure 4.2 displays a comparison of a 44-layer, low horizontal resolution, seasonal ocean model simulation with North Pacific observations. The ability of the model to reproduce observed features, such as the tongue of relatively high CFC-11 laden water extending downward and equatorward from the surface at higher latitudes, helps confirm the benefits gained by including into this model more complicated horizontal mixing schemes, wind-forced vertical mixing, increased vertical resolution and the annual cycle of density and momentum forcing.

Because of the deep gap between South America and Antarctica, a "normal" thermohaline circulation (i.e. poleward flow of upper ocean water and equatorward flow of bottom water) does not exist in the southern hemisphere. Instead, southward flowing upper ocean water is forced downward north of the Drake Passage, while deep water upwells south of the Drake Passage (mb). Theory and ocean models predict that the combination of this "distorted" thermohaline circulation with the northward Ekman drift imposed by strong southern hemisphere westerlies between 40°S and 50°S produces a deep

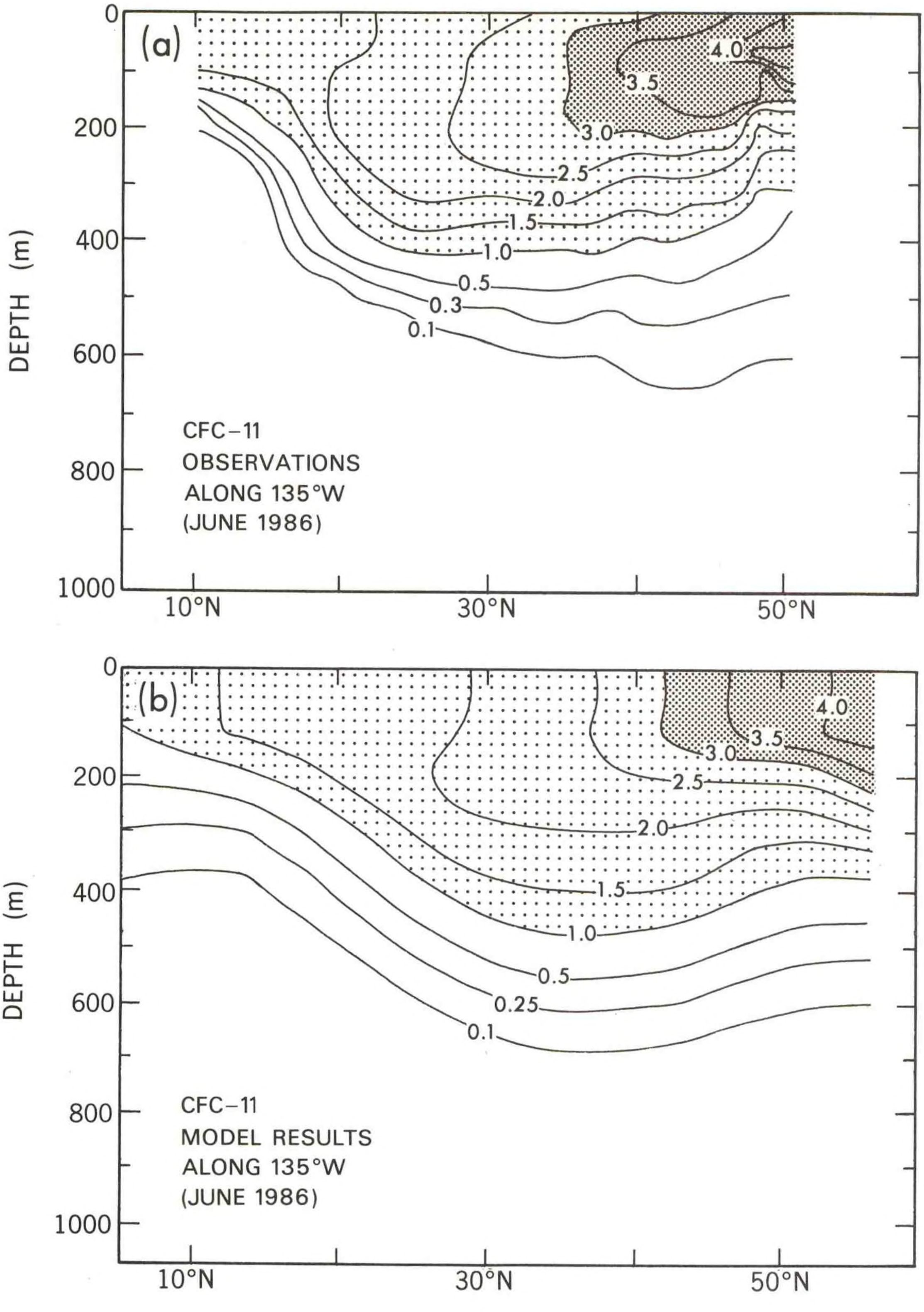


Fig. 4.2. A comparison of observed (top) and model predicted (bottom) CFC-11 concentrations in the North Pacific along 135°W longitude during June 1984. Model results are from a world ocean model in which the oceanic uptake and redistribution of CFC's were simulated for the period 1932-1990. The observations are courtesy of R. Gammon of PMEL/NOAA. CFC-11 values are in units of picomoles per liter.

overturning cell in which surface water flows equatorward while deep water paradoxically flows poleward. The upwelling of cold water on the poleward side of the cell causes a pronounced delay in the greenhouse warming of the entire southern hemisphere (870, kg, mh).

While observed features of the ocean are broadly consistent with the existence of such a cell, most of the particulars of the cell (e.g. the location of downwelling regions along the northern side of the Drake Passage, and the depth of the deep poleward flow) have not been confirmed by oceanic observations. Given that the vertical and north-south flows which make up the overturning cell coexist in the same domain with the Antarctic Circumpolar Current, these motions may be very difficult to detect directly. The distribution of radiocarbon in the ocean is particularly sensitive to how this cell operates (kn). A series of sensitivity experiments have been carried out to elucidate the relationships between predicted radiocarbon distributions, both bomb-produced and natural, and 1) the width of the Drake Passage, and 2) the intensity of circumpolar westerly winds. These experiments have been used as a basis for planning and participation in tracer field measurements during the upcoming WOCE (World Ocean Circulation Experiment) expeditions.

PLANS FY90

The analysis of ocean-only and coupled air-sea models using CFCs as tracers will continue. CFC-aided analysis of ventilation processes on decadal timescales should be particularly applicable when analyzing the ocean's response to greenhouse warming in coupled atmosphere-ocean climate models. Collaborations with PMEL/NOAA will continue in order to more fully develop analysis products using the CFC tracers.

Analysis of the sensitivity of carbon-14 to Drake Passage geometry and winds will be completed. The standard 12-layer run and at least one of these sensitivity experiments will be repeated in a model with 30 layers in the vertical. A model with 2° x 2° latitude and longitude resolution will be set up in order to investigate the radiocarbon properties of a model with much less friction in the Drake Passage.

4.5 OCEAN MODELING DEVELOPMENT

K. Bryan K. Dixon
M. D. Cox R. Gerdes

ACTIVITIES FY89

A terrain-following vertical coordinate (s-coordinate) has been implemented in the existing (z-coordinate) ocean model. The new representation of the bottom topography leads to a considerable improvement in the simulation of topographic Rossby waves in a channel. A simplified model of the Greenland-Scotland Ridge region has been constructed for both cases in order to explore the processes that allow the overflow of dense water masses from the Norwegian Sea to take place.

The development of a model which correctly simulates the formation of the observed temperature and salinity field of the World Ocean remains a challenging problem. To explore water mass formation a model with

200 km x 200 km resolution and idealized World Ocean geometry has been developed. In a series of four key experiments, major factors such as wind-driving, the geometry of the Drake Passage, and the Mediterranean salt water source in the Atlantic are introduced (mb). The experiments shown in Figure 4.3 illustrate the major factors governing the observed temperature and salinity distribution, particularly the dominant role of the North Atlantic thermohaline circulation in the World Ocean circulation. The contribution of different geographic areas in water mass renewal is shown through a series of "color" experiments. The fraction color of different water masses show the relative contribution of different areas in quantitative detail unobtainable using conventional water mass analysis.

PLANS FY90

The intercomparison of the z- and s-coordinate models will continue for the overflow problem. The influence of bottom boundary layer parameterizations, resolution, variability and geometry will be examined. The calculations will be extended to a more realistic model of the northern North Atlantic in order to improve the generation of North Atlantic Deep Water in the model and to verify the results against observations.

4.6 GULF STREAM MODEL

T. Ezer L.-Y. Oey
G. Mellor H.-J. Xue

ACTIVITIES FY89

The dynamics and thermodynamics of the North Atlantic Gulf Stream region, continue to be explored using an orthogonal curvilinear model which conforms to the oceanic western boundary. Studies indicate that Gulf Stream separation is sensitive to the southwestward slope current and small changes in the inflow salinity. Coupled, single-layered atmospheric and ocean models indicate that the coupling per se increases stream variability and imposes a southward tendency on the separation point. Linear stability analysis together with the primitive equation ocean model are being used to understand the stability characteristics of the Gulf Stream north and south of Cape Hatteras.

The basic framework of a data assimilation scheme has been developed which, initially, will make use of satellite altimetry data and subsequently will also incorporate satellite SST data.

PLANS FY90

Group plans include continued research aimed at understanding Gulf Stream dynamics. It also hopes to achieve a working assimilation and nowcast/forecast system by the end of FY90.

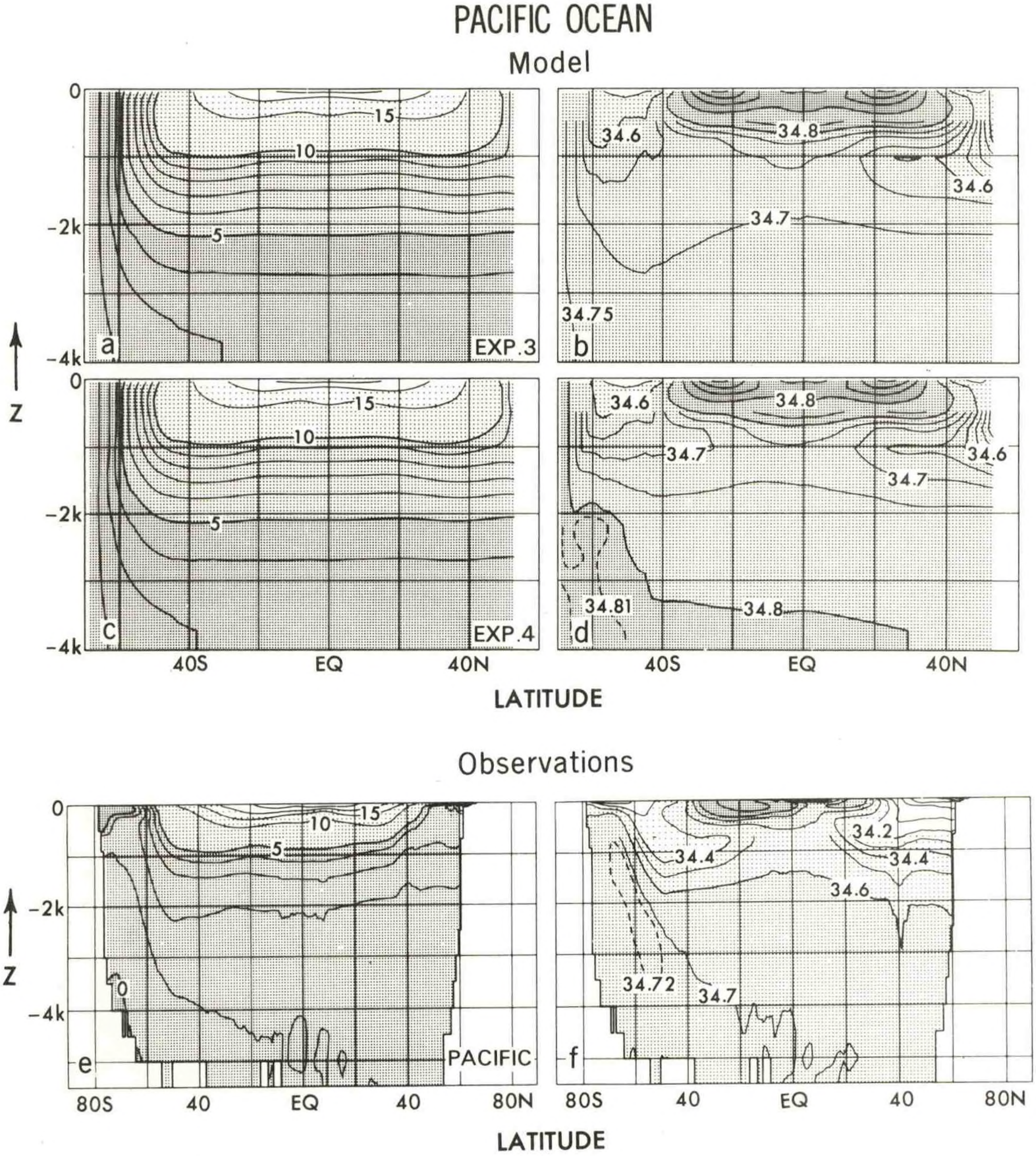


Fig. 4.3. North-south temperature °C (left) and salinity ‰ (right) sections in the Pacific Ocean. Simulations in a World Ocean model with idealized geometry and 200 km x 200 km horizontal resolution are shown in the 4 upper panels. Observations are shown in the two lower panels. The difference between Experiment 3 and Experiment 4 is caused by adding a Mediterranean salinity source to the North Atlantic.

4.7 COUPLED ICE-OCEAN MODELS

S. Hakkinen G. L. Mellor

ACTIVITIES FY89

Previously, one- and two-dimensional ocean models incorporating second-moment turbulence closure coupled to a dynamic, thermodynamic, 3-level ice model has been constructed (kc,kd). In a further development, a one-dimensional model simulation of Arctic ice cover variations for one hundred years is described using long term air temperature data sets (mx). The simulated strong ice-growth years coincide well with the heavy ice years in the Icelandic ice index, which suggests that appearance of heavy ice around Iceland is primarily connected to growing Arctic ice mass, and not to the local hydrographic conditions. Of course, thicker than average multi-year ice export could modify local hydrography considerably.

The development of a three-dimensional version of the model has been completed and applied to simulate deep convective regions. The most important factor in creating a deep convective region is upwelling taking place at the ice edge due to stronger surface momentum flux over the multi-year ice than over the open water for winds parallel to the ice edge. To create individual small scale convective plumes called "chimneys", the existence of bottom topography and barotropic flow provides necessary preconditioning.

PLANS FY90

The three-dimensional model will be applied to the main Arctic basin and the Norwegian-Greenland-Barents Seas. The main thrust of the research will be in simulating the seasonal cycle of the large scale circulation in the Arctic region, and water mass modification in various basins. The different renewal rates will be derived from tracer fields which will be described as prognostic variables in the model formulation. Another objective of the modeling effort is to study lead ice formation as a result of a divergence in the local field or through a passage of an atmospheric front.

4.8 MEDITERRANEAN MODEL

G. L. Mellor M. Zavaratelli

ACTIVITIES FY89

As part of a joint US, Israeli, Egyptian cooperative program, a model of the Mediterranean Sea will be created. The first step has been to collect bathymetric and hydrographic data for analysis on a 1/4° by 1/4° grid.

PLANS FY90

An orthogonal curvilinear model of the Mediterranean will be set up. It will be a nice test of the model in a nearly enclosed basin. Processes such as Levantine intermediate water formation and deep water formation will be studied.

4.9 TURBULENCE CLOSURE MODELING

B. Galperin G. L. Mellor

ACTIVITIES FY89

Calculated results from the turbulence closure model have been compared with laboratory, near-surface flow data (my) which are stabilized or destabilized by rotation or flow curvature. The comparisons are favorable; no adjustment of the basic model constants are required.

5. PLANETARY CIRCULATIONS

GOALS

* To understand the fundamental dynamical processes influencing global circulations.

* To develop numerical models capable of simulating planetary-scale processes in a planetary context.

5.1 PLANETARY CIRCULATIONS

J. L. Holloway G. P. Williams

ACTIVITIES FY89

5.1. Planetary Vortices

Numerical studies of the stability and genesis of the Rossby vortices seen in the single layer system (852) were extended to the full three-dimensional system. These vortices provide a basic model for coherence in GFD flows, in the ocean, and provide a prototype for Jupiter's Great Red Spot and Ovals, Saturn's Ovals, and Neptune's Great Blue Spot. Vortex behavior is found to depend on latitudinal position, balances among five or more dynamical processes, and on the vertical structure of the static stability.

Stable anticyclones exist at all latitudes but under constraints that vary from midlatitudes to low latitudes to the equator. In midlatitudes, stable anticyclones exist in a variety of sizes and balances and merge during encounters. In low latitudes, stable anticyclones exist only when a strong equatorial westerly jet and a subtropical easterly jet are present to limit the growth of the nearby highly-dispersive equatorial modes. At the equator, stable anticyclones exist only when they have a special Hermite latitudinal form and a Korteweg-deVries longitudinal form; they act like solitons among themselves but tend to reduce low latitude vortices. Vortices can be generated by shear instability or by eddy forcing and merging. The range of vertical structures exhibiting this behavior in continuous fluids has been examined using the new model.

To extend vortex theory to continuously stratified fluids, a three-dimensional model was developed that has a fast Poisson solver and weakly dissipative differencing formulation to make it highly accurate and efficient. Auxiliary procedures allow initialization using normal mode structures and analysis.

5.2 Global Circulations

The GCM being developed for planetary studies was converted to the triangular truncation method of spectral representation and its radiative-orbital parametric formulation upgraded. Items requiring generalization to make the model more universal were analyzed.

PLANS FY90

The new three-dimensional vortex model will be applied to examine the influence of location and structure on stability and genesis of Rossby vortices. New analysis procedures will be developed to illuminate the dynamics of three-dimensional vortices. The new circulation model will be developed to examine the role of the various physical factors controlling global circulations.

6. OBSERVATIONAL STUDIES

GOALS

* To determine and evaluate the physical processes by which the earth's climate and the atmospheric and oceanic general circulations are maintained in the mean, and by which they change from year to year and from decade to decade, using all available observations.

* To compare results of observational studies with similar diagnostic studies of model atmospheres and model oceans developed at GFDL and thereby develop a feedback to enhance understanding in both areas.

6.1 CLIMATE OF THE ATMOSPHERE

D. J. Karoly
Y. Kushnir
A. K. Lau
N.-C. Lau
M. J. Nath
A. H. Oort
J. P. Peixóto*
M. Rosenstein

* University of Lisbon, Portugal

ACTIVITIES FY89

6.1.1 Data Processing

A multi-year project of making detailed global monthly-mean atmospheric analyses for the 15-year period May 1973 - April 1988 was completed. This is an important milestone, providing a first and unique opportunity to study global trends over a 30-year homogeneous record (May 1958 - April 1988). Attempts to improve the Southern Hemisphere analyses with additional data from Australia were not pursued further because the limited possible improvements did not justify the required input of resources.

A 40-year set of daily gridded analyses produced by NMC for the Northern Hemisphere extratropics has been acquired for investigating the dynamical interactions between midlatitude atmospheric fluctuations of various time scales. Considerable effort has been spent in unpacking this massive data set, identifying problematic data grids, interpolation, time-filtering, and computation of variance and covariance statistics. The preliminary data handling tasks are nearly completed. The processed data set includes daily analyses of the wind, temperature and geopotential height fields at representative pressure levels in the troposphere and lower stratosphere. This extensive archive will provide an invaluable source of information for future studies on the interrelationships among transient eddies in different portions of the frequency spectrum.

A sample tape with pre-1958 rawinsonde data from R. Jenne at NCAR was successfully unpacked and processed. It shows the feasibility of a new project in cooperation with R. Jenne to extend the analyses back to the year 1950, at least for the Northern Hemisphere. However, the NCAR data are largely missing over Eurasia, requiring additional data sources from other archives.

6.1.2 Angular Momentum, Water and Energy Budgets

Further calculations of the mountain torque, both globally and regionally over southeast California, were completed for individual years and used in a study of the angular momentum cycle in the atmosphere-ocean-solid earth system (11). The mountain torque appears to be an important factor in the seasonal exchange of angular momentum between the atmosphere and the solid earth. The negative torque by the Rocky Mountains on the atmosphere around April may be largely responsible for the shortening of the day in northern summer, and the positive torque by the Himalayas around October for the lengthening of the day in northern winter.

Several improvements and extensions were made to a forthcoming comprehensive publication on the earth's climate system,[1] especially in the chapters on Nature of the Problem, Radiation Balance, Exchange Processes between the Earth's Surface and the Atmosphere, and Interannual and Interdecadal Variability in the Climate System. An overall balance in the presented material seems to have been obtained.

6.1.3 Recent Atmospheric Temperature Variations

Following an earlier limited study of observed radiosonde temperature variations in the troposphere and lower stratosphere for the period 1964-85 (930), the more extensive GFDL data set of global objective analyses of monthly mean temperatures (see 6.1.1) has been examined. Over this period, (1958-1988) a general warming of the troposphere and cooling of the stratosphere were found. The tropospheric warming is most pronounced in the tropics and Southern Hemisphere, with cooling over the North Atlantic and northwest Pacific Oceans. The pattern of warming in the troposphere and cooling in the stratosphere is in agreement with model projections of the effects of increasing concentrations of greenhouse gases in the atmosphere but the horizontal pattern does not agree with most model projections.

A review of data availability and data quality for the Southern Hemisphere stratosphere was completed (mi). This review made use of earlier results (737) addressing the issue of the reliability of satellite temperature soundings of the stratosphere using the GFDL SKYHI model.

6.1.4 Structure and Propagation Characteristics of Summertime Synoptic-Scale Disturbances in the Tropics

The nature of tropical disturbances with time scales of several days has been investigated by statistical analysis of an 8-year set of global gridded data processed at ECMWF. Enhanced levels of synoptic activity have been discerned in several tropical regions, namely, the western Pacific, Bay of Bengal/northern India, northern Africa/Atlantic/Caribbean Sea, and the eastern Pacific. The prevalent disturbances at most of these active regions possess a characteristic wavelike structure with well-defined wavelengths, phase speeds, as well as horizontal and vertical tilts. The occurrence of active disturbances are often accompanied by pronounced changes in the quasistationary, large-scale circulation. Similarities and differences in the behavior of these transient disturbances between various geographical locations have also been documented (mn).

---

[1] Peixóto, J. P., and A. H. Oort, Physics of Climate, American Institute of Physics, New York, NY (in preparation).

PLANS FY90

All available daily pre-1958 upper air data, mainly for the Northern Hemisphere, will be requested from NCAR. Monthly mean station statistics will be produced for the period January 1950 through April 1958. Additional data sets for the Eurasian sector are needed; attempts will be made to arrange a cooperative project with NCDC (National Climate Data Center) at Asheville, N.C. This project aims at extending the GFDL upper air analyses to encompass the 38-year period 1950-1988.

Climatological analyses of the present 30-year data set will be actively pursued. Trend analyses and comparisons with other data sets will be done in joint projects with J. Angell of the NOAA Air Resources Laboratory and D. J. Karoly of Monash University. Efforts to eliminate the effects of ENSO events and volcanic eruptions on the observed atmospheric temperatures will continue.

The water cycle over North America will be investigated in detail in cooperation with C. Milly of USGS/GFDL.

The processed NMC data base will be used to examine the effects of heat and vorticity transports by baroclinic disturbances on the low-frequency variability of the extratropics at various pressure levels. Particular emphasis will be placed on the patterns of three-dimensional geopotential tendency associated with eddy forcing for individual winter months or seasons (see 583).

The interactions between the synoptic-scale perturbations and the semi-permanent background flow field will be examined by computing detailed energy and vorticity budgets. The relationships between these wavelike disturbances and the occurrence of typhoons, hurricanes and monsoon depressions in various tropical regions will be explored.

6.2 AIR-SEA INTERACTIONS

M. Jackson
Y. Kushnir
N.-C. Lau
S. Levitus
M. J. Nath
A. H. Oort
M. Rosenstein

ACTIVITIES FY89

6.2.1 Data Processing and Preparation of a Long-Term Climatology

The preparation of an atlas of climatological fields of the means and variances of various surface marine parameters, such as the sea surface temperature, air temperature, and wind components, relative humidity and cloudiness, has continued. These analyses are based on the entire COADS record from 1870 through 1979.

Individual monthly analyses of specific humidity and cloudiness have been made for the period January 1950 - December 1979 and are being used in a study of the propagation of the ENSO signal over the equatorial Pacific Ocean.

The correlation between world-wide SST anomalies and the ENSO phenomenon is being investigated (kf) to test whether the estimated regional interdecadal differences are significant.

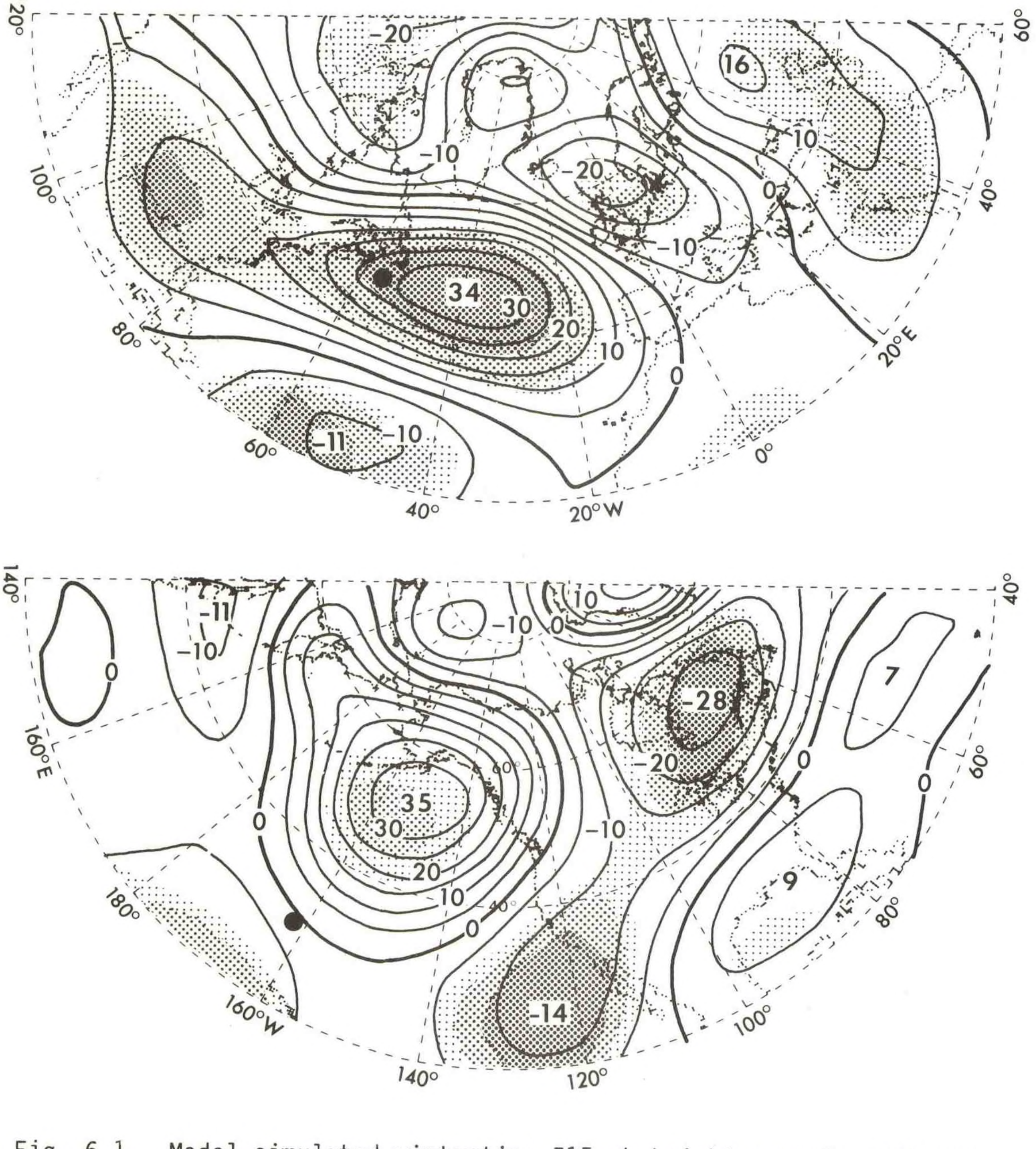
6.2.2 GCM Experiments on the Atmospheric Response to Extratropical SST Anomalies

The atmospheric GCM maintained by the Climate Dynamics Project, has been used for experiments aimed at studying the effect of anomalies in the distribution of sea surface temperature (SST) over the extratropical oceans on the general circulation during winter. The model was integrated for 1350 days in a perpetual January mode with climatological SST's to determine the "normal" response of the atmosphere to such boundary conditions ("control" run). A "typical" wintertime SST anomaly was then added to the climatological distribution of SST over the North Pacific Ocean. A preliminary analysis of the results indicates that the characteristic atmospheric response during a switch-on forcing experiment is significantly different from that during a perpetual forcing experiment. Moreover, only the response during the switch-on experiment compares well with observational evidence and a recent GFDL atmospheric GCM experiment with time-varying SST distribution (ls). These results may indicate that the observed relationship between SST anomalies and the atmosphere should be interpreted as a transient rather than a steady dynamical process. The results may also explain why previous experiments with other GCMs, some with perpetual and some with transient SST anomalies, did not yield consistent results.

The response of the atmospheric circulation to near-global SST anomalies has been investigated by diagnosing a 30-year GCM experiment, with the lower boundary condition at all oceanic grid points between 40°S and 60°N being prescribed to follow the observed SST changes during the 1950-1979 period. The results on the relationships between the model response and SST anomalies located in the North Pacific and North Atlantic have been completed (ls). It was demonstrated that the maritime sites at 45°N, 56°W near Newfoundland, and 31°N, 161°W in the North Pacific are particularly effective in influencing the extratropical flow patterns (Figure 6.1). The spatial distributions of the simulated atmospheric anomalies accompanying oceanic changes in these two locations bear a considerable resemblance to recent observational results. The model diagnoses also reveal a notable reorientation of the storm tracks during the warm and cold SST episodes. Such spatial shifts in the preferred locations of synoptic activity are seen to be associated with movements of the midlatitude rainbelts, and alteration of the eddy forcing of the stationary flow.

6.2.3 Diagnosis of ENSO Phenomena Appearing in Extended Integrations with Air-Sea Coupled GCMs

With the model data supplied by the Climate Dynamics Project, the space-time evolution of ENSO-like episodes in a 140-year experiment with a low-resolution ocean-atmosphere coupled GCM has been studied using extended empirical orthogonal function and regression techniques. It was demonstrated that the model framework for the Pacific Basin admits a westward propagating mode with a characteristic period of approximately 36 months. This oscillatory mode is associated with well-organized changes in sea surface temperature, sea level pressure, surface wind stress, as well as in the flow



120°
60°
-20
16
-10
10
100°
-20
0
40°
-10
34
30
80°
20
10
20°E
0
-11
-10
60°
0°
40°
20°W
140°
40°
10
-11
-10
0
-10
0
7
-28
160°E
-20
0
0
60°
35
30
0
-10
20
180°
10
9
0
80°
160°W
-14
100°
140°
120°

field and heat content of the upper ocean. Some of these changes are reminiscent of observed ENSO events. A detailed heat balance for the top ocean layer has been computed for both the climatological GCM data and for the ENSO anomalies. These computations clearly delineate the relative importance of the different physical and dynamical processes in various portions of the ocean basin during the ENSO cycle.

In collaboration with the Oceanic Circulation Project, the nature of ENSO events occurring in another 30-year integration of a coupled model with a much better-resolved ocean has been examined. Some aspects of the ENSO cycles simulated in this model are quite realistic. The phenomena in this model run have been contrasted with those in the low-resolution experiment. The anomalous ENSO features in the high-resolution model are much more irregular, and notable differences exist between individual events. Propagating oceanic wave modes are more prominent in the higher-resolution run (1s).

Details of the ENSO phenomena in both the high- and low-resolution experiments are available in (1o).

PLANS FY90

Further diagnoses of the North Pacific SST anomaly experiments will be made. These are conducted to understand the dynamical reasons for the different response in the perpetual and switch-on forcing experiments. More experiments are also being planned in order to establish the degree of reproducibility of the results. One set of experiments, now in progress, is performed with a "typical" North Atlantic SST anomaly.

The impact of SST anomalies located in regions other than the central North Pacific and Newfoundland sites will be examined. The linkage between SST anomalies occurring in the North Pacific and North Atlantic Basins will be explored. Lead-lag relationships between SST forcing and atmospheric response will be investigated.

Two comprehensive manuscripts summarizing the ENSO features in the two extended experiments with complex GCM's will be completed. The differences between two simulations will be explored in detail. The GCM results will also be interpreted in terms of simpler mechanistic models.

The nature of anomalous events occurring in the equatorial Atlantic and Indian Oceans of the low-resolution model will be investigated.

6.3 CLIMATE OF THE OCEAN

L. A. Anderson S. Levitus
M. Jackson A. H. Oort

ACTIVITIES FY89

6.3.1 Data Processing

The National Oceanic Data Center (NODC) files containing mechanical bathythermograph (MBT) data, expendible bathythermograph (XBT) data, hydrographic data, and CTD (conductivity/temperature with depth) data complete through the end of 1988 are beginning to be processed. These data will be used to study temporal variability of the thermohaline structure of the world ocean as well as the climatological annual cycle of these parameters.

6.3.2 Climatological Annual Cycle in the Upper Ocean

Studies of the climatological annual cycle of steric sea level are near completion. This work quantitatively describes the annual cycle of steric sea level. The results are being used to aid in the design of algorithms used to process satellite altimeter data for obtaining the signal of ocean surface currents and sea level.

6.3.3 Long-Term Variations in the Thermohaline Structure of the Ocean

A sequence of studies of temporal variability of the thermohaline structure of the North Atlantic Ocean have been completed (932,940,1k,1z,ma). All of these studies deal with changes between the 1955-59 and 1970-74 pentads. Changes in the thermohaline structure at intermediate depths and in the Upper North Atlantic Deep Water are described as well as the corresponding changes in steric sea level and geopotential thickness. Changes in the salinity field in the upper 150m of the North Atlantic have also been found.

6.3.4 Ocean Energetics

Work has now been completed on the available potential energy in the oceans with comparisons of the energy components in the ocean and atmosphere. Details are available in (911).

PLANS FY90

Quality control and analysis of all NODC hydrographic, XBT, MBT, and CTD data files as of 1988 will continue. The quality controlled versions of these data sets will be used in the study of temporal variability of the thermohaline structure of the world ocean as well as describing the climatological annual cycle.

The generation of available potential energy in the ocean due to density changes induced by atmospheric heating, precipitation, and evaporation patterns at the surface will be investigated as a first step to obtaining a more complete picture of the energy cycle in the oceans. The results will be compared with the energy cycle in the atmosphere.

7. HURRICANE DYNAMICS

GOALS

* To understand the genesis, development and decay of tropical disturbances by investigating the thermo-hydrodynamical processes using numerical simulation models.

* To study small-scale features of hurricane systems, such as the collective role of deep convection, the exchange of physical quantities at the lower boundary and the formation of organized spiral bands.

* To investigate the capability of numerical models in the prediction of hurricane movement and intensity.

7.1 EXPERIMENTAL HURRICANE PREDICTION

M. A. Bender   R. J. Ross
Y. Kurihara   R. E. Tuleya

ACTIVITIES FY89

7.1.1 Model Conversion

Conversion of the GFDL hurricane research model to a real data mode has significantly progressed. The converted model, called Multiply-Nested Movable Mesh (MMM) model, is now in a working status. It can be run with a triple nest with finest horizontal resolution of 1/6 degrees and 18 sigma levels compatible to the NMC/MRF model, using NMC T80 data and Navy high resolution topography. The model can also be run at lower horizontal and vertical resolutions and also with other initial data sets such as FGGE IIIB.

7.1.2 Experimental Prediction of Gloria

Experimental predictions of Hurricane Gloria, 1985, were successfully performed in cooperation with NMC where all necessary data sets were prepared. In an Experiment G25I, the MMM model was integrated for 72 hours, starting from the NMC T80 analysis for 00 UTC 25 September 1985 without initialization and using the NMC T80 forecast for the time-dependent lateral boundary forcing. The overall performance of the MMM model is quite promising. The predicted track of Gloria is compared in Figure 7.1 against the best track determined by the National Hurricane Center and the official forecast by NHC. The model was able to simulate significant acceleration of the storm's movement after 48h. The forecast error at 72h is 156 km in the MMM model as compared with 480 km for the NHC forecast. Good correspondence was noticed between the storm track and the field of deep layer mean wind. It is encouraging that the outer structure of the model hurricane resembled that of the observed one. Shown in Figure 7.2 is the distributions of the low level maximum wind in the model during the passage of Gloria as well as the observed values shown in circles. The model results show the observed features such as the abrupt decrease on the land across the coast and strong winds at a large distance east of the storm track. The observation indicated the presence of a band of precipitation ahead of the Gloria center after 60h. This feature appeared in the model integration. The distribution of accumulated total precipitation in the model exhibited effects of mountains on the rainfall and favorably compared with the observations. It is interesting to note that, both in the model and observations, a significant structural change took place in coincidence with an accelerated movement of the storm. In this experiment, the model could not generate the banded structure in the interior of the storm.

In order to investigate issues concerning the spin-up of the model storm and its impact on the prediction, experimental predictions are under way starting at two earlier times, 12 UTC 22 September and 00 UTC 24 September.

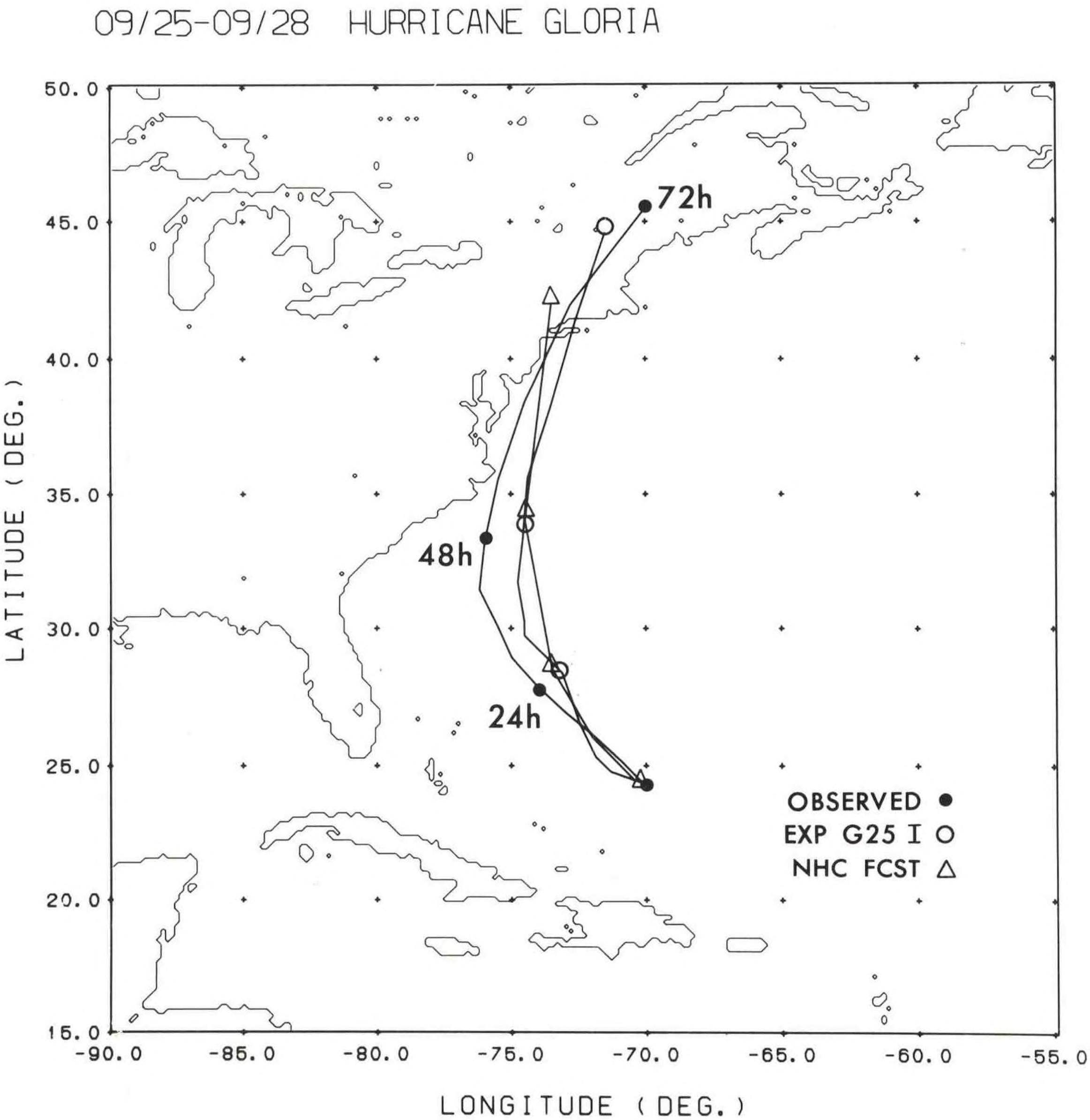


Fig. 7.1 Tracks of Hurricane Gloria for 72 hours after 00 UTC 25 Sept 1985. Positions at 24h interval are plotted on the observed track (the best track determined by the National Hurricane Center) (black circles), for the Experiment G25I with the MMM hurricane model at GFDL (open circles) and for the NHC official forecast (triangles), respectively. Note the accelerated movement after 48h.

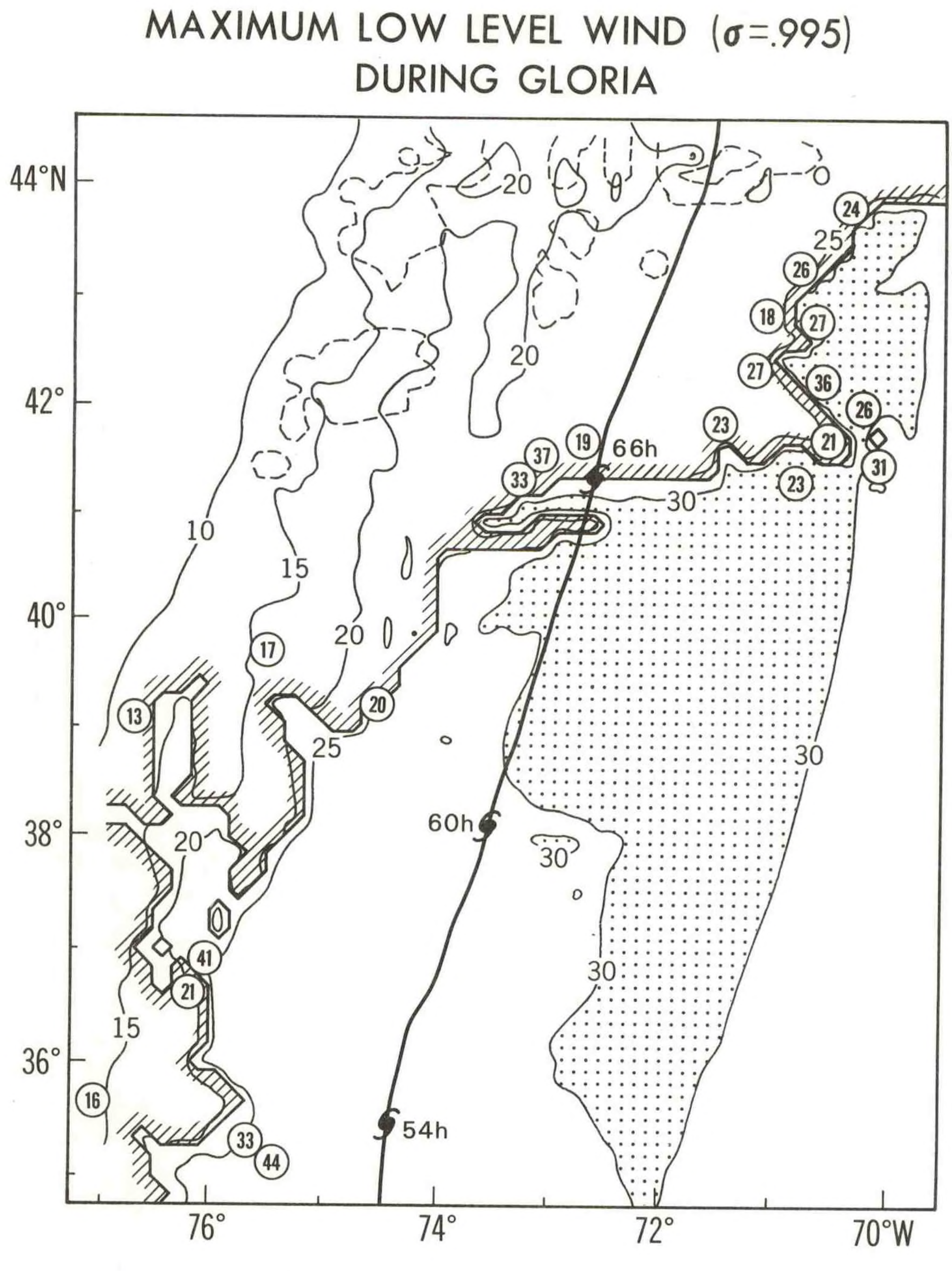


Fig. 7.2 Distribution of the predicted maximum low level wind (σ=.995) during the passage of Hurricane Gloria in the Exp. G25I (in m s^{-1}). Solid lines are the contours drawn every 5 m s^{-1} and areas above 30 m s^{-1} are shaded. Heavy solid lines with short hatches attached indicate the shorelines. Dashed lines are the 500 and 1000 m contours of mountains. The numbers in circles are the observed values (in m s^{-1}).

7.1.3 Sensitivity

A number of experiments were conducted to investigate the sensitivity of the model forecast to the physical parameters and the computational schemes. The storm track after 48 hours was influenced largely by the grid resolution and the data set used for lateral boundary forcing. It was found that sufficient resolution, i.e., at least one degree, was required for making accurate prediction while maintaining Gloria for 72 hours in the model. The forecast track was noticeably degraded in coarse horizontal and vertical resolution model experiments. When the lateral boundary forcing was kept fixed to the initial values during the integration, the accelerated movement of Gloria after 48h was not predicted, perhaps due to the failure in positioning of the trough which advanced to the east coast during the experiment period. The choice of values for some model physics parameters affected the storm track through a subtle impact on the momentum and heat budgets of the model.

High resolution representation of mountains and coast lines was certainly required for the improvement of prediction of the surface wind and precipitation. As expected, the surface wind over the land was sensitive to the value of the roughness length. When the ground wetness was specified to a high value, the precipitation over the coastal areas increased and the atmosphere over the continent was noticeably moistened. Model integrations were carried out to examine the effect of the 4th-order horizontal diffusion scheme in comparison to the non-linear diffusion scheme. The evaluation of the results was not easy because of disposable parameters involved in both schemes, although the former tended to produce less noisy fields.

PLANS FY90

Experimental prediction of Hurricane Gloria will be continued with an emphasis put on the issue of vortex spin-up. Also, the experiments may be conducted for other cases such as Hurricane Gilbert.

Study on the prediction of forecast skill will be planned. Some preliminary experiments may be initiated.

7.2 GENESIS OF TROPICAL CYCLONES

Y. Kurihara   R. E. Tuleya

ACTIVITIES FY89

7.2.1 Budget Analyses

The heat, vorticity, and momentum budget analyses were conducted to emphasize the contrast between the developing case of Hurricane David, 1979, and a non-developing disturbance occurring a week earlier. Both cases were rather well simulated previously (871).

At 30h into the integrations, the two systems were similar to each other in many ways. However, the similar appearance did not yield nearly the same evolutions. The vorticity and heat tendencies above the disturbance center exhibited sharp contrast due to differences in magnitudes of and correlations among quantities. For example, the sum of the effects of vertical motion and latent heat release caused a positive tendency in the temperature equation, meaning the formation of a warm core in the case of David, while it was negative in the non-developing case. It was also discovered that the developing system moved along with the easterly wave, with its center contained in the trough area. On the other hand, the non-developing disturbance was uncoupled from and lagged behind the area of strong wind which was associated with the easterly wave trough.

7.2.2 Sensitivity

It was found from additional experiments that the David simulation results were rather insensitive to the change of sea surface temperature from analyzed Sept. 1979 to climatological values. In the non-developing case, a 10% increase of relative humidity did not lead to storm development. Apparently, the flow field is quite important in determining whether a disturbance will develop or not.

PLANS FY90

The results of sensitivity experiments as well as those of Southern Hemisphere genesis cases previously simulated will be further analyzed.

Some case studies may be attempted with the revised FGGE IIIB data sets of GFDL and ECMWF.

7.3 MODEL IMPROVEMENT

M. Bender	Y. Kurihara
M. DiPaola	R. J. Ross
C. L. Kerr*	R. E. Tuleya

* CRAY Research, Inc.

ACTIVITIES FY89

7.3.1 Initialization Scheme

Continued effort was made to formulate an initialization method for the MMM hurricane model on the basis of bounded time tendencies. With the use of the results from the previous year, a scheme to initialize the wind in the planetary boundary layer was formulated and tested. It consists of two steps: the computation of wind component in the Ekman-inertia regime and that in the isallobaric regime. The second step is required if the wind field at the top of the boundary layer is non-divergent. In this case, the acceleration, i.e., the sum of time tendency and inertia terms, is appropriately split into a part associated with isallobaric wind and the remaining part related to the Stokes regime. When the wind at the boundary layer top has a divergent component, the first step yields good approximation of the wind in the boundary layer.

7.3.2 Time Integration and Analysis

A new technique of open lateral boundary forcing which had been developed in the previous year was successfully implemented in the MMM hurricane model and yielded satisfactory performance (lw).

From the consideration of a possible problem of time integration efficiency, the model was given flexibility in the longitude-latitude grid configuration. A better scheme to suppress two-grid scale noise during the model integration was also investigated. The method of smoothing-desmoothing could produce a rather sharp filter at two-grid scale wave length. Also, the use of height correction was effective for removal of noise from the surface pressure field.

The readability of model code was greatly improved by an extensive revision of commenting. Various analysis programs were prepared to considerably increase the analysis capabilities of the experimental results.

PLANS FY90

The initialization scheme will be tested with the real data set of Hurricane Gloria.

An effort will continue to implement an advanced radiation code into the hurricane model. Also, formulas may be established to relate the surface roughness and the ground wetness to the climatological data of vegetation type.

8. MESOSCALE DYNAMICS

GOALS

* To produce accurate numerical simulations of mesoscale processes in order to understand what role synoptic scale parameters play in their generation and evolution.

* To understand the dynamics of mesoscale phenomena and their interaction with larger and smaller scales.

* To determine practical limits of mesoscale predictability by means of sensitivity studies on numerical simulations of mesoscale phenomena.

8.1 THE GENERATION OF CYCLONES

I. Held L. Polinsky
N. Nakamura** S. Solman *
I. Orlanski

*Center for Ocean and Atmospheric Research
Buenos Aires, Argentina

**University of Washington

ACTIVITIES FY89

8.1 1 The Life Cycle of Cyclone Waves

Studies have been completed to investigate the three-dimensional characteristics of the life cycle of baroclinic instability for an idealized basic state. Both meridional mixing of the temperature gradient and enhancement of the static stability by the growing wave act to stabilize the environment and thus lead to the saturation of the wave amplitude. It was confirmed through an analysis of the energy budget that the enhancement of the static stability increases its importance relative to the horizontal mixing as the horizontal scale of the wave decreases (or the characteristic Richardson number is reduced) (mj).

Presently, the results of the three-dimensional evolution of baroclinic waves in a beta plane are being extended to spherical geometry and realistic mean flows. The GFDL world ocean model has been converted to an atmospheric model. This model has the advantage of treating the topography explicitly and is more appropriate for simulations around the Antarctic and the Andes. The integration for baroclinic waves within a westerly flow shows eddy activity splitting the initial jet into two branches: one in the subtropical region and the other in the subpolar latitudes. These results are similar to the observed mean winds over the South Pacific Ocean.

PLANS FY90

The analysis of baroclinic waves development will continue. Different initial conditions will be studied.

8.2 COASTAL CYCLOGENESIS

J. Katzfey I. Orlanski

ACTIVITIES FY89

8.2.1 High Resolution Presidents' Day Cyclone Simulations

Analysis of the dynamics for the Presidents' Day cyclone of 18-19 February 1979 was completed (845, 865) using the 18-level, 50-km horizontal resolution Limited-Area HIBU Model (LAHM). The coastal and explosive stages of development were successfully simulated by the model. First, strong ageostrophic onshore flow across the coastal front and the associated direct circulation provided energy for the coastal storm to intensify. In the second stage, in which explosive development occurred, the advection of cool, dry air associated with a short wave approaching from the west over the warm, moist air along the coast caused weak static stabilities. As the mid-tropospheric wave merged with the low-level baroclinicity, explosive deepening ensued and heavy precipitation developed west and north of the storm.

8.2.2 GALE Simulations

Successful LAHM simulations have been completed for the period 25-28 January during the GALE IOP-2 (Genesis of Atlantic Lows Experiment/Intensive Observation Period 2). During this time period, three cases occurred along the East Coast that illustrate the different processes by which cyclones are generated. In one case, initial weak cyclogenesis developed as a shallow baroclinic wave along the coastal front. Surface moisture fluxes aided the intensification of the storm by destabilizing the lower troposphere, thus causing stronger vertical motions. As the storm moved over land, the source of moisture was removed, and the storm dissipated. The first explosive cyclogenesis event during the period was delayed until the upper-tropospheric wave interacted with the low-level baroclinicity and vorticity. The second case of strong cyclone development occurred west of the surface front as the upper tropospheric wave and low-level baroclinicity intensified together.

It is well known that the deformation field associated with a baroclinic wave can force frontogenesis in the lower troposphere. However, the current results suggest that pre-existing low-level baroclinicity can play an important role in the timing and location of cyclogenesis. It is suggested that low-level baroclinic development without upper-level development is not conducive to explosive cyclogenesis. In the two explosive cases, an upper-level trough and low-level baroclinicity were required, although the conditions by which the surface baroclinicity was established were different.

8.2.3 Sensitivity Experiments

In all of the cases of coastal cyclogenesis analyzed, latent heating was crucial to the development. The weaker effective static stability associated with moist ascent allows more intense cyclogenesis. Sensitivity studies of surface heat and moisture fluxes indicate that surface latent heat fluxes are very important for the coastal cyclone cases studied. Simulations without surface moisture fluxes were similar to those without latent heating, indicating that most of the moisture producing the heating originated at the surface. Although surface fluxes of heat are initially important for the intensification of the coastal front, they decrease in importance with time. Coarse initial data had a negative impact on the development of mesoscale features within a high-resolution model during the first 12 hours.

PLANS FY90

The dynamics of explosively developing coastal cyclones will continue to be investigated. Sensitivity studies will be performed in order to determine the factors important for cyclone development. The effect of higher resolution initial data will evaluated.

8.3 SOUTHERN HEMISPHERE CYCLONES

J. Katzfey C. Menendez*
M. Marino* I. Orlanski

* Center for Ocean and Atmospheric Research (CIMA)
Buenos Aires, Argentina

ACTIVITIES FY89

8.3.1 Cyclogenesis in the South Pacific

The strong cyclonic development in the Southern Pacific for the period of 4-5 September 1987 has been successfully simulated using the GFDL/LAHM. Cyclogenesis occurred as the jet stream near 40°S migrated poleward and merged with the jet stream near 60°S. Development appeared to have a large barotropic component, since the vertical wind shear in the mid-troposphere was small.

Many innovative diagnostics of this storm have been completed. Trajectories within the simulation during the first 24 hours are shown in Figure 8.1. The air originating in mid-latitudes at 850 mb flowed poleward and rose rapidly to near 350 mb by 24 hours, with some parcels flowing eastward onto the ridge and others flowing westward around the low. Air originating west and north of the low, moved equatorward and downward. The parcels originating in the ridge east of the developing wave moved equatorward and subsided as they approached the low east of South America over the Atlantic.

Several tracer experiments have been performed using wind data from the simulation stored every 9 minutes. Tracer diagnostics of potential temperature show two regions of diabatic heating, one in the mid-troposphere associated with the moist ascent within the baroclinic wave and a second in the upper troposphere associated with weak static stability formed by differential horizontal advection in the vertical. Tracer analysis of mixing ratio confirmed the regions of diabatic heating. The quasi-conservative nature of the potential vorticity was demonstrated.

In order to isolate the barotropic and baroclinic contributions, vertical-mean values of the vorticity equation and the energetics have been computed. Large poleward transport of heat occurs as the storm develops, primarily by the vertical-mean (barotropic) flow. Baroclinic conversion of potential to kinetic energy is occurring locally as the storm develops, but the potential energy appears to be the result of larger-scale barotropic instability. The results suggest that the baroclinic cyclone development is embedded within an unstable large-scale barotropic wave.

8.3.2 The Effect of Cyclones on Ozone Transport

A study is being carried out on the impact of cyclone activity on ozone transport in high latitudes of the southern hemisphere. This study suggests that cyclonic activity in the periphery of Antarctica may expand the low ozone area over the polar regions to sub-polar latitudes. The tracer distribution in the model is initialized with the time-mean zonally-averaged ozone

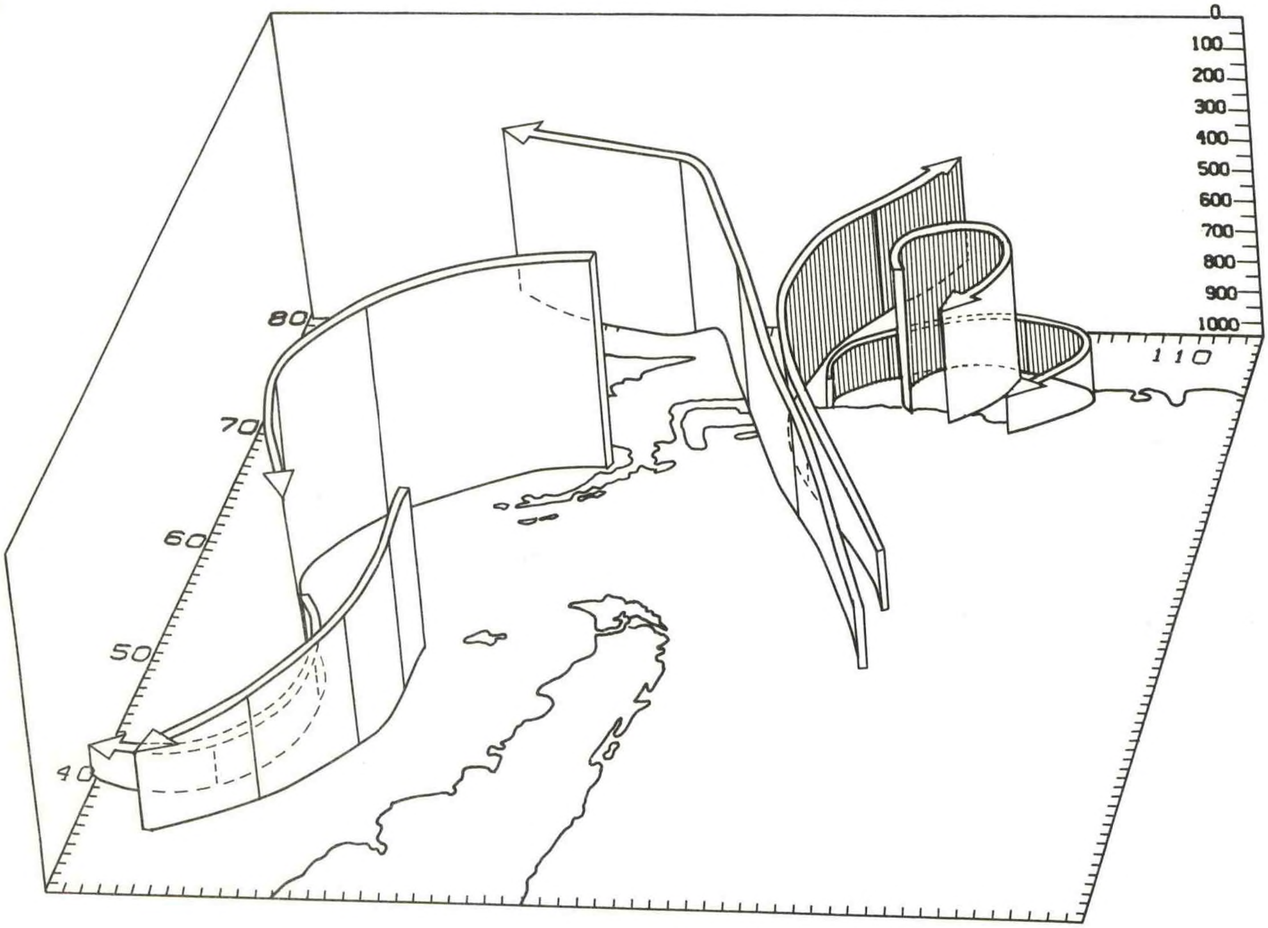


Fig. 8.1. Three dimensional trajectories computed from data saved every 6 min. during the first 24 hours of the model simulation. Lower line indicates vertical projection of parcel position onto the surface. The vertical lines are located every 6 hours. The main cyclone is evident west of the Palmer Penninsula while a cut-off low is located east of South America.

distribution and is integrated for 24 hours. Comparison of the vertically integrated ozone content of the model simulation with the observed ozone content corresponding to the same time show a striking similarity. A minimum in the ozone content exists over the Palmer Peninsula with low values extending equatorward along and ahead of the cold front where low ozone air in the low troposphere moves poleward and upward. Maxima of ozone content are located near the ridges in mid-latitudes through subsidence and convergence of ozone transport in upper layers.

PLANS FY90

Cases of Austral cyclogenesis will continue to be investigated. Analysis of how cyclogenesis within a limited-area domain relates to the planetary scale will be investigated. Sensitivity studies will be carried out to identify the factors that are important for their development.

8.4 CHARACTERISTICS OF CONVECTION WITHIN MESOSCALE SYSTEMS

R. Hemler
J. Katzfey
F. Lipps
I. Orlanski
B. Ross

ACTIVITIES FY89

8.4.1 Convective Parameterization

A study is continuing in order to test the effect of different convective parameterizations on the accuracy and distribution of precipitation amounts and the vertical redistribution of heat and moisture. The parameterizations currently under study include: moist convective adjustment, Arakawa-Schubert convective parameterization, explicit convection, and Betts' convective scheme.

Results indicate the Arakawa-Schubert scheme gives the best results, both in spatial distribution and intensity of the precipitation. However, only wintertime coastal cyclogenesis cases have been analyzed to date.

8.4.2 Squall Lines

Research has continued, in collaboration with the GFDL Convection Group, to study the dynamics of convective systems using a nested system of a cloud-scale model within a mesoscale model. Analysis of the SESAME I (Severe Storms and Mesoscale Experiment) case demonstrates that the cloud-scale model produces important detailed features of the squall line; however, the development time and initial location of the system in the nested model are still the same as occurred in the host mesoscale model.

PLANS FY90

Further investigations will be made of convective parameterizations in the GFDL/LAHM.

The nested cloud/mesoscale model study of the SESAME-I squall line will be completed.

8.5 MESOSCALE FOUR-DIMENSIONAL DATA ASSIMILATION

I. Orlanski B. Ross
L. Polinsky

ACTIVITIES FY89

An on-going numerical study is being carried out to investigate techniques for assimilating standard synoptic and nonstandard asynoptic mesoscale data into limited-area numerical models. This study employs fraternal-twin model simulations of the President's Snowstorm period, February 18-20, 1979, using intermittent insertion of simulated observed data into the MAC/BES (Meso-Alpha Scale/Meso-Beta Scale) model. The use of fraternal-twin "sounding" data in these experiments are shown in the results to produce a very realistic response of the model to the inserted data, thus demonstrating the value of this approach as an evaluation tool.

Experiment results indicate a substantial improvement in the analysis produced by the dynamic assimilation procedure over corresponding static analyses. Initial tests were performed with a random distribution of observational error throughout the model domain. Further experiments are now underway in which error magnitudes are increased within regions of low Richardson number so as to simulate the correlation of observational errors with areas of low stability.

PLANS FY90

The data assimilation experiments using fraternal-twin models will be completed.

8.6 MODEL DEVELOPMENT

J. Katzfey L. Polinsky
I. Orlanski B. Ross

ACTIVITIES FY89

The GFDL/LAHM has continued to be improved. Implementation of E4 physics and more sophisticated and efficient radiation scheme has been started. The analysis package has been greatly expanded. The new NMC eta-coordinate model is under development. This model includes Mellor-Yamada 2.5 turbulence closure, Betts convection, and the ability to run in either sigma or step-mountain ('eta') coordinates.

Extensive changes were made to the data assimilation version (Section 8.5) of the MAC/BES model in order to improve its computational and I/O efficiency. A number of different codes were also developed in support of the assimilation effort in order to prepare initialization fields and to analyze model results.

PLANS FY90

Improvements in the LAHM will continue through vectorization and more sophisticated physics. The LAHM and the new NMC model will be compared for speed and accuracy. In addition, the eta-coordinate feature will be tested.

9. CONVECTION AND TURBULENCE

GOALS

* To develop and improve three-dimensional numerical models capable of simulating dry and moist thermal convection in the atmosphere.

* To understand the dynamics of deep moist convection and its role in the vertical transfer of heat, moisture, momentum and atmospheric tracers.

* To develop numerical models capable of simulating turbulence in homogeneous and stratified fluids by simulating the large turbulent eddies directly and by testing various parameterizations of the subgrid-scale flow.

9.1 SIMULATION OF MOIST CONVECTION

R. S. Hemler
F. B. Lipps

ACTIVITIES FY89

9.1.1 Simulation of an African Squall Line

Three-dimensional numerical simulations have been carried out for the African squall line observed on 22 June 1981 during the COPT 81 (Convection Profonde Tropicale) experiment. This line had a lifetime of at least 30 hours during which it propagated to the west with a mean speed of 14 m s^{-1}. The line consisted of a leading edge with warm rain cells followed by a weak echo region and then a long trailing anvil. A significant feature of this line was the 3 km depth of the strong rear-to-front flow behind the leading updraft. The passage of the gust front was associated with a 4K temperature drop and a 2 mb pressure rise. The total rainfall was approximately 2.7 cm.

The three-dimensional simulations of this line have been performed using the present numerical model with/without a simplified ice bulk cloud physics. The present numerical scheme and the simplified ice bulk cloud physics are described in GFDL A88/P89. The basic ingredients in the ice bulk cloud physics are the inclusion of snow and cloud ice which are expected to be relevant for the long trailing anvil.

These calculations are for a Cartesian model domain 256 km in length, 16 km in width and 20 km in vertical extent. To simulate squall line convection, periodic lateral boundary conditions are applied along the side boundaries of the domain. The convection is initiated by a horizontally variable cooling rate applied during the first 8 minutes near the eastern end of the channel. For both model simulations, integrations were continued for a total time of 6 hours.

A primary conclusion is that the basic characteristics of both calculations are similar. Both simulations show a typical squall line structure with two-dimensional features at low levels and increasing three dimensionality with height. At 5 km both lines are broken in appearance and at 10 km a single cell of 8 km diameter is present. The major effect of the ice phase is the existence of stronger maximum vertical velocities in the trailing anvil during the last 2 hours of the simulation. Thus a larger area with rainwater below the anvil occurs when the ice phase is included. The mean propagation speed for both lines is near 12.25 m s^{-1}. Both models give a 3.5K temperature drop behind the gust front and peak values of surface rainfall greater than 2 cm.

A deficiency of the present simulations is that the convection is weaker than observed. This is seen perhaps most clearly in the pressure rise behind the front. Both simulations give a pressure rise of 0.5 mb whereas the observed was 2 mb. This result is similar to that reported in GFDL A88/P89 last year for the two-dimensional calculations using a channel length of 512 km.

9.1.2 Scale Analysis for Deep Moist Convection

The scale analysis for deep moist convection in the troposphere (516, 691) has been reexamined. The anelastic set of equations obtained from the scale analysis conserves energy and give an accurate solution for the frequency of gravity waves in an isothermal atmosphere. These two aspects of the present equations are superior to the corresponding properties of the anelastic equations most commonly used to simulate deep moist convection.

PLANS FY90

The analysis of the two three-dimensional simulations of the African squall line will be completed. The present results will be compared with the earlier two-dimensional calculations.

A long term goal is to include orography in the collaborative effort with the Mesoscale Group (866). For this purpose, a numerical model with compressible equations will be developed and tested. This alternative removes the need of solving a Poisson equation with horizontally-varying coefficients, which is required when orography is included with the anelastic set of equations.

9.2 STATISTICS OF MOIST CONVECTION

R. S. Hemler
F. B. Lipps

ACTIVITIES FY89

Numerical simulations of a continental and a tropical maritime squall line have been carried out using the present numerical model. A detailed analysis of in-cloud and out-of-cloud vertical fluxes of mass, heat, water vapor and momentum have been performed following the similar analysis given in (742). The intent of obtaining these statistics for both cases is to provide relevant information for cumulus parameterization in large-scale models. The statistics were calculated during the last 2 hours of the 4-hour integrations when well-defined squall lines were present.

Vertical fluxes of heat, moisture and momentum were virtually negligible in the environment compared with values associated with the squall line. The mass flux was a factor of 5 larger in the line than in the environment where subsidence took place. These features of the convection were valid for both types of squall lines.

A significant difference between the two lines is that stronger convection was associated with the continental line. Maximum vertical velocities were generally between 20-25 m s^{-1} for the continental line and between 10-15 m s^{-1} for the tropical maritime line. In addition, the values of upward mass flux for the continental line were generally a factor of 3 larger than for the tropical maritime line.

Observational data for the disturbance momentum fluxes associated with tropical maritime squall lines have been obtained by LeMone et al.[1] For a coordinate system in which the line propagation speed is positive, they find that the vertical flux of horizontal momentum normal to the line is negative. The present data for both types of squall lines are in agreement with this conclusion.

LeMone et al.[2] also find that the vertical flux of horizontal momentum parallel to the line is downgradient. The present data agree with this conclusion below cloud base. Above cloud base, however, the present analysis indicates that the gradient of the vertical flux of horizontal momentum parallel to the line correlates with the negative vertical wind shear parallel to the line. This latter conclusion should be taken as tentative; the unrealistic periodic boundary conditions on the lateral side boundaries of the domain are a reason for concern.

PLANS FY90

The analysis of the present statistics for squall line convection will be completed and a thorough comparison of the data for the two lines will be made.

A similar statistical analysis will be carried out for isolated convective cells for both continental and tropical maritime convection.

9.3 PASSIVE TRACER STUDY

R. Hemler F. B. Lipps
H. Levy II J. D. Mahlman

ACTIVITIES FY89

9.3.1 Calculations for Three Types of Tracer

Three-dimensional calculations for an insoluble tracer, a fully soluble tracer and a partially soluble tracer have been carried out using the continental and tropical maritime squall line models described in Section 9.2. For the partially soluble tracer, thermodynamic equilibrium determines the partition of the tracer between the atmosphere and the cloud water droplets. SO_2 gas, with a simplified cloud and rain water chemistry, is the partially soluble tracer. For all three types of tracer, the initial distribution is a constant mixing ratio (normalized to unity) in the surface boundary layer and zero above. In the continental calculation the surface boundary layer is 1.8 km deep and in the tropical maritime case it is 0.875 km deep.

The horizontal-average vertical distributions for all three tracers are shown in Figure 9.1 for both simulations at 4 hours. In either simulation, the only tracer to reach the upper atmosphere in significant amounts is the insoluble tracer. Much more of the insoluble tracer reaches upper levels in the continental simulation than in the tropical case. This corresponds with

---

[1]LeMone, M. A., G. M. Barnes, and E. J. Zipser, 1984: Momentum Flux by Lines of Cumulonimbus Over the Tropical Oceans, Journal of the Atmospheric Sciences, 41, 1914-1932.

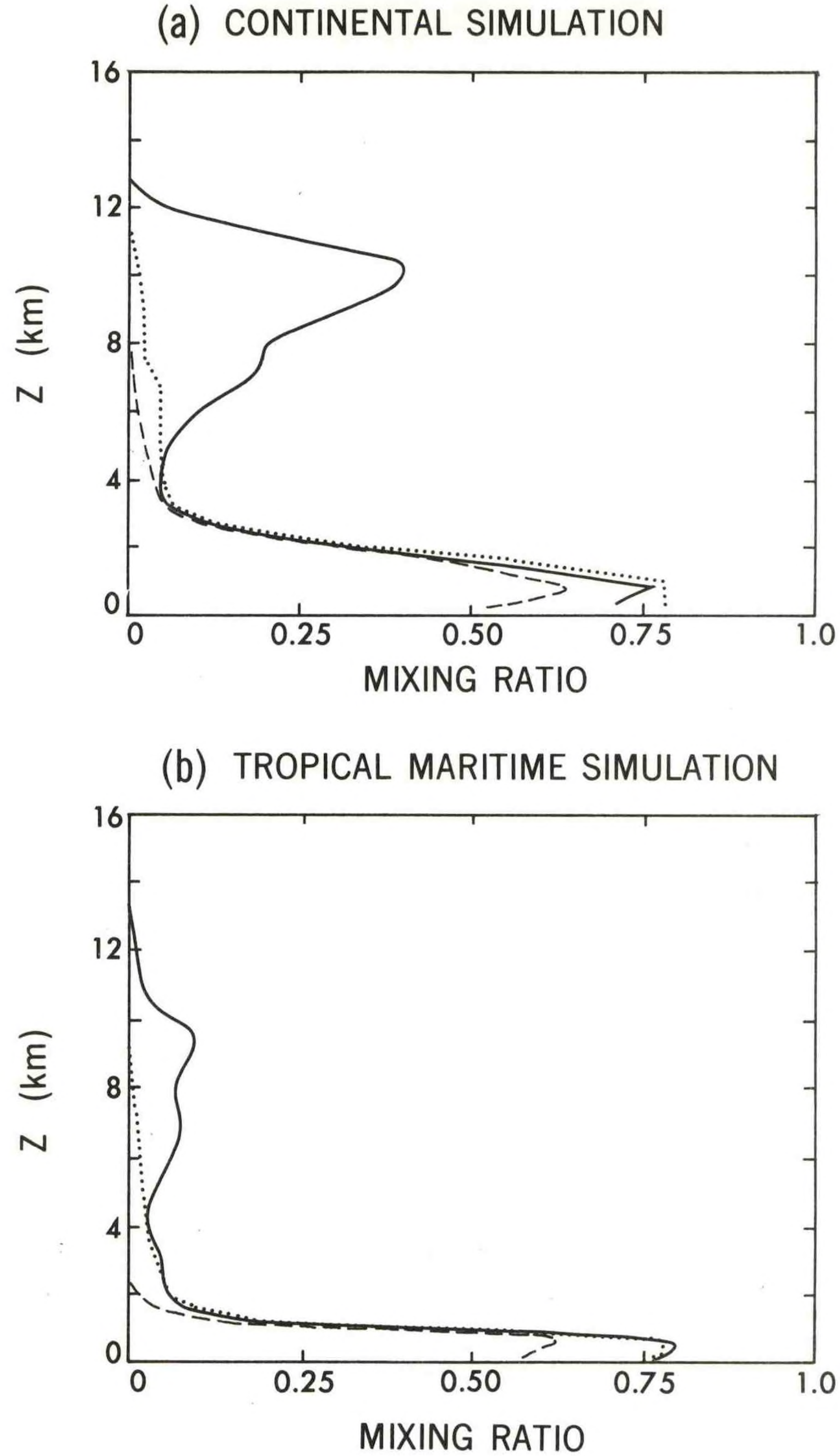


Fig. 9.1 Vertical distribution of tracer mixing ratios at 4 hours: insoluble tracer (solid line), soluble tracer (dashed line) and partially soluble tracer (dotted line). Abscissa represents normalized tracer mixing ratio. (a) Continental simulation. (b) Tropical maritime simulation.

the stronger vertical velocities and the larger vertical mass flux for the continental case (Section 9.2). Only a small amount of the partially soluble tracer rises and remains in the upper levels whereas virtually none of the fully soluble tracer is found at 10 km or above. Thus Figure 9.1 indicates that rainout is a very efficient mechanism for preventing boundary layer tracers from reaching the upper levels.

A related topic is the mean amount of tracer, relative to the initial total amount in the surface boundary layer, that rises through the 6 km vertical level per hour. For the continental (tropical) insoluble tracer 14.5 (5.7) per cent per hour passes through this level which is consistent with the data in Figure 9.1. For the soluble tracer very small amounts of tracer pass through this level. For the partially soluble tracer about three-tenths of the amount corresponding to the insoluble tracer passes upward through this level associated with the cloud water and air; however, approximately two-thirds of this amount falls downward, back through this level associated with the falling rain water.

9.3.2 Stratospheric Tritium Source

The project undertaken to study the transfer of tritium from the stratosphere to the ocean surface has been continued using the present warm rain cloud model. Observational data suggest that one-third of the tritium entering the ocean is associated with rain water and two-thirds with vapor diffusion.

A key factor in determining the downward flux of tritium is the speed at which tritium is able to escape from falling precipitation. As discussed in GFDL A88/P89, tritium escapes much more freely from rain water than frozen precipitation. For the tritium, frozen particles are assumed to exist above the freezing level at 4.5 km and rain water below this level.

Calculations are carried out for four different initial vertical distributions of tritium mixing ratio. A hyperbolic tangent form is used, centered at 14.1 km (tropopause). These calculations, denoted by Cases 1-4, correspond to four half-widths (0.5 km, 1.0 km, 2.0 km and 4.0 km) for the hyperbolic tangent profile. Two-dimensional (64 km long x 25 km high) numerical integrations of 24 hours duration have been performed for these four cases using a tropical maritime base state. The convection is initiated by a boundary layer moisture disturbance which is applied during the first two hours and again between four to six hours into the integration.

For all four cases the deposition of tritium into the ocean by rainout stopped at 7 hours, when precipitation due to the second boundary layer forcing stopped. Deposition of tritium into the ocean by vapor diffusion, however, continued for the full 24 hours. These aspects of the tritium calculation for Case 4 are shown in Figure 9.2. At 12 hours the ratio of deposition by vapor diffusion to deposition by rainout is 0.95. Due to the continued deposition by vapor diffusion, as seen in Figure 9.2a, this ratio is 1.67 by 24 hours. In Figure 9.2b it is seen that the boundary layer has a significant amount of tritium at the beginning of the calculations. The rain events increase the tritium in the boundary layer, but by the end of the integration the distribution looks similar to early in the run.

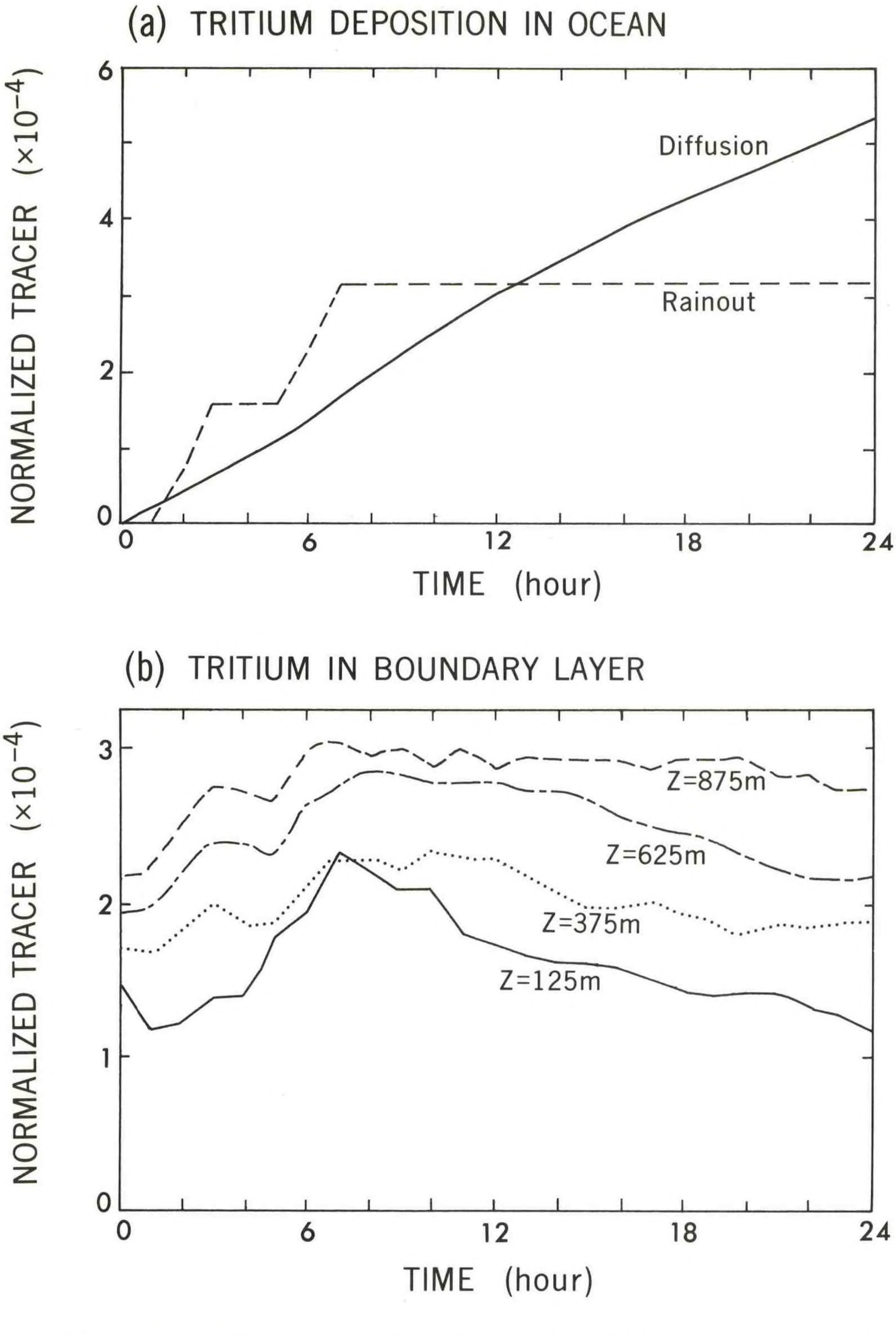


Fig. 9.2 Tritium time history for Case 4. (a) Tritium deposition into ocean by vapor diffusion (solid line) and by rainout (dashed line). Ordinate shows tritium deposition normalized by the initial total tritium in the atmosphere. (b) Normalized values of tritium in the boundary layer at z=125 m (solid line), z=375 m (dotted line), z=625 m (dash-dotted) and z=875 m (dashed-line).

For Case 4 the rate of total deposition of tritium into the ocean corresponds to removing the total atmospheric tritium in 3.25 years while the boundary layer distributions of tritium are similar near the beginning and the end of the calculation. These appear to be realistic. In contrast, Case 1 has characteristics very similar to the calculations discussed in GFDL A88/P89 in which an unrealistically small fraction of the total atmospheric tritium was deposited into the ocean after 24 hours.

Cases 2 and 3 are intermediate in character to the two cases discussed here.

PLANS FY90

Similar calculations will be carried out for the three types of tracers for isolated convective cells for both continental and tropical maritime convection.

The analysis of the four calculations for the stratospheric source of tritium will be completed.

Similar calculations will be carried out for a stratospheric source of a fully soluble tracer and an insoluble tracer.

APPENDIX A

GFDL Staff Members

and

Affiliated Personnel

during

Fiscal Year 1989

Jerry D. Mahlman	Director
Betty M. Williams	Secretary
Bruce B. Ross	Assistant Director
Joan M. Pege	Administrative Assistant

CLIMATE DYNAMICS

Manabe, Syukuro	Sr. Research Scientist	FTP
Broccoli, Anthony	Research Associate	FTP
Brooks, Kevin	Junior Fellow	FTP*
Delworth, Thomas	Research Associate	FTP
Lofgren, Brent M.	Student	PU
Fels, Stephen	Sr. Research Scientist	FTP
Friedenreich, Stuart	Research Associate	FTP
Ma, Chung-Chun	Student	PU
Ramaswamy, V.	Program Scientist	PU
Saravanan, R.	Student	PU
Schwarzkopf, M. Daniel	Sr. Research Associate	FTP
Zhu, Xun	Program Scientist	PU*
Hayashi, Yoshikazu	Research Scientist	FTP
Golder, Donald	Sr. Research Associate	FTP
Held, Isaac	Sr. Research Scientist	FTP
Cook, Kerry	Research Associate	FTP
Fyfe, John	Program Scientist	PU
Lee, Sukyoung	Student	PU
O'Brien, Enda W.	Program Scientist	PU
Phillipps, Peter	Research Associate	FTP
Ting, Mingfang	Student	PU
Mitsumoto, Shigeki	Program Scientist	PU
Spelman, Michael	Sr. Research Associate	FTP
Stouffer, Ronald	Sr. Research Associate	FTP
Wetherald, Richard	Sr. Research Associate	FTP

MIDDLE ATMOSPHERE DYNAMICS AND CHEMISTRY

Mahlman, Jerry D.	Sr. Research Scientist	FTP
Hamilton, Kevin P.	Research Scientist	FTP
Yuan, Li	Student	PU
Wilson, Robert J.	Research Associate	FTP
Levy, Hiram II	Research Scientist	FTP
Kasabhatla, Prasad	Georgia Tech Res. Associate	RA
Moxim, Walter J.	Sr. Research Associate	FTP
Pinto, Joseph P.	Program Scientist	PU*
Tao, Xin	Student	PU
Umscheid, Ludwig J.	Sr. Research Associate	FTP
Fesenko, John	Junior Fellow	FTP*

*Affiliation Terminated Prior to September 30, 1989

EXPERIMENTAL PREDICTION

Miyakoda, Kikuro	Sr. Research Scientist	FTP
da Silva, Arlindo	Program Scientist	PU
Derber, John	Assoc. Research Scientist	FTT*
Gordon, Charles T.	Research Scientist	FTP
Gudgel, Richard G.	Research Associate	FTP
Manzini, Eliza	Student	PU
Pierrehumbert, Raymond	Professor	PU*
Anderson, Jeffrey	Student	PU
Lin, Shian-Jiann	Student	PU*
Ploshay, Jeffrey	Research Associate	FTP
Rosati, Anthony	Sr. Research Associate	FTP
Sirutis, Joseph	Sr. Research Associate	FTP
Stern, William	Sr. Research Associate	FTP
Smith, Robert	Computer Operator	FTP
Wyman, Bruce	Research Associate	FTP

OCEANIC CIRCULATION

Bryan, Kirk	Sr. Research Scientist	FTP
Cox, Michael	Research Scientist	FTP*
Dixon, Keith	Research Associate	FTP
Gerdes, Rudiger	Program Scientist	PU
Philander, Samuel G.H.	Sr. Research Scientist	FTP
Chai, Fei	Student	PU
Chao, Yi	Student	PU
Hurlin, William	Research Associate	FTP
Ji, Zhen-Gang	Program Scientist	PU
Matano, Ricardo P.	Student	PU
Pacanowski, Ronald	Sr. Research Associate	FTP
Samuels, Bonita	Research Associate	FTP
Toggweiler, John R.	Research Scientist	FTP

PLANETARY CIRCULATIONS

Williams, Gareth	Sr. Research Scientist	FTP
Holloway, Leith	Sr. Research Associate	PTT

*Affiliation Terminated Prior to September 30, 1989

OBSERVATIONAL STUDIES

Oort, Abraham	Sr. Research Scientist	FTP
Karoly, David J.	Program Scientist	PU*
Lau, Ngar-Cheung	Research Scientist	FTP
Kushnir, Yochanan	Program Scientist	PU
Lau, Alexis K.-H.	Student	PU
Nath, Mary J.	Research Associate	FTP
Levitus, Sydney	Sr. Research Associate	FTP*
Jackson, Martha	Sr. Technician	FTP
Rosenstein, Melvin	Sr. Technician	FTP

HURRICANE DYNAMICS

Kurihara, Yoshio	Sr. Research Scientist	FTP
Bender, Morris A.	Sr. Research Associate	FTP
Ross, Rebecca J.	Research Associate	FTP
Tuleya, Robert E.	Sr. Research Associate	FTP
DiPaola, Michael	Junior Fellow	FTP*

MESOSCALE DYNAMICS

Orlanski, Isidoro	Sr. Research Scientist	FTP
Katzfey, Jack	Research Associate	FTP
Polinsky, Larry	Research Associate	FTP
Ross, Bruce	Research Scientist	FTP

CONVECTION AND TURBULENCE

Lipps, Frank	Research Scientist	FTP
Hemler, Richard	Research Associate	FTP

*Affiliation Terminated Prior to September 30, 1989

CENTRALIZED SUPPORT SERVICES

Administrative and Technical Support

Mahlman, Jerry D.	Director	FTP
Hahn, Douglas G.	Assistant Director	FTP*
Ross, Bruce B.	Acting Assistant Director	FTP
Baker, Philip	Computer Programmer Analyst	FTP
Pege, Joan	Administrative Assistant	FTP
Amend, Beatrice	Clerk Typist	PTT
Tunison, Philip	Supv. Scientific Illustrator	FTP
Raphael, Catherine	Scientific Illustrator	PTP
Varanyak, Jeffrey	Scientific Illustrator	FTP
Zadworney, Michael	Jr. Office Draftsman	FTP*
Urbani, Elaine	Travel Clerk	FTP
Uveges, Frank	Supv. Computer Specialist	FTP
Byrne, James	Jr. Technician	FTP
Conner, John	Photographer	FTP
Williams, Betty M.	Secretary	FTP
Blessing, Mae	Clerk-Typist	PTP*
Kennedy, Joyce	Editorial Assistant	FTP
Marshall, Wendy	Editorial Assistant	FTP

Computer Systems Support

Welsh, James	Sr. Computer Sys. Analyst	FTP
Kranz, Christopher	Computer Sys. Programmer	FTT
Molinaro, Richard	Computer Sys. Programmer	FTP
White, Robert	Computer Sys. Programmer	FTP
Yeager, William	Computer Sys. Programmer	FTP

Computer Operational Support

Shearn, William	Operations Manager	FTP
Hopps, Frank	Supv. Computer Operator	FTP
Adams, Bonnie	Peripheral Equip. Oper.	PTT
Davis, Manuel	Peripheral Equip. Oper.	FTT
Deuringer, James	Peripheral Equip. Oper.	FTT
King, John	Computer Operator	FTP
Rodman, Edward	Computer Operator	FTP
Taylor, Thomas	Computer Operator	FTP
Watson, Cornelius	Computer Ser. Student Tr.	FTT
Hand, Joseph	Supv. Computer Operator	FTP
Brandbergh, Gerald	Computer Operator	FTP
Cordwell, Clara	Computer Operator	FTP
Henne, Ronald	Computer Operator	FTP
Krueger, Scott	Peripheral Equip. Oper.	FTT
Heinbuch, Ernest	Supv. Computer Operator	FTP
Conover, Leonard	Computer Operator	FTP
Miller, Almore	Computer Operator	FTP*

*Affiliation Terminated Prior to September 30, 1989.

AOS PROGRAM

Sarmiento, Jorge	Professor	PU
Anderson, Laurence A.	Student	PU
Callan, Johann V.	Tech. Secretary	PU
Key, Robert M.	Research Oceanographer	PU
Koehler, Nancy Duprey	Technical Specialist	PU*
McDonald, Gerard	Research Associate	PU
Murnane, Richard J.	Research Associate	PU
Najjar, Raymond G.	Student	PU*
Nicoletti, Mary Ann	Program Manager	PU
Olsen, Esther B.	Administrative Assistant	PU
Orr, James	Technical Staff	PU
Rintoul, Stephen R.	Program Scientist	PU
Rotter, Richard	Sr. Research Associate	PU
Slater, Richard D.	Technical Staff	PU
Slater, Rochelle D.	Technical Staff	PU
Wong, Richard	Technical Staff	PU
Mellor, George	Professor	PU
Ezer, Tal	Program Scientist	PU
Hakkinen, Sirpa M. A.	Research Staff	PU
Xue, Hui-Jie	Student	PU
Zavatarelli, Marco	Program Scientist	PU

CONTROL DATA CORPORATION

Robert Kazawic, Sales Representative

Stringer, John	Analyst in Charge	CDC
Helster, Paul	Senior Engineer in Charge	CDC
Cerkan, John	Senior Customer Engineer	CDC
Csapo, Michael	Customer Engineer	CDC
Dorado, Manual	Senior Customer Engineer	CDC
Johnson, Eric	Senior Customer Engineer	CDC
Jones, John	Senior Customer Engineer	CDC
Smith, Alain	Senior Customer Engineer	CDC
Valin, Chris	Customer Engineer	CDC
Weiss, Edward	Senior Customer Engineer	CDC

*Affiliation Terminated Prior to September 30, 1989

PERSONNEL SUMMARY

September 30, 1989

GFDL/NOAA	
Full Time Permanent (FTP)	78
Part Time Permanent (PTP)	1
Full Time Temporary (FTT)	5
Part Time Temporary (PTT)	3
Research Affiliates (RA)	1
PRINCETON UNIVERSITY (PU)	
Program Scientists	11
Students	16
Professors	2
Research Staff	5
Support Staff	3
Technical Staff	4
CONTROL DATA CORPORATION (CDC)	
Computer Support Staff	11
TOTAL	140

APPENDIX B

GFDL

Bibliography

1984-1989

NOTE: THIS IS A PARTIAL LISTING OF GFDL PUBLICATIONS. A COPY OF THE COMPLETE BIBLIOGRAPHY CAN BE OBTAINED BY CALLING 609-452-6502 (FTS AND COMMERCIAL) OR BY WRITING TO:

Director
Geophysical Fluid Dynamics Laboratory
Princeton University - Post Office Box 308
Princeton, New Jersey 08542

(567) Spelman, M. J., and S. Manabe, Influence of Oceanic Heat Transport upon the Sensitivity of a Model Climate, Journal of Geophysical Research, 89(C1):571-586, 1984.

(568) Miyakoda, K., J. Ploshay, and W. Stern, Guide and Caution on the GFDL/FGGE III-b Data Set. Global Weather Experiment, Newsletter, No.1, pp.8-14, 1984.

* (569) Andrews, D. G., J. D. Mahlman and R. W. Sinclair, Eliassen-Palm Diagnostics of Wave-Mean Flow Interaction in the GFDL "SKYHI" Circulation Model, Journal of the Atmospheric Sciences, 40(12): 2768-2784, 1984.

(570) Hayashi, Y., Studies of the Mechanism of Planetary-Scale Atmospheric Disturbances using New Analysis Methods, Journal of the Meteorological Society, Japan, 30(1):3-12, 1984.

(571) Orlanski, I. and B. Ross, The Mesoscale Structure of a Moist Cold Front Simulation with Explicit Convection. Proceedings of CIMMS Symposium on Mesoscale Modeling, Norman, Okla. June, 1984.

(572) Lau, Ngar-Cheung, Mid-Latitude Wintertime Circulation Anomalies Appearing in a 15-year GCM Experiment, Large-Scale Dynamical Processes in the Atmosphere, (eds. B.J. Hoskins and R.P. Pearce), Academic Press, 111-125, 1984.

(573) Held, Isaac, Stationary and Quasi-Stationary Eddies in the Extra-Tropical Troposphere: Theory, Large-Scale Dynamics Processes in the Atmosphere, (eds. B.J. Hoskins, R.P. Pearce), Academic Press, 127-168, 1984.

* (574) Pierrehumbert, R. T. and P. Malguzzi, Forced Coherent Structures and Local Multiple Equilibria in a Barotropic Atmosphere, Journal of the Atmospheric Sciences, 41(2):246-257, 1984.

* (575) MacAyeal, Douglas R., Numerical Simulations of the Ross Sea Tides, Journal of Geophysical Research, 89(C1):607-615, 1984.

*In collaboration with other organizations

* (576) MacAyeal, Douglas R., Thermohaline Circulation below the Ross Ice Shelf: A Consequence of Tidally Induced Vertical Mixing and Basal Melting, Journal of Geophysical Research, 89(C1): 597-606, 1984.

* (577) Salby, Murry L., Evidence for Equatorial Kelvin Modes in Nimbus-7 LIMS, Journal of the Atmospheric Sciences, 41(2), 220-235: 1984.

* (578) Wahr, John M., and Abraham H. Oort, Friction- and Mountain-Torque Estimates from Global Atmospheric Data, Journal of the Atmospheric Sciences, 41(2):190-204, 1984.

* (579) MacAyeal, Douglas R., and R. H. Thomas, Numerical Modeling of Ice-Shelf Motion, Annals of Glaciology 3, 189-194, 1984.

(580) Tuleya, Robert E., Morris A. Bender and Yoshio Kurihara, A Simulation Study of the Landfall of Tropical Cyclones using a Movable Nested-Mesh Model, Monthly Weather Review, 112(1): 124-136, 1984.

* (581) Carton, J. A., Coastal Circulation Caused by an Isolated Storm, Journal of Physical Oceanography, 14(1):114-124, 1984.

(582) Orlanski, Isidoro, Orographically Induced Vortex Centers. Proceedings Joint U.S. - China Mountain Meteorology Symposium, Beijing, China, Mountain Meteorology, Sino - U.S. Academies of Science, 1982, 311-340. 1984.

* (583) Lau, Ngar-Cheung and Eero Holopainen, Transient Eddy Forcing of the Time-Mean Flow as Identified by Geopotential Tendencies, Journal of the Atmospheric Sciences, 41(3):313-328, 1984.

(584) Gordon, Charles T. and William F. Stern, Medium Range Prediction by a GFDL Global Spectral Model: Results for Three Winter Cases and Sensitivity to Dissipation, Monthly Weather Review, 112(2):217-245, 1984.

* (585) Philander, S. G. H., T. Yamagata and R.C. Pacanowski, Unstable Air-Sea Interactions in the Tropics, Journal of the Atmospheric Sciences, 41(4):604-613, 1984.

* (586) Williams, Gareth P., and Toshio Yamagata, Geostrophic Regimes, Intermediate Solitary Vortices and Jovian Eddies, Journal of the Atmospheric Sciences, 41(4):453-478, 1984.

(587) Miyakoda, K. and A. Rosati, Parameterization of the ABL and OBL in a GFDL Model, "Report of the WMO/CAS Expert Meeting on Atmospheric Boundary Layer Paramerization over the Oceans for Long Range Forecasting and Climate Models" Reading, UK., 5-9 December, 1983, World Climate Programme, 1-10, 1984.

*In collaboration with other organizations

(588) Lipps, F., Some Recent Simulations using the GFDL Cloud Model. Proceedings of the International Cloud Modelling Workshop, Aspen, Colorado. April, 1984, 1-21, 1984.

* (589) Mahlman, J. D., D. Andrews, D. Hartmann, T. Matsuno, R. Murgatroyd, Transport of Trace Constituents in the Stratosphere. Proceedings of U.S. - Japan Seminar on Middle Atmosphere Dynamics, Tokyo, Japan, Advances in Earth and Planetary Sciences, TERRA Scientific Publishing Co. Tokyo, Japan, 387-416, 1984.

(590) Mahlman, J. D., and L. J. Umscheid, Dynamics of the Middle Atmosphere: Successes and Problems of the GFDL "SKYHI" General Circulation Model. Dynamics of the Middle Atmosphere, Advances in Earth and Planetary Sciences, Terra Scientific Publishing Co., Tokyo, Japan, 501-525, 1984.

* (591) Yeh, T. C., R. T. Wetherald, and S. Manabe, The Effect of Soil Moisture on the Short-Term Climate and Hydrology Change - A Numerical Experiment, Monthly Weather Review, 112(3):474-490, 1984.

* (592) Sardeshmukh, P. D., and I. Held, The Vorticity Balance in the Tropical Upper Troposphere of a General Circulation Model, Journal of the Atmospheric Sciences, 41(5):768-778, 1984.

(593) Tuleya, R. E., and Y. Kurihara, The Formation of Comma Vortices in a Tropical Numerical Simulation Model, Monthly Weather Review, 112(3):491-502, 1984.

* (594) Bryan, K., F. G. Komro, and C. Rooth, The Ocean's Transient Response to Global Surface Temperature Anomalies. In Climate Processes and Climate Sensitivity, 29(5), James E. Hansen and Taro Takahashi (eds.), American Geophysical Union, Washington, DC 29-38, 1984.

(595) Cox, M. D., and K. Bryan, A Numerical Model of the Ventilated Thermocline, Journal of Physical Oceanography, 14(4):674-687, 1984.

* (596) Zeng, Qing-Cun, The Development Characteristics of Quasi-Geostrophic Baroclinic Disturbances, Tellus, 40(1):73-84, 1984.

(597) Lau, Ngar-Cheung, The Frequency Dependence of the Structure and Evolution of Geopotential Height Fluctuations appearing in a GFDL General Circulation Model, NCAR/TN-227, 151-207, 1984.

(598) Oort, Abraham, The Scope of Recent Climate Research in the Observational Studies Group of GFDL, NCAR/TN-227, 151-207, 1984.

*In collaboration with other organizations

(599) Oort, Abraham, Global Atmospheric Circulation Statistics. 1958-1973, NOAA Professional Paper No.14, U.S. Printing Office, Washington, DC, 180 pp., 1983.

* (600) Peixoto, Jose, P., and Abraham Oort, Physics of Climate, Review of Modern Physics, 56(3):365-429, 1984.

(601) Levitus, S., Annual Cycle of Temperature and Heat Storage in the World Ocean, Journal of Physical Oceanography, 14(4):727-746, 1984.

* (602) Hibler, W. D. III, and K. Bryan, Ocean Circulations: Its Effect on Seasonal Sea-Ice Simulations, Science, Vol. 224:489-491, 1984.

(603) Gordon, C. T., R. D. Hovanec, and W. F. Stern, Analyses of Monthly Mean Cloudiness and their Influence upon Model-Diagnosed Radiative Fluxes, Journal of Geophysical Research, 89(D3): 4713-4738, 1984.

* (604) Oort, Abraham H., and Yi-Hong Pan, Sea Surface Temperature Anomalies in the Equatorial Pacific Ocean and Global Climate Variations. Proceedings of the Eighth Annual Climate Diagnostics Workshop Canadian Climate Centre, Atmospheric Environment Service, Downsview, Ontario, 17-21 October, 1984.

(605) Miyakoda, K. and A. Rosati, The Variation of Sea Surface Temperature in 1976 and 1977. 2. The Simulation with Mixed Layer Models, Journal of Geophysical Research, 89(C4):6533-6542, 1984.

* (606) Nigam, Sumant and Isaac M. Held, The Influence of a Critical Latitude on Topographically Forced Stationary Waves in a Barotropic Model, Journal of the Atmospheric Sciences, 40(11): 2610-2622, 1984.

(607) Bryan, Kirk, Accelerating the Convergence to Equilibrium of Ocean-Climate Models, Journal of Physical Oceanography, 14(4): 667-673, 1984.

* (608) Oey, Li-Yauw, On Steady Salinity Distribution and Circulation in Partially Mixed and Well Mixed Estuaries, Journal of Physical Oceanography, 14(3):629-645, 1984.

(609) Pierrehumbert, R. T., Linear Results on the Barrier Effects of Mesoscale Mountains, Journal of the Atmospheric Sciences, 41(8): 1984.

* (610) Lemke, P., and T. O. Manley, The Seasonal Variation of the Mixed Layer, and the Pycnocline under Polar Sea Ice, Journal of the Atmospheric Sciences, 89(C4):6494-6504, 1984.

*In collaboration with other organizations

* (611) Sarmiento, J. L., and J. R. Toggweiler, A New Model for the Role of Determining Atmospheric PCO_2, Nature, 308(5960):621-624, 1984.

(612) Manabe, S., and A. J. Broccoli, Ice-Age Climate and Continental Ice Sheets: Some Experiments, Annals of Glaciology, 5, 100-105, 1984.

(613) Orlanski, Isidoro and Bruce B. Ross, The Evolution of an Observed Cold Front. Part II: Mesoscale Dynamics, Journal of the Atmospheric Sciences, 41(10):1669-1703, 1984.

(614) Philander, S. G. H. and R. C. Pacanowski, Simulation of the Seasonal Cycle in the Tropical Atlantic Ocean, Geophysical Research Letters, 11(8):802-804, 1984.

(615) Orlanski, Isidoro and Larry Polinsky, Predictability of Mesoscale Phenomena, Nowcasting II, Mesoscale Observations and Very Short Range Weather Forecasting, Proceedings of the Second International Symposium on Nowcasting, Norrkoping, Sweden, 3-7 September 1984, ESA SP-208. 171-280, 1984.

(616) Manabe, S., and A. J. Broccoli, Influence of the CLIMAP Ice Sheet on the Climate of a General Circulation Model: Implications for the Milankovitch Theory, A.L. Berger et al. (eds) Milankovitch and Climate, Part 2, D. Reidel Publishing Co., 789-799, 1984.

(617) Hayashi, Y., D. G. Golder, and J. D. Mahlman, Stratospheric and Mesospheric Kelvin Waves Simulated by the GFDL "SKYHI" General Circulation Model, Journal of the Atmospheric Sciences, 41(12): 1971-1984, 1984.

(618) Fels, Stephen B., The Radiative Damping of Short Vertical Scale Waves in the Mesosphere, Journal of the Atmospheric Sciences, 41(10):1755-1764, 1984.

* (619) Salby, Murry L., Survey of Planetary-Scale Traveling Waves: The State of Theory and Observations, Reviews of Geophysics and Space Physics, 22(2):209-236, 1984.

* (620) Gwinn, Elizabeth and Jorge L. Sarmiento, A Model for Predicting Strontium-90 Fallout in the Northern Hemisphere (1954-1974), Ocean Tracers Laboratory Technical Report #3, 1-57, August 1984.

(621) Pierrehumbert, R. T., Local and Global Baroclinic Instability of Zonally Varying Flow, Journal of the Atmospheric Sciences, 41(14):2141-2162, 1984.

* (622) Domaradzki, J. A., and G. L. Mellor, A Simple Turbulence Closure Hypothesis for the Triple-Velocity Correlation Functions in Homogeneous Isotropic Turbulence, Journal of Fluid Mechanics, Vol.140:45-61, 1984.

*In collaboration with other organizations

* (623) Domaradzki, J. A., and G. L. Mellor, The Importance of Large Scales of Turbulence for the Predictability of the Turbulent Energy Decay, Proceedings of a Workshop on Predictability of Fluid Motions, La Jolla, CA. February 1983, American Institute of Physics. 571-575, 1984.

(624) Lau, Ngar-Cheung, Circulation Statistics based on FGGE Level III-B Analyses Produced GFDL, NOAA Data Report ER1/GFDL-5, U.S. Government Printing Office, 427 pp. 1984.

* (625) Richez, C., S. G. H. Philander, and M. Crepon, Oceanic Response to Coastal Winds with Shear, Oceanologica Acta, 7(4):409-416, 1984.

* (626) Carton, J. A., and S. G. H. Philander, Coastal Upwelling Viewed as a Stochastic Phenomenon, Journal of Physical Oceanography, 14(9): 1499-1509, 1984.

(627) Miyakoda, K., and J. Sirutis, Impact of Subgrid-Scale Parameterizations on Monthly Forecasts, Proceedings of ECMWF Workshop on Convection in Large-Scale Numerical Models, December 1983, Reading, England. ECMWF Workshop Book, 231-277: 1985.

* (628) Bryan, Frank and Abraham H. Oort, Seasonal Variation of the Global Water Balance based on Aerological Data, Journal of Geophysical Research, 89(D7):11,717-11,730, 1985.

(629) Lau, Ngar-Cheung, A Comparison of Circulation Statistics based on FGGE Level III-B Analyses Produced by GFDL and ECMWF for the Special Observing Periods, NOAA Data Report, NOAA-ERL-GFDL-6, 237 pp. 1985.

(630) Manabe, S., and A. J. Broccoli, The Influence of Continental Ice Sheets on the Climate of an Ice Age, Journal of Geophysical Research, 90(D1):2167-2190, 1985.

* (631) Lau, Ngar-Cheung and Ka-Ming Lau, The Structure and Energetics of Midlatitude Disturbances Accompanying Cold-Air Outbreaks over East Asia, Monthly Weather Review, 112(7):1309-1327, 1985.

(632) Lau, Ngar-Cheung, Comparison of Level III-B FGGE Analyses Produced by GFDL and ECMWF during the Special Observing Periods, Proceedings of the Scientific Seminar on Global Diagnostic Studies Based on Data Collected during the Global Weather Experiment. Helsinki, Finland, 28-31 August 1984, 1-17, 1985.

(633) Lau, Ngar-Cheung, Transient Eddy Forcing of the Stationary Waves as Identified by Geopotential Tendencies. Proceedings of Workshop on "Dynamics and Long Waves in the Atmosphere" sponsored by the University of Stockholm and Royal Netherlands Meteorological Institute, October 1984, 167-176, 1985.

*In collaboration with other organizations

* (634) Mesinger, Fedor, Vertical Finite-Difference Representation in Weather Prediction Models. Report of the Seminar on Progress in Numerical Modelling and Understanding of Predictability as a Result of the Global Weather Experiment held at Sigtuna, Sweden, October 1984, GARP Special Report No. 43, 1-49, 1985.

* (635) Philander, George, David Halpern, Donald Hansen, Richard Legeckis, Laury Miller, Carl Paul, Randolph Watts, Long Waves in the Equatorial Pacific Ocean, EOS, Transactions, American Geophysical Union, 66(14):154-156, 1985.

* (636) Schemm, Charles E. and Frank B. Lipps, A Three-Dimensional Numerical Study of Turbulence in Homogeneous Fluids, Computers and Fluids, 13(2):185-205, 1985.

* (637) Kurihara, Yoshio and Mitsuhiro Kawase, On the Transformation of a Tropical Easterly Wave into a Tropical Depression: A Simple Numerical Study, Journal of the Atmospheric Sciences, 42(1): 68-77, 1985.

* (638) Miyahara, Saburo, Suppression of Stationary Planetary Waves by Internal Gravity Waves in the Mesosphere, Journal of the Atmospheric Sciences, 42(1):100-107, 1985.

* (639) Levy, H., J. D. Mahlman, W. J. Moxim, and S. C. Liu, Tropospheric Ozone: The Role of Transport, Journal of Geophysical Research, 90(C4):3753-3772, 1985.

* (640) Fels, S. B., J. T. Schofield, and D. Crisp, Observations and Theory of the Solar Semidiurnal Tide in the Mesosphere of Venus, Nature, 431-434, 1985.

* (641) Salby, Murry L., Transient Disturbances in the Stratosphere: Implications for Theory and Observing Systems, Journal of Atmospheric and Terrestrial Physics, 46(11):1009-1047, 1985.

(642) Miyakoda, K., Impact of the Centre's Research, The History and Achievement of CMRC/ANMRC, Australia. Reprint from CMRC/ANMRC Valedictory Report 1969-1984, Australian Numerical Meterology Research Centre, 32-39, 1985.

* (643) Rosen, Richard D., David A. Salstein, Jose P. Peixoto, Abraham H. Oort, and Ngar-Cheung Lau, Circulation Statistics Derived from Level III-b and Station-Based Analyses during FGGE, Monthly Weather Review, 113(1):65-88, 1985.

* (644) Carissimo, B. C., A. H. Oort, and T. Vonder Haar, On Estimating the Meridional Energy Transports in the Atmosphere and Ocean, Journal of Physical Oceanography, 15(1):82-91, 1985.

*In collaboration with other organizations

* (645) Yamagata, Toshio and Y. Hayashi, A Simple Diagnostic Model for the 30-50 Day Oscillation in the Tropics, Journal of the Meteorological Society of Japan, 62(5):709-717, 1985.

(646) Pierrehumbert, R. T., Stratified Semigeostrophic Flow over Two-Dimensional Topography in an Unbounded Atmosphere, Journal of the Atmospheric Sciences, 42(5):523-526, 1985.

(647) Bender, M. A., R. Tuleya, and Y. Kurihara, A Numerical Study of the Effect of a Mountain Range on a Landfalling Tropical Cyclone, Monthly Weather Review, 113(4):567-582, 1985.

* (648) Puri, Kamal, Sensitivity of Low-Latitude Velocity Potential Field in a Numerical Weather Prediction Model to Initial Conditions, Initialization and Physical Processes, Monthly Weather Review, 113(4):449-466, 1985.

(649) Stern, W. F., J.J. Ploshay, and K. Miyakoda, Continuous Data Assimilation at GFDL during FGGE. Proceedings at European Center for Medium-Range Weather Forecasting on Data Assimilation Systems and Observation Systems Experiment with Particular Emphasis on FGGE. September 3-11, 1984, Vol.2, 125-156, 1985.

(650) Pierrehumbert, R. T., and B. Wyman, Upstream Effects of Mesoscale Mountains, Journal of the Atmospheric Sciences, 42(10): 977-1003, 1985.

* (651) Held, I., R .L. Panetta, and R. Pierrehumbert, Stationary External Rossby Waves in Vertical Shear, Journal of the Atmospheric Sciences, 42(9):865-883, 1985.

* (652) Puri, K., and W. Stern, Investigations to Reduce Noise and Improve Data Acceptance in the GFDL 4-Dimensional Analysis System. Proceedings at European Center for Medium-Range Weather Forecasting on Data Assimilation Systems and Observation Systems Experiment with Particular Emphasis on FGGE, September 3-11, 1984, Vol. 2, 157-190, 1985.

* (653) Toggweiler, J. R., and J. L. Sarmiento, Glacial to Interglacial Changes in Atmospheric Carbon Dioxide: The Critical Role of Ocean Surface Water in High Latitudes, The Carbon Cycle and Atmospheric CO_2: Natural Variations Archean to Present. E. T. Sundquist and W. S. Broecker, eds., Geophysical Monograph 32, American Geophysical Union, Washington, DC, 163-184, 1985.

(654) Williams, Gareth P., Geostrophic Regimes on Sphere and Beta Plane, Journal of the Atmospheric Sciences, 42(12):1237-1243, 1985.

* (655) Dritschel, David, The Stability and Energetics of Corotating Uniform Vortices, Journal of Fluid Mechanics, 157:95-134, 1985.

*In collaboration with other organizations

(656) Pierrehumbert, R. T., A Theoretical Model of Orographically Modified Cyclogenesis, Journal of the Atmospheric Sciences, 42(12): 1244-1258, 1985.

(657) Hayashi, Y., and D. G. Golder, Nonlinear Energy Transfer between Stationary and Transient Waves Simulated by a GFDL Spectral General Circulation Model, Journal of the Atmospheric Sciences, 42(12):1340-1344, 1985.

* (658) Daley, R., A. Hollingsworth, J. Ploshay, K. Miyakoda, W. Baker, E. Kalnay, C. Dey, T. Krishnamurti, and E. Barker, Objective Analysis and Assimilation Techniques used for the Production of FGGE IIIb Analyses, Bulletin of the American Meteorological Society, 66(5):532-538, 1985.

(659) Orlanski, I., B. B. Ross, L. Polinsky, and R. Shaginaw, Advances in the Theory of Atmospheric Fronts. In Advances in Geophysics, (28), B. Weather Dynamics, B. Saltzman (ed.), Academic Press, New York, 223-252, 1985.

(660) Kurihara, Y., Numerical Modeling of Tropical Cyclones. In Advances in Geophysics, (28), B. Weather Dynamics, B. Saltzman (ed.), Academic Press, New York, 255-281, 1985.

(661) Miyakoda, K., and J. Sirutis, Extended Range Forecasting. In Advances in Geophysics, (28), B. Weather Dynamics, B. Saltzman (ed.), Academic Press, New York, 55-85, 1985.

(662) Manabe, S. and R. T. Wetherald, CO_2 and Hydrology. In Advances in Geophysics, (28), A. Climate Dynamics, B. Saltzman (ed.), Academic Press, New York, 131-156, 1985.

(663) Philander, S. G., Tropical Oceanography. In Advances in Geophysics, (28), A. Climate Dynamics, B. Saltzman (ed.), Academic Press, New York, 461-475, 1985.

* (664) Bryan, K., and J. L. Sarmiento, Modeling Ocean Circulation. In Advances in Geophysics, (28), A. Climate Dynamics, B. Saltzman (ed.), Academic Press, New York, 433-459, 1985.

(665) Oort, A. H., Balance Conditions in the Earth's Climate System. In Advances in Geophysics, (28), A. Climate Dynamics, B. Saltzman (ed.), Academic Press, New York, 75-97, 1985.

* (666) Wallace, J. M., and N.C. Lau, On the Role of Barotropic Energy Conversions in the General Circulation. In Advances in Geophysics, (28), A. Climate Dynamics, B. Saltzman (ed.), Academic Press, New York, 33-72, 1985.

*In collaboration with other organizations

* (667) Philander, S. G. H., and E. M. Rasmusson, The Southern Oscillation and El Niño. In Advances in Geophysics, (28), A. Climate Dynamics, B. Saltzman (ed.), Academic Press, New York, 197-213, 1985.

(668) Mahlman, J. D., Mechanistic Interpretation of Stratospheric Tracer Transport. In Advances in Geophysics, (28), A. Climate Dynamics, B. Saltzman (ed.), Academic Press, New York, 301-320, 1985.

(669) Fels, S. B., Radiative-Dynamical Interaction in the Middle Atmosphere. In Advances in Geophysics, (28), A. Climate Dynamics, B. Saltzman (ed.), Academic Press, New York, 277-298, 1985.

(670) Williams, Gareth P., Jovian and Comparative Atmospheric Modeling. In Advances in Geophysics, (28), A. Climate Dynamics, B. Saltzman, (ed.), Academic Press, New York, 381-423, 1985.

* (671) Held, Isaac M. and Brian J. Hoskins, Large-Scale Eddies and the General Circulation of the Troposphere. In Advances in Geophysics, (28), A. Climate Dynamics, B. Saltzman (ed.), Academic Press, New York, 3-29, 1985.

* (672) Snieder, R., The Origin of the 100,000 Year Cycle in a Simple Ice Age Model, Journal of Geophysical Research, 90(D3):5661-5664, 1985.

* (674) Moore, W. S., R. M. Key, and J. L. Sarmiento, High Precision ^{226}Ra and ^{228}Ra Measurements in the North Atlantic Ocean, Journal of Geophysical Research, 90(C4):6983-6994, 1985.

* (675) Key, R. M., R. F. Stallard, W. S. Moore, and J. L. Sarmiento, Distribution and Flux of Ra-^{226} and Ra-^{228} in the Amazon River Estuary, Journal of Geophysical Research, 90(C4):6995-7004, 1985.

* (676) Brewer, Peter G., Jorge L. Sarmiento, and William M. Smethie, Jr., The Transient Tracers in the Ocean (TTO) Program, The North Atlantic Study: 1981, The Tropical Atlantic Study: 1983, Journal of Geophysical Research, 90(C4):6903-6906, 1985.

* (677) Mellor, George L., Ensemble Average Turbulence Closure. In Advances in Geophysics, (28), B. Weather Dynamics, B. Saltzman (ed.), Academic Press, New York, 345-358, 1985.

(678) Bryan, K., and S. Manabe, A Coupled Ocean-Atmosphere and the Response to Increasing Atmospheric CO_2. Proceedings of the Liege Colloquium (1984), World Climate Research Programme. J. C. J. Nihoul (ed). Coupled-Ocean Atmosphere Models, Elsevier Science Pub. Amsterdam, Holland, 1-6, 1985.

*In collaboration with other organizations

(679) Lau, Ngar-Cheung and A. H. Oort, Response of a GFDL General Circulation Model to SST Fluctuations Observed in the Tropical Pacific Ocean during the Period 1962-1976. Proceedings of the Liege Colloquium (1984), World Climate Research Programme. J.C.J. Nihoul (ed). Coupled Ocean Atmosphere Models, Elsevier Science Pub. Amsterdam, Holland, 289-302, 1985.

* (680) Oort, Abraham H., and M. A. C. Maher, Observed Long-Term Variability in the Global Surface Temperatures of the Atmosphere and Oceans. Proceedings of the Liege Colloquium (1984), World Climate Research Programme. J.C.J. Nihoul (ed). Coupled-Ocean Atmosphere Models, Elsevier Science Publ. Amsterdam, Holland, 183-198, 1985.

(681) Philander, S. G. H., and A. D. Seigel, Simulation of El Niño of 1982-1983. Proceedings of the Liege Colloquium World Climate Research Programme. J.C.J. Nihoul (ed). Coupled-Ocean Atmosphere Models, Elsevier Science Publ. Amsterdam, Holland, 517-541, 1985.

* (682) Toggweiler, J. R., and Susan Trumbore, Bomb-Test ^{90}Sr in Pacific and Indian Ocean as Surface Water Recorded by Banded Corals, Earth and Planetary Science Letters, 74:306-314, 1985.

* (683) Bowman, K., Sensitivity of an Energy Balance Climate Model with Predicted Snowfall Rates, Tellus, 37A:233-248, 1985.

* (684) Oey, L. Y., G. L. Mellor, and R. I. Hires, Tidal Modeling of the Hudson-Raritan Estuary, Estuarine-Coastal-&-Shelf Science, (20):511-527, 1985.

* (685) Miyahara, S., On the Mean Wind Induced by Internal Gravity Wave Packets in the Atmosphere, Journal of the Meteorological Society, Japan, 63(4):523-533, 1985.

(686) Orlanski, I., Mesoscale Modeling and Predictability - Summer Colloquium. 26 June 1984, NCAR, Boulder, CO. In Dynamics of Mesoscale Weather Systems, 393-407, 1985.

* (687) Kawase, M. and J. L. Sarmiento, Nutrients in the Atlantic Thermocline, Journal of Geophysical Research, 90(C5):8961-8979, 1985.

* (688) Greatbatch, Richard J., Kelvin Wave Fronts, Rossby Solitary Waves and the Non-Linear Spin-Up of the Equatorial Oceans, Journal of Geophysical Research (Oceans), 90(C5):9097-9107, 1985.

(689) Hayashi, Yoshikazu, Theoretical Interpretations of the Eliassen-Palm Diagnostics of Wave-Mean Flow Interaction, Part I: Effects of Lower Boundary, Journal of the Meteorological Society of Japan, 63(4):497-512, 1985.

*In collaboration with other organizations

(690) Hayashi, Yoshikazu, Theoretical Interpretations of the Eliassen-Palm Diagnostics of Wave-Mean Flow Interaction, Part II: Effects of Mean Damping, Journal of the Meteorological Society of Japan, 63(4):513-521, 1985.

(691) Lipps, F. B., and R. S. Hemler, Another Look at the Scale Analysis for Deep Moist Convection, Journal of the Atmospheric Sciences, 42(18):1960-1964, 1985.

* (692) Moore, G. W. Kent, The Organization of Convection in the Narrow-Cold Frontal Rainband, Journal of the Atmospheric Sciences, 42(17):1777-1791, 1985.

(693) Schwarzkopf, M. Daniel, and Stephen B. Fels, Improvements to the Algorithm for Computing CO_2 Transmissivities and Cooling Rates, Journal of Geophysical Research, 90(C10):10,541-10,550, 1985.

(694) Cox, Michael D., An Eddy Resolving Numerical Model of the Ventilated Thermocline, Journal of Physical Oceanography, 15(10):1312-1324, 1985.

(695) Gordon, Charles T., William F. Stern and Russell D. Hovanec, A Simple Scheme for Generating Two Layers of Radiatively Constrained Effective Clouds in GCM's, Journal of Geophysical Research, 90(D6):10,563-10,585, 1985.

* (696) Garzoli, Sylvia L., and S. G. H. Philander, Validation of an Equatorial Atlantic Simulation Model using Inverted Echo Sounders, Journal of Geophysical Research, 90(C5):9199-9201, 1985.

* (697) Greatbatch, Richard J. and Toshio Yamagata, Fofonoff-Type Inertial Mode Steady States in a Model of the Equatorial Oceans, Journal of Physical Oceanography, 15(10):1349-1354, 1985.

(698) Held, Isaac M., Pseudomomentum and the Orthogonality of Modes on Shear Flows, Journal of the Atmospheric Sciences, 42(21): 2280-2288, 1985.

(699) Bryan, Kirk, and Michael J. Spelman, The Ocean's Response to a CO_2-Induced Warming, Journal of Geophysical Research, 90(C6): 11,679-11,688, 1985.

(700) Manabe, Syukuro, and Kirk Bryan, Jr., CO_2-Induced Change in a Coupled Ocean-Atmosphere Model and Its Paleoclimatic Implications, Journal of Geophysical Research, 90(C11): 11,689-11707, 1985.

* (701) Greatbatch, Richard J., On the Role Played by Upwelling of Water in Lowering Sea-Surface Temperatures during the Passage of a Storm, Journal of Geophysical Research, 90(C6):11,751-11,755, 1985.

*In collaboration with other organizations

(702) Lau, Ngar-Cheung, Modeling the Seasonal Dependence of the Atmospheric Response to Observed El Niños in 1962-1976, Monthly Weather Review, 113(11):1970-1996, 1985.

(703) Lau, Ngar-Cheung, Publication of Circulation Statistics based on FGGE Level III-B Analyses produced by GFDL and ECMWF Bulletin of the American Meteorological Society, 66(10):1293-1301, 1985.

* (704) Sarmiento, Jorge L., and Pierre E. Biscaye, Radon-222 in the Benthic Boundary Layer, Journal of Geophysical Research, 91(C1): 833-844, 1985.

* (705) Yamagata, Toshio, and S. G. H. Philander, The Role of Damped Equatorial Waves in the Oceanic Response to Winds, Journal of the Oceanographical Society of Japan, 41(5):345-357, 1985.

(706) Philander, S. G. H., El Niño and La Niña, Journal of the Atmospheric Sciences, 42(23):2652-2662, 1985.

(707) Manabe, S., and A. J. Broccoli, A Comparison of Climate Model Sensitivity with Data from the Last Glacial Maximum, Journal of Atmospheric Sciences, 43(23):2643-2651, 1985.

* (708) Carton, James A., and John M. Wahr, Modelling the Pole Tide and its Effect on the Earth's Rotation, Geophys. J. R. Astr. Soc., 84(1):121-138, 1985.

(709) Pierrehumbert, R.T., Formation of Shear Layers Upstream of the Alps. Proceedings of Fifth Course on Meteorology of the Mediterranean, Rome, Italy, July 1984, Revista Meteorologica i Aeronautica, 237-248, 1985.

(710) Gordon, C. T., The Sensitivity of One Month GCM Forecasts at GFDL to Zonally Symmetric Clouds, Quasi-Realistic Specified Clouds, and Model-Predicted Clouds. Proceedings of Report of JSC/CAS Workshop on Cloud-Capped Boundary Layer, Fort Collins, CO. 22-26 April 1985, WMO/TD No.75, 1-21, 1985.

* (711) Oey, Lie-Yauw, George L. Mellor, and Richard I. Hires, A Three-Dimensional Simulation of the Hudson-Raritan Estuary, Part I: Description of the Model and Model Simulations, Journal of Physical Oceanography, 15(12):1676-1692, 1985.

* (712) Oey, Lie-Yauw, George L. Mellor, and Richard I. Hires, A Three-Dimensional Simulation of the Hudson-Raritan Estuary, Part II: Comparison with Observation, Journal of Physical Oceanography, 15(12):1693-1709, 1985.

*In collaboration with other organizations

* (713) Oey, Lie-Yauw, George L. Mellor, and Richard I. Hires, A Three-Dimensional Simulation of the Hudson-Raritan Estuary, Part III: Salt Flux Analyses, Journal of Physical Oceanography, 15(12): 1711-1720, 1985.

* (714) Huang, Rui-Xin, Solutions of the Ideal Fluid Thermocline with Continuous Stratification, Journal of Physical Oceanography, 16(1):39-59, 1986.

* (715) Crook, Norman A., The Effect of Ambient Stratification and Moisture on the Motion of Atmospheric Undular Bores, Journal of the Atmospheric Sciences, 43(2):171-181, 1986.

(716) Mahlman, J. D., H. Levy II, and W. J. Moxim, Three-Dimensional Simulations of Stratospheric N_2O: Predictions for other Trace Constituents, Journal of Geophysical Research, 91(D2): 2687-2707, 1986.

(717) Fels, Stephen B., Analytic Representations of Standard Atmosphere Temperature Profiles, Journal of the Atmospheric Sciences, 43(2):219-221, 1986.

* (718) Seigel, Anne D., A Comment on Long Waves in the Pacific Ocean, Journal of Physical Oceanography, 15(12):1881-1883, 1986.

(719) Levitus, Sydney, Annual Cycle of Salinity in the World Ocean, Journal of Pnysical Oceanography, 16(2):322-343, 1986.

(720) Pierrehumbert, R. T., Remarks on a paper by Aref and Flinchem, Journal of Fluid Mechanics, (163):21-26, 1986.

(721) Wetherald, R.T., and S. Manabe, An Investigation of Cloud Cover Change in Response to Thermal Forcing, Climatic Change, (8): 5-23, 1986.

* (722) Held, Isaac M., Raymond T. Pierrehumbert, and R. Lee Panetta, Dissipative Destabilization of External Rossby Waves, Journal of the Atmospheric Sciences, 43(4):388-396, 1986.

(723) Manabe, S., and R. T. Wetherald, Reduction in Summer Soil Wetness Induced by an Increase in Atmospheric Carbon Dioxide, Science Magazine, 232:626-628, 1986.

* (724) Galperin, B., and S. Hassid, A Modified Turbulent Energy Model for Geophysical Flows: Influence of the Ground Proximity, Boundary Layer Meteorology, 35, 155-165, 1986.

* (725) Sarmiento, J.L., Three-Dimensional Ocean Models for Predicting the Distribution of CO_2 between the Ocean and Atmosphere, In The Changing Carbon Cycle: A Global Analysis, D. Richle and E. Trabalka (eds.), Springer-Verlag, New York, 279-294, 1986.

*In collaboration with other organizations

* (726) Wajsowicz, Roxana C., Free Planetary Waves in Finite-Difference Numerical Models, Journal of Physical Oceanography, 16(4): 773-789, 1986.

* (727) Wang, Bin, and Albert Barcilon, On the Moist Stability of a Baroclinic Zonal Flow with Conditionally Unstable Stratification, Journal of the Atmospheric Sciences, 43(7): 706-719, 1986.

(728) Broccoli, Anthony J., Characteristics of Seasonal Snow Cover as Simulated by GFDL Climate Models. Proceedings of SNOW WATCH 1985: 28-30 October 1985 at the University of Maryland, College Park, MD. Glaciological Data, Report GD-18, pp. 241-248, 1986.

(729) Orlanski, Isidoro and Bruce B. Ross, Low-Level Updrafts in Stable Layers Forced by Convection, Journal of the Atmospheric Sciences, 43(10):997-1005, 1986.

* (730) Sarmiento, Jorge L., and Elisabeth Gwinn, Strontium 90 Fallout Prediction, Journal of Geophysical Research, 91(C1):7631-7646, 1986.

(731) Miyakoda, K. Assessment of Results from Different Analysis Schemes, Proceedings of the International Conference on the Results of the Global Weather Experiments and their Implications for the World Weather Watch, Geneva, Switzerland, 27-31 May 1985. WMO/TD No. 107, 217-253, 1986.

(732) Hayashi, Yoshikazu, Statistical Interpretations of Ensemble-Time Mean Predictability, Journal of the Meteorological Society of Japan, 64(2):167-181, 1986.

* (733) Bogue, Neil M., Rui Xin Huang, and Kirk Bryan, Verification Experiments with an Isopycnal Coordinate Ocean Model, Journal of Physical Oceanography, 16(5):985-990, 1986.

(734) Bryan, Kirk, Poleward Buoyancy Transport in the Ocean and Mesoscale Eddies, Journal of Physical Oceanography, 16(5):928-933, 1986.

* (735) Moore, Willard S., Jorge L. Sarmiento, and R. M. Key, Tracing the Amazon Component of Surface Atlantic Water using ^{228}Ra, Salinity and Silica, Journal of Geophysical Research, 91(C2): 2574-2580, 1986.

* (736) Olson, Donald B., Gote H. Ostlund, and Jorge Sarmiento, The Western Boundary Undercurrent Off the Bahamas, Journal of Physical Oceanography, 16(2):233-240, 1986.

*In collaboration with other organizations

* (737) Graves, Denise Stephenson, Evaluation of Satellite Sampling of the Middle Atmosphere using the GFDL SKYHI General Circulation Model, Ph.D. Dissertation, Geophysical Fluid Dynamics Program, Princeton University, 1986.

* (738) Kawase, Mitsuhiro and Jorge L. Sarmiento, Circulation and Nutrients in Mid-Depth Atlantic Waters, Journal of Geophysical Research, 91(C8):9749-9770, 1986

* (739) Wang, Bin, and Albert Barcilon, The Weakly Nonlinear Dynamics of a Planetary Green Mode and Atmospheric Vacillation, Journal of the Atmospheric Sciences, 43(12):1275-1287, 1986.

* (740) Wang, Bin and Albert Barcilon, Two Dynamic Regimes of Finite Amplitude Charney and Green Waves, Journal of the Atmospheric Sciences, 43(12):1288-1296, 1986.

* (741) Sarmiento, Jorge L., On the North and Tropical Atlantic Heat Balance, Journal of Geophysical Research, 91(C10):11,677-11,689, 1986.

(742) Lipps, Frank B., and Richard S. Hemler, Numerical Simulation of Deep Tropical Convection Associated with Large-Scale Convergence, Journal of the Atmospheric Sciences, 43(17):1796-1816, 1986.

* (743) Miyahara, S., Y. Hayashi, and J. D. Mahlman, Interactions Between Gravity Waves and Planetary Scale Flow Simulated by the GFDL "SKYHI" General Circulation Model, Journal of the Atmospheric Sciences, 43(17):1844-1861, 1986.

* (744) Crisp, David, Stephen B. Fels, and M. D. Schwarzkopf, Approximate Methods for Finding CO_2 15 Micron Band Transmission Functions in the Atmospheres of Venus, Earth, and Mars, Journal of Geophysical Research, 91(D11):11851-11866, 1986.

(745) Lau, Ngar-Cheung, Diagnosis of Intraseasonal Oscillations Appearing in GCM Experiments Conducted at GFDL. Proceedings of WMO Workshop on Comparison of Simulations by Numerical Models of the Sensitivity of the Atmospheric Circulation to Sea Surface Temperature Anomalies, Boulder, CO, 9-12 December 1985. WMO/TD No. 138, Geneva, 63-68, 1986.

* (746) Kang, In-Sik and Ngar-Cheung Lau, Principal Circulation Anomalies in Model Atmosphere With and Without Intraseasonal Variations of Tropical Pacific SST. Proceedings of WMO Workshop on Comparison of Simulations by Numerical Models of the Sensitivity of the Atmospheric Circulation to Sea Surface Temperature Anomalies, Boulder, CO, 9-12 December 1985. WMO/TD No. 138, Geneva, 56-62, 1986.

*In collaboration with other organizations

* (747) Galperin, B., and S. Hassid, A Two Layer Model for the Barotropic Stationary Turbulent Planetary Boundary Layer, Israel Journal of Technology, 22, 233-242, 1986.

(748) Pierrehumbert, R. T., The Effect of Local Baroclinic Instability on Zonal Inhomogeneities of Vorticity and Temperature, Advances In Geophysics, 29, 165-182, 1986.

* (749) Lau, Ngar-Cheung, and Ka-Ming Lau, The Structure and Propagation of Intraseasonal Oscillations Appearing in a GFDL GCM, Journal of the Atmospheric Sciences, 43(19):2023-2047, 1986.

* (750) Bryan, Frank, High Latitude Salinity Effects and Interhemispheric Thermohaline Circulations, Nature, 323(6086):301-304, 1986.

* (751) Huang, Rui-Xin, Numerical Simulation of Wind-Driven Circulation in a Subtropical/Subpolar Basin, Journal of Physical Oceanography, 16(10):1636-1650, 1986.

(752) Pierrehumbert, R. T., Spatially Amplifying Modes of the Charney Baroclinic Instability Problem, Journal of Fluid Mechanics, 170:203-317, 1986.

(753) Mahlman, J. D., and S. B. Fels, Antarctic Ozone Decreases: A Dynamical Cause? Geophysical Research Letters, 13(12): 1316-1319, 1986.

* (754) Galperin, Boris, A Modified Turbulent Energy Model for Diffusion from Elevated and Ground Point Sources in Neutral Boundary Layers, Boundary-Layer Meteorology, 37:245-262, 1986.

* (755) Wang, B., A. Barcilon, and L. N. Howard, Linear Dynamics of Transient Planetary Waves in the Presence of Damping, Journal of the Atmospheric Sciences, 42(18):1893-1910, 1986.

(756) Philander, S. G. H., and R. C. Pacanowski, The Mass and Heat Budget in a Model of the Tropical Atlantic Ocean, Journal of Geophysical Research, 91(C12):14212-14220, 1986

(757) Philander, S. G. H., and R. C. Pacanowski, A Model of the Seasonal Cycle in the Tropical Atlantic Ocean, Journal of Geophysical Research, 91(C12):14192-14206, 1986.

(758) Philander, S. G. H., W. J. Hurlin, and R. C. Pacanowski, Properties of Long Equatorial Waves in Models of the Seasonal Cycle in the Tropical Atlantic and Pacific Oceans, Journal of Geophysical Research, 91(C12):14207-14211, 1986.

(759) Bryan, Kirk, Man's Great Geophysical Experiment: Can We Model the Consequences? Oceanus, 29(4):36-42, 1986.

*In collaboration with other organizations

* (760) Sarmiento, J. L., Modeling Oceanic Transport of Dissolved Constituents, The Role of Air-Sea Exchange in Geochemical Cycling. NATO Advanced Study Institute Series, P. Buat-Menard (ed), D. Reidel, Amsterdam, 65-82, 1986.

(761) Pierrehumbert, R. T., A Universal Shortwave Instability of Two-Dimensional Eddies in an Inviscid Fluid, Physical Review Letters, 57(17):2157-2159, 1986.

* (762) Dritschel, David G., The Stability of Vortices in Near Solid-Body Rotation, Journal of Fluid Mechanics, 172, 157-182, 1986.

* (763) Sarmiento, J. L., and J. R. Toggweiler, A Preliminary Model of the Role of Upper Ocean Chemical Dynamic in Determining Oceanic Oxygen and Atmospheric Carbon Dioxide Levels. In Dynamic Processes in the Chemistry of the Upper Ocean, J. D. Burton, P. G. Brewer, and R. Chesselet, (eds). Plenum Publishing Corp. 233-240, 1986.

* (764) Mellor, George L., Miles G. McPhee, and Michael Steele, Ice-Seawater Turbulent Boundary Layer Interaction with Melting or Freezing, Journal of Physical Oceanography, 16(11):1829-1846, 1986.

* (765) Kang, In-Sik, and Ngar-Cheung Lau, Principal Modes of Atmospheric Variability in Model Atmospheres With and Without Anomalous Sea Surface Temperature Forcing in the Tropical Pacific, Journal of the Atmospheric Sciences, 43(22):2719-2735, 1986.

(766) Philander, S. G. H., and R. C. Pacanowski, Nonlinear Effects in the Seasonal Cycle of the Tropical Atlantic Ocean, Deep Sea Research, 34(1):123-137, 1986.

* (767) Richardson, P. L., and S. G. H. Philander, The Seasonal Variations of Surface Currents in the Tropical Atlantic Ocean: A Comparison of Ship Drift Data with Results from a General Circulation Model, Journal of Geophysical Research, 92(C1): 715-724, 1986.

(768) Miyakoda, K., J. Sirutis, and J. Ploshay, One-Month Forecast Experiments - Without Anomaly Boundary Forcings, Monthly Weather Review, 114(12):2363-2401, 1986.

(769) Broccoli, A. J., and S. Manabe, The Influence of Continental Ice, Atmospheric CO_2, and Land Albedo on the Climate of the Last Glacial Maximum, Climate Dynamics, 1:87-99, Springer-Verlag, 1986.

* (770) Wajsowicz, Roxana, Adjustment of the Ocean under Buoyancy Forces, I: The Role of Kelvin Waves, Journal of Physical Oceanography, 16(12):2097-2114, 1986.

*In collaboration with other organizations

* (771) Wajsowicz, Roxana, Adjustment of the Ocean under Buoyancy Forces, II: The Role of Planetary Waves, Journal of Physical Oceanography, 16(12):2115-2136, 1986.

(772) Ross, Bruce, An Overview of Numerical Weather Prediction, In Mesoscale Meteorology and Forecasting, Peter S. Ray (ed). American Meteorological Society, Boston, MA.,720-751, 1986.

* (773) Kantha, Lakshmi H., Comments on "A Heat Balance for the Bering Sea Ice Edge", Journal of Physical Oceanography, 16(12):2205-2207, 1986.

(774) Fels, Stephen B., An Approximate Analytical Method for Calculating Tides in the Atmosphere of Venus, Journal of the Atmospheric Sciences, 43(23):2757-2772, 1986.

(775) Orlanski, I. Localized Baroclinicity: A Source for Meso-Cyclones, Journal of the Atmospheric Sciences, 43(23):2857-2885, 1986.

* (776) Kang, In-Sik, and Isaac M. Held, Linear and Nonlinear Diagnostic Models of Stationary Eddies in the Upper Troposphere During Northern Summer, Journal of Atmospheric Sciences, 43(24): 3045-3057, 1986.

(777) Hayashi, Y., and D. G. Golder, Tropical Intraseasonal Oscillations Appearing in a GFDL General Circulation Model and FGGE Data, Part I: Phase Propagation, Journal of the Atmospheric Sciences, 43(24):3058-3067, 1986.

* (778) Nigam, Sumant, Isaac M. Held, and Steven W. Lyons, Linear Simulation of the Stationary Eddies in a GCM, Part I: The 'No-Mountain Model', Journal of the Atmospheric Sciences, 43(23):2944-2961, 1986.

* (779) Kurihara, Yoshio and Mitsuhiro Kawase, Reply (in reference to Interpretation of Kurihara-Kawase's 2-Dimensional Tropical-Cyclone Development Model), Journal of the Atmospheric Sciences, 43(24):3284-3286, 1986.

* (780) Lin, S. J., and R. T. Pierrehumbert, Comments on "Richardson Criteria for Stratified Vortex Motions under Gravity" Physics of Fluids, 30(4):1231-1232, 1986.

* (781) Navarra, A., An Application of the Arnoldi's Method to a Geophysical Fluid Dynamics Problem, Journal of Computational Physics, 69(1):143-162, 1986.

(782) Pierrehumbert, R. T., Lee Cyclogenesis, In Mesoscale Meteorology and Forecasting, Peter S. Ray (ed.). American Meteorological Society, Boston, MA. 493-515, 1986.

*In collaboration with other organizations

(783) Lau, Ngar-Cheung, and Mary Jo Nath, Frequency Dependence of the Structure and Temporal Development of Wintertime Tropospheric Fluctuations - Comparison of a GCM Simulation with Observations, _Monthly Weather Review_, 115(1):251-271, 1987.

(784) Held, Isaac and Peter Phillips, Linear and Nonlinear Barotropic Decay on the Sphere, _Journal of Atmospheric Sciences_, 44(1): 200-207, 1987.

(785) Philander, S. G. H., W. Hurlin, and R. C. Pacanowski, Initial Conditions for a General Circulation Model of Tropical Oceans, _Journal of Physical Oceanography_, 17(1):147-157, 1987.

* (786) Garcia, Rolando R., and Murry L. Salby, Transient Response to Localized Episodic Heating in the Tropics Part II: Far-Field Behavior, _Journal of the Atmospheric Sciences_, 44(2):499-530, 1987.

* (787) Neelin, J. David, and Isaac M. Held, Modelling Tropical Convergence Based on the Moist Static Energy Budget, _Journal of the Atmospheric Sciences_, 115(1):3-12, 1987.

* (788) Plumb, R. A., and J. D. Mahlman, The Zonally-Averaged Transport Characteristics of the GFDL General Circulation/Transport Model, _Journal of the Atmospheric Sciences_, 44(2):298-327, 1987.

(789) Philander, S. G. H., Unusual Conditions in the Tropical Atlantic Ocean in 1984, _Nature_, 322(6076):236-238, 1987.

(790) Philander, S. G. H., Predictability of El Niño, _Nature_, 321(6073): 810-811, 1987.

(791) Miyakoda, K., J. Sirutis, and T. Knutson, Experimental 30-Day Forecasting at GFDL, Proceedings of Workshop on Predictability in the Medium and Extended Range Forecasts, ECMWF, Reading, England, 17-19 March. 1986. ECMWF Internal Report, 17-50, 1987.

(792) Levitus, Sydney, A Comparison on the Annual Cycle of Two Sea Surface Temperature Climatologies of the World Ocean, _Journal of Physical Oceanography_, 17(4):197-214, 1987.

(793) Levitus, Sydney, Rate of Change of Heat Storage in the World Ocean, _Journal of Physical Oceanography_, 17(4):518-528, 1987.

* (794) Oort, A., Y. H. Pan, R. W. Reynolds, and C. F. Ropelewski, Historical Trends in the Surface Temperature over the Oceans Based on the COADS, _Climate Dynamics_, 2:29-38, 1987.

(795) Manabe, S., and R. Wetherald, Large Scale Changes of Soil Wetness Induced by an Increase in Atmospheric Carbon Dioxide, _Journal of the Atmospheric Sciences_, 44:1211-1235, 1987.

*In collaboration with other organizations

* (796) Kraus, Eric B., and Sydney Levitus, Annual Heat and Mass Flux Variations across the Tropics of Cancer and Capricorn in the Pacific, Journal of Physical Oceanography, 16:1479-1486, 1987.

* (797) Mesinger, Fedor and Raymond T. Pierrehumbert, Alpine Lee Cyclogenesis: Numerical Simulation and Theory, Proceedings of the Scientific Conference on the Results of the Alpine Experiment (ALPEX), 28 Oct - 1 Nov. 1985, Venice, Italy. WMO/TD-108, 27:141-163, 1987.

* (798) Huang, Rui-Xin, A Three Layer Model for Wind Driven Circulation in a Subtropical/Subpolar Basin, Part I: Model Formulation and the Subcritical State, Journal of Physical Oceanography, 17(5): 664-678, 1987.

* (799) Huang, Rui-Xin, A Three Layer Model for Wind Driven Circulation in a Subtropical/Subpolar Basin. Part II: The Supercritical and Hypercritical States, Journal of Physical Oceanography, 17(5):679-697, 1987.

(800) Derber, John C., Variational Four-Dimensional Analysis Using Quasi-Geostrophic Constraints, Monthly Weather Review, 115(5): 998-1008, 1987.

(801) Gordon, Charles Tony, The Specification of Radiatively Constrained, Effective Clouds in GCM's: Methodology and Some Preliminary Results. Proceedings of the ECMWF Workshop on Cloud Cover Parameterization in Numerical Models, Reading, England, November 26-28, 1984, pp. 133-161, 1987.

* (802) Wang, Bin, The Nature of CISK in a Generalized Continuous Model, Journal of the Atmospheric Sciences, 44(10):1411-1426, 1987.

* (803) Sarmiento, J. L., Tracers and Modeling, Reviews of Geophysics, 25(6):1417-1419, 1987.

* (804) Albritton, Daniel L., James K. Angell, Jerry D. Mahlman, Alvin J. Miller, James T. Peterson, Walter G. Planet, Stratospheric Ozone: The State of the Science and NOAA's Current and Future Research, NOAA Report, 1-39, 1987.

(805) Oort, A.H., Variability of the Hydrological Cycle in the Asian Monsoon Region, Talk presented at the Beijing International Symposium on Climate, Oct 30 - Nov. 3, 1984, in the Symposium Proceedings, Oceanic Press, Beijing, 270-285, 1987.

* (806) Oort, Abraham H., and Yi-Hong Pan, Diagnosis of Historical ENSO Events, Proceedings First WMO Workshop on the Diagnosis and Prediction of Monthly and Seasonal Atmospheric Variations over the Globe, College Park, MD. 29 July - 2 August 1985, WMO/TD No. 87, 1987.

*In collaboration with other organizations

* (807) Oort, Abraham H., and Barry Saltzman, The Impact of Jose Peixoto's Work on Geophysics, METEORO, Lisbon, Portugal, 6:13-18, 1987.

* (808) Salby, Murry L., and Rolando R. Garcia, Transient Response to Localized Episodic Heating in the Tropics Part I: Excitation and Short-Time Near-Field Behavior, Journal of the Atmospheric Sciences, 44(2):458-498, 1987.

(809) Gardiner-Garden, Robert S., Some Aspects of Modelling the Structure of Currents in Wind-Forced Coastal Upwelling Systems, Ph.D. Dissertation, Atmospheric and Oceanic Sciences Program, Princeton University, 1987.

(810) Bacmeister, Julio T., Nonlinearity in Transient, Two-Dimensional Flow over Topography, Ph.D. Dissertation, Atmospheric and Oceanic Sciences Program, Princeton University, 1987.

(811) Rajkovic, Borivoj M., Air-Sea Interaction in the Vicinity of a Land-Sea Boundary in the Presence of Upwelling, Ph.D. Dissertation, Atmospheric and Oceanic Sciences Program, Princeton University, 1987.

(812) Steele, Michael, Numerical Models of Sea Ice-Ocean Interaction in the Marginal Ice Zone, Ph.D. Dissertation, Atmospheric and Oceanic Sciences Program, Princeton University, 1987.

(813) Carissimo, Bertrand C., The Pressure Drag and Momentum Flux during a Cold Frontal Passage Over the Alps, Ph.D. Dissertation, Atmospheric and Oceanic Sciences Program, Princeton University, 1987.

(814) Neelin, J. David, Simple Models of Steady and Low Frequency Circulations in the Tropical Atmosphere, with Application to Tropical Air-Sea Interactions, Ph.D. Dissertation, Atmospheric and Oceanic Sciences Program, Princeton University, 1987.

(815) Broccoli, A. J., and S. Manabe, The Effects of the Laurentide Ice Sheet on North American Climate during the Last Glacial Maximum, Geographie Physique et Quaternaire,XLI(2):291-299, 1987.

* (816) Park, Jeffrey, Craig R. Lindberg, and Frank L. Vernon III, Multitaper Spectral Analysis of High-Frequency Seismograms, Journal of Geophysical Research, 1-9, 1987.

* (817) Park, Jeffrey, Frank L. Vernon III, and Craig R. Lindberg, Frequency Dependent Polarization Analysis of High-Frequency Seismograms, Journal of Geophysical Research, 1-7, 1987.

*In collaboration with other organizations

(818) Lau, Ngar-Cheung, The Influences of Orography on Large-Scale Atmospheric Flow Simulated by a General Circulation Model. Proceedings of International Symposium of the Qinghai-Xizang Plateau and Mountain Meteorology, Beijing. People's Republic of China, 20-24 March, 1984. American Meteorological Society, Boston, MA. 241-269, 1987.

(819) Bender, Morris A., Robert E. Tuleya, Yoshio Kurihara, A Numerical Study of the Effect of Island Terrain on Tropical Cyclones, Monthly Weather Review, 115(1):130-155, 1987.

* (820) Bryan, Frank, Parameter Sensitivity of Primitive Equation Ocean General Circulation Models, Journal Of Physical Oceanography, 17(7):970-985, 1987.

(821) Pacanowski, R. C., Effect of Equatorial Currents on Surface Stress, Journal of Physical Oceanography, 17(6):833-838, 1987.

(822) Cox, Michael D., An Eddy-Resolving Numerical Model of the Ventilated Thermocline:Time Dependence, Journal of Physical Oceanography, 17(7):1044-1056, 1987.

* (823) Ramanathan, V., L. Callis, R. Cess, J. Hansen, I. Isaksen, W. Kuhn, A. Lacis, F. Luther, J. Mahlman, R. Reck, and M. Schlesinger, Climate-Chemical Interactions and Effects of Changing Atmospheric Trace Gases, Reviews of Geophysics, 25(7):1441-1482, 1987.

* (824) Knutson, Thomas R., and Klaus M. Weickmann, 30-60 Day Atmospheric Oscillations: Composite Life Cycles of Convection Anomalies, Monthly Weather Review 115(7):1407-1436, 1987.

* (825) Wang, Bin and Isidoro Orlanski, Study of a Heavy Rainfall Vortex Formed over the Eastern Flank of the Tibetan Plateau, Monthly Weather Review, 115(7):1370-1393, 1987.

(826) Hayashi, Yoshikazu, A Modification of the Atmospheric Energy Cycle, Journal of the Atmospheric Sciences, 44(15):2006-2017, 1987.

(827) Bender, Morris A., and Yoshio Kurihara, A Numerical Study of the Effect of the Mountainous Terrain of Japan on Tropical Cyclones, Proceedings of Short- and Medium-Range Numerical Weather Prediction, WMO/IUGG NWP Symposium, Tokyo, Japan, 4-8 August 1986, 651-663, 1987.

(828) Stern, W., R. Pierrehumbert, J. Sirutis, J. Ploshay and K. Miyakoda, Recent Developments in the GFDL Extended-Range Forecasting System, Proceedings of Short- and Medium-Range Numerical Weather Prediction, WMO/IUGG NWP Symposium, Tokyo, Japan, 4-8 August 1986, 359-363, 1987.

*In collaboration with other organizations

* (829) Neelin, J. David, Isaac M. Held, and Kerry H. Cook, Evaporation-Wind Feedback and Low Frequency Variability in the Tropical Atmosphere, Journal of the Atmospheric Sciences, 44(16):2341-2348, 1987.

(830) Held, Isaac M., New Conservation Laws for Linear Quasi-Geostrophic Waves in Shear, Journal of the Atmospheric Sciences, 44(16): 2349-2351, 1987.

* (831) Karoly, David J., and Abraham H. Oort, A Comparison of Southern Hemisphere Circulation Statistics Based on GFDL and Australian Analyses, Monthly Weather Review, 115(9):2033-2059, 1987.

(832) Levitus, Sydney, Meridional Ekman Heat Fluxes for the World Ocean and Individual Ocean Basins, Journal of Physical Oceanography, 17(9):1484-1492, 1987.

(833) Mahlman, J. D., and L. J. Umscheid, Comprehensive Modeling of the Middle Atmosphere: The Influence of Horizontal Resolution, In Transport Processes in the Middle Atmosphere, G. Visconti and R. Garcia (eds.), D. Reidel:NATO Scientific Affairs Division 251-266, 1987.

(834) Fels, S. B., Response of the Middle Atmosphere to Changing O_3 and CO_2 - A Speculative Tutorial, In Transport Processes in the Middle Atmosphere, G. Visconti and R. Garcia (eds.), D. Reidel: NATO Scientific Affairs Division, 371-386, 1987.

* (835) Hibler, W. D., and K. Bryan, A Diagnostic Ice-Ocean Model, Journal of Physical Oceanography, 17(7):978-1015, 1987.

(836) Ross, Bruce B., The Role of Low-Level Convergence and Latent Heating in a Simulation of Observed Squall Line Formation, Monthly Weather Review, 115(10):2298-2321, 1987.

* (837) Huang, Rui-Xin, Partial Solutions for Inertial Western Boundary Current with Continuous Stratification, Proceedings of Gulf Stream Workshop, Exeter, R.I., 23-26 April 1985, 11320-11361, 1987.

(838) Bryan, Kirk, Potential Vorticity in Models of the Ocean Circulation, Quarterly Journal of the Royal Meteorological Society, 113, 713-734, 1987.

(839) Park, Jeffrey and Timothy Herbert, Hunting for Paleoclimatic Periodicities in a Geologic Time Series with an Uncertain Time Scale, Journal of Geophysical Research, 92(B13):14027-14040, 1987.

*In collaboration with other organizations

(840) Levy, Hiram, II, and Walter J. Moxim, Fate of U.S. and Canadian Combustion Nitrogen Emissions, Nature, 328(No.6129):414-416, 1987.

* (841) Huang, Rui-Xin and Kirk Bryan, A Multi-Layer Model of the Thermohaline and Wind Driven Ocean Circulation: Model Development and Initial Test, Journal of Physical Oceanography, 17(11):1909-1924, 1987.

* (842) Wang, Bin, On the Development Mechanism for Tibetan Plateau Warm Vortices, Journal of the Atmospheric Sciences, 44(20):2978-2994, 1987.

* (843) Philander, S. G. H., W. J. Hurlin, and A. D. Seigel, Simulation of the Seasonal Cycle of the Tropical Pacific Ocean, Journal of Physical Oceanography 17(11):1986-2002, 1987.

(844) Hayashi, Y., and D. Golder, Effects of Wave-Wave and Wave-Mean Flow Interactions on the Growth and Maintenance of Transient Planetary Waves in the Presence of a Mean Thermal Restoring Force, Journal of the Atmospheric Sciences, 44(22):3392-3401, 1987.

(845) Orlanski, Isidoro and Jack J. Katzfey, Sensitivity of Model Simulations for a Coastal Cyclone, Monthly Weather Review, 115(11): 2792-2821, 1987.

(846) Crook, N. Andrew, Moist Convection at a Surface Cold Front, Journal of the Atmospheric Sciences, 44(23):3469-3494, 1987.

(847) Hayashi, Y., and S. Miyahara, A Three-Dimensional Linear Response Model of the Tropical Intraseasonal Oscillation, Journal of the Meteorological Society of Japan, 65(6):843-852, 1987.

* (848) Held, Isaac M., and In-Sik Kang, Barotropic Models of the Extratropical Response to El Nino, Journal of the Atmospheric Sciences, 44(23):3576-3586, 1987.

* (849) Galperin, Boris, S. Hassid, L. Kantha, and A. Rosati, A Quasi-Equilibrium Turbulent Energy Model for Geophysical Flows, Journal of the Atmospheric Sciences, 45(1):55-62, 1988.

* (850) Savijarvi, Hannu, On the Maintenance Mechanisms of Daily Transient Large-Scale Variations in the Atmosphere, Part I: Journal of the Atmospheric Sciences, 45(1):29-40, 1988.

* (851) Bacmeister, J. T., and R. T. Pierrehumbert, On High Drag States of Nonlinear Stratified Flow Over an Obstacle, Journal of the Atmospheric Sciences, 45(1):63-80, 1988.

*In collaboration with other organizations

(852) Williams, Gareth P., and R. J. Wilson, The Stability and Genesis of Rossby Vortices, Journal of the Atmospheric Sciences, 45(2): 207-241, 1988.

(853) Levy, II. H., Global Transport of Ozone, In Tropospheric Ozone, I.S.A. Isaksen (ed.). D. Reidel Publishing Co. 319-325, 1988.

(854) Fels, Stephen B., Reply to A Parameterization of Scale-Dependent Radiative Damping in the Middle Atmosphere, Journal of the Atmospheric Physics, 44(24):3829-3832, 1988.

* (855) Boning, Claus W., and Michael D. Cox, Particle Dispersion and Mixing of Conservative Properties in an Eddy-Resolving Model, Journal of Physical Oceanography, 18(2):320-338, 1988.

* (856) Savijarvi, H. I., Global Energy and Moisture Budgets from Rawindsonde Data, Monthly Weather Review, 116(2):417-430, 1988.

(857) Levitus, Sydney, Ekman Volume Fluxes for the World Ocean and Individual Ocean Basins, Journal of Physical Oceanography, 18(2):270-279, 1988.

* (858) Panetta, R. Lee, Isaac M. Held, and Raymond T. Pierrehumbert, External Rossby Waves in the Two-Layer Model, Journal of the Atmospheric Sciences, 44(20):2924-2933, 1988.

(859) Wetherald, R. T., and S. Manabe, Cloud Feedback Processes in a General Circulation Model, Journal of the Atmospheric Sciences, 45(8):1397-1415, 1988.

* (860) Wang, Bin, Another Look at CISK in Polar Oceanic Air Masses, Tellus, 39A:179-186, 1988.

* (861) Neelin, J. David, A Simple Model for Surface Stress and Low Level Flow in the Tropical Atmosphere Driven by Prescribed Heating, Quarterly Journal of the Royal Meteorological Society, 114: 747-770, 1988.

* (862) Navarra, A., and K. Miyakoda, Anomaly General Circulation Models, Journal of the Atmospheric Sciences, 45(9):1509-1530, 1988.

* (863) Nigam, Sumant, Isaac M. Held, and Steven W. Lyons, Linear Simulation of the Stationary Eddies in a GCM, Part II: The "Mountain" Model, Journal of the Atmospheric Sciences, 45(9):1433-1452, 1988.

(864) Williams, Gareth P., The Dynamical Range of Global Circulations - I, Climate Dynamics, 2, 205-260, 1988.

*In collaboration with other organizations

(865) Orlanski, I., and J. Katzfey, Sensitivity of Numerical Simulations of the President's Day Snowstorm, Preprints, 8th Conference on Numerical Weather Prediction, Baltimore, MD, February 22-26, 1988. American Meteorology Society, Boston, 674-681, 1988.

(866) Lipps, Frank B., Richard S. Hemler, and Bruce B. Ross, Numerical Simulation of a Squall Line Using a Nested Grid, Preprints, 8th Conference on Numerical Weather Prediction, Baltimore, MD, February 22-26, 1988. American Meteorology Society, Boston, J141-J160, 1988.

(867) Stern, W. F., and R. T. Pierrehumbert, The Impact of an Orographic Gravity Wave Drag Parameterization on Extended Range Predictions with a GCM, Preprints, 8th Conference on Numerical Weather Prediction, Baltimore, MD, February 22-26, 1988. American Meteorology Society, Boston, 745-750, 1988.

* (868) Savijarvi, H. I., Atmospheric Energy Budgets from FGGE and Station Data, Geophysica, 23(2):79-96, 1988.

* (869) Crook, N. Andrew, Trapping of Low Level Internal Gravity Waves, Journal of the Atmospheric Sciences, 45(10):1533-1541, 1988.

(870) Bryan, K., S. Manabe, and M. J. Spelman, Interhemispheric Asymmetry in the Transient Response of a Coupled Ocean-Atmosphere Model to a CO_2 Forcing, Journal of Physical Oceanography, 18(6):851-867, 1988.

(871) Tuleya, Robert, A Numerical Study of the Genesis of Tropical Storms Observed during the FGGE Year, Monthly Weather Review, 116(5): 1188-1208, 1988.

* (872) Sarmiento, Jorge L., J. R. Toggweiler, and Raymond Najjar, Ocean Carbon-Cycle Dynamics and Atmospheric p_{CO2}, Philosophical Transactions of the Royal Society, London, A 325, 3-21, 1988.

(873) Toggweiler, J. R., Deep-Sea Carbon, A Burning Issue, Nature, 334, p. 468, 1988.

* (874) Zhu, Xun, An Improved Voigt Line Approximation for the Calculations of Equivalent Width and Transmissions, Journal of Quantitative Spectroscopy and Radiative Transfer, 39(6):421-427, 1988.

* (875) Ramaswamy, V., Dehydration Mechanism in the Antarctic Stratosphere During Winter, Geophysical Research Letters, 15(8):863-866, 1988.

* (876) Nakamura, Noboru, and Abraham H. Oort, Atmospheric Heat Budgets of the Polar Regions, Journal of Geophysical Research - Atmospheres, 93(D8):9510-9524, 1988.

*In collaboration with other organizations

(877) Oort, A. H., Climate Observations and Diagnosis, In Physically-Based Modelling and Simulation of Climate and Climatic Change - Part II, M. E. Schlesinger (ed.), Kluwer Academic Publishers, 813-840, 1988.

(878) Delworth, T., and S. Manabe, The Influence of Potential Evaporation on the Variabilities of Soil Wetness and Climate, Journal of Climate, 1(5):523-547, 1988.

(879) Philander, S. G. H., and W. J. Hurlin, The Heat Budget of the Tropical Pacific Ocean in a Simulation of El Niño of 1982-1983, Journal of Physical Oceanography, 18(6):926-931, 1988.

* (880) Sarmiento, J. L., T. Herbert, and J. R. Toggweiler, Causes of Anoxia in the World Ocean, Global Biogeochemical Cycles, 2(2):115-128, 1988.

* (881) Mesinger, Fedor, Zavisa I. Janjic, Slobodan Nickovic, Dusanka Gavrilov, and Dennis Deaven, The Step-Mountain Coordinate: Model Description, and Performance for Cases of Alpine Lee Cyclogenesis and for a Case of an Appalachian Redevelopment, Monthly Weather Review, 116(7):1493-1518, 1988.

(882) Lau, Ngar-Cheung, Modeling of ENSO Phenomena at GFDL. Proceedings of U.S.-Japan Workshop on the El Niño Southern Oscillation Phenomenon, University of Tokyo, November 3-7, 1987, Division of Meteorology, Geophysical Institute, Tokyo, Japan, 160-168, 1988.

* (883) Carissimo, B. C., R. T. Pierrehumbert, and H. L. Pham, An Estimate of Mountain Drag during ALPEX for Comparison with Numerical Models, Journal of the Atmospheric Sciences, 45(13):1949-1960, 1988.

(884) Williams, Gareth P., The Dynamical Range of Global Circulations - II. In Climate Dynamics, 3:45-84, Springer-Verlag, 45-84, 1988.

(885) Lipps, Frank B., and Richard S. Hemler, Numerical Modelling of a Line of Towering Cumulus on Day 226 of GATE, Journal of the Atmospheric Sciences, 45(17):2428-2444, 1988.

* (886) Brasseur, G.P., J. C. Farman, I.S.A. Isaksen, B.C. Kruger, K. Labitzke, J.D. Mahlman, M.P. McCormick, P. Solomon, R.S. Stolarski, A. Turco, R.T. Watson, Changes in Antarctic Ozone. In The Changing Atmosphere, F.S. Rowland and I.S.A. Isaksen (eds). Wiley- Interscience, New York, 235-256, 1988.

(887) Cook, Kerry H., and Isaac M. Held, Stationary Waves of the Ice Age Climate, Journal of Climate, 9(8):807-819, 1988.

*In collaboration with other organizations

(888) Oort, Abraham H., The Search for Unity in the Climate System, Summary of a Lecture Series given at the Proceedings of Institut d 'Astronomie et de Geophysique, Lourain-la-Neuve, Belgium, 1-28, 1988.

(889) Lau, Ngar-Cheung, Variability of the Observed Midlatitude Storm Tracks in Relation to Low-Frequency Changes in the Circulation Pattern, Journal of the Atmospheric Sciences, 45(1):2718-2743, 1988.

* (890) Lin, Shian-Jiann and Ray Pierrehumbert, Does Ekman Friction Suppress Baroclinic Instability? Journal of the Atmospheric Sciences, 45(20):2920-2933, 1988.

* (891) Nakamura, Noboru, On the Scale Selection of Baroclinic Instability-Effects of Stratification and Non-Geostrophy, Journal of the Atmospheric Sciences, 45(21):3253-3267, 1988.

(892) Hayashi, Y., and D. G. Golder, Tropical Intraseasonal Oscillations Appearing in a GFDL General Circulation Model and FGGE Data Part II: Structure and Moisture Effects, Journal of the Atmospheric Sciences, 45(21):3017-3033, 1988.

* (893) Hamilton, Kevin and J. D. Mahlman, General Circulation Model Simulation of the Semiannual Oscillation of the Tropical Middle Atmosphere, Journal of the Atmospheric Sciences, 45(21):3212-3235, 1988.

(894) Panetta, R. Lee, and Isaac M. Held, Baroclinic Eddy Fluxes in a One-Dimensional Model of Quasi-geostrophic Turbulence, Journal of the Atmospheric Sciences, 45(22):3354-3365, 1988.

* (895) Miyakoda, K., A. Rosati, and R. Gudgel, and Y. Chao, Study of ENSO with an Ocean GCM, In Persistent Meteo-Oceanographic Anomalies and Teleconnections, C. Chagas and G. Puppi (eds.), Pontificaiae Academiae Scientiarvm Scripta Varia, 69:97-119, 1988.

(896) Manabe, S., and R. J. Stouffer, Two Stable Equilibria of a Coupled Ocean-Atmosphere Model, Journal of Climate, 1(9):841-866, 1988.

(897) Mahlman, Jerry D., Theoretical Projections of Stratospheric Change Due to Increasing Greenhouse Gases and Changing Ozone Concentrations, In Ozone Depletion, Greenhouse Gases, and Climate Change, National Research Council, National Academy Press, Washington, DC., 66-78 pp. 1988.

(898) Rosati, A., and K. Miyakoda, A GCM for Upper Ocean Simulation, Journal of Physical Oceanography, 18(11):1601-1626, 1988.

*In collaboration with other organizations

(899) Levitus, Sydney, Decadal and Pentadal Distributions of Hydrographic Stations at 1000m Depth for the World Ocean, Progress in Oceanography, 20:83-101, 1988.

* (900) Hamilton, K., and A. M. Allingham, A Note on Equatorial Atlantic Sea Surface Temperature Variations, Atmosphere-Ocean (Canada), 26(4):668-678, 1988.

* (901) Sarmiento, J. L., T. Herbert, and J. R. Toggweiler, Mediterranean Nutrient Balance and Episodes of Anoxia, Global Biogeochemical Cycles, 2(4):427-444, 1988.

* (902) Snieder, Roelof K., and Stephen B. Fels, The Flywheel Effect in the Middle Atmosphere, Journal of Atmospheric Sciences, 45(24):3996-4004, 1988.

* (903) Lau, Ngar-Cheung, Isaac M. Held, and J. David Neelin, The Madden-Julian Oscillations in an Idealized General Circulation Model, Journal of the Atmospheric Sciences, 45(24):3810-3832, 1988.

* (904) Held, Isaac, Steven W. Lyons, and Sumant Nigam, Transients and the Extratropical Response to El Nino, Journal of the Atmospheric Sciences, 46(1):163-174, 1989.

(905) Ramaswamy, V., Aerosol Radiative Forcing and Model Responses. In Aerosols and Climate, M.P. McCormick and P.V. Hobbs (eds.). A. Deepak Publishing Co., 349-372, 1989.

(906) Toggweiler, J. R., Are Rising and Falling Particles Microbial Elevators? Nature, 337(23):691-692, 1989.

(907) Lau, Ngar-Cheung, Variability of the Wintertime Cyclone Tracks in the Extratropical Northern Hemisphere, Proceedings of NCAR Summer Colloquium on "Dynamics of Low-Frequency Phenomena in the Atmosphere", Vol. 1:139-154, 1989.

(908) Boning, Claus W., Influences of a Rough Bottom Topography on Flow Kinematics in an Eddy Resolving Circulation Model, Journal of Physical Oceanography, 19(1):77-97, 1989.

* (909) Steele, Michael, George L. Mellor, and Miles G. McPhee, Role of the Molecular Sub-layer in the Melting or Freezing of Sea Ice, Journal of Physical Oceanography, 19(1):139-147, 1989.

(910) Thompson, Starley L., V. Ramaswamy, and Curt Covey, Atmospheric Effects of Nuclear War Aerosols in General Circulation Model Simulations: Influence of Smoke Optical Properties, Journal of Geophysical Research, 92(D9):10942-10960, 1989.

*In collaboration with other organizations

* (911) Oort, Abraham H., Stephen C. Ascher, Sydney Levitus, Jose P. Peixoto, New Estimates of the Available Potential Energy in the World Ocean, Journal of Geophysical Research, 94(C3):3187-3200, 1989.

(912) Miyakoda, K., and J. Sirutis, A Proposal of Moist Turbulence Closure Scheme, and the Rationalization of Arakawa-Schubert Cumulus Parameterization, Meteorology and Atmospheric Physics, 40:110-122, 1989.

* (913) Chang, Ping and S. G. H. Philander, Rossby Wave Packets in Baroclinic Mean Currents, Deep Sea Research, No. 1, 17-37, 1989.

(914) Miyakoda, K., Atmospheric Forecast Model Data Assimilation and Air Sea Flux Computations, Workshop Report on Atmospheric Forcing of Ocean Circulation, Tulane University, New Orleans, LA. January 4-7, 1988, sponsored by (INO),(WOCE), and (TOGA), 55-94, 1989.

* (915) Hayashi, Y., D. G. Golder, J. D. Mahlman, and S. Miyahara, The Effect of Horizontal Resolution on Gravity Waves Simulated by the GFDL "SKYHI" General Circulation Model, PAGEOPH, 130(2/3): 421-443, 1989

(916) Levy, Hiram II, Simulated Global Deposition of Reactive Nitrogen Emitted by Fossil Fuel Combustion, Proceedings of IAHS Third Scientific Assembly, Symposium I, Atmospheric Deposition, 11 May 1989, Baltimore, MD. 3-9, 1989.

(917) Hamilton, Kevin, Evaluation of the Gravity Wave Field in the Middle Atmosphere of the GFDL "SKYHI" General Circulation Model, Proceedings of Workshop on Systematic Errors in Models of the Atmosphere, Toronto, Canada, 19-23 September 1988, WMO/TD No. 273, 264-271, 1989.

(918) Sirutis, J., and K. Miyakoda, Systematic Bias in Predictions with A Coupled Air-Sea Model, Proceedings of Workshop on Systematic Errors in Models of the Atmosphere, Toronto, Canada, 19-23 September 1988, WMO/TD No. 273, 136-140, 1989.

(919) Stern, W. F., and K. Miyakoda, Systematic Errors in GFDL's Extended Range Prediction, Proceedings of Workshop on Systematic Errors in Models of the Atmosphere, Toronto, Canada, 19-23 September 1988, WMO/TD No. 273, 78-122, 1989.

(920) Kantha, Lakshmi, and George L. Mellor, A Numerical Model of the Atmospheric Boundary Layer Over a Marginal Ice Zone, Journal of Geophysical Research, 94(C4):4959-4970, 1989.

*In collaboration with other organizations

(921) Kantha, L. H., A. Rosati, and B. Galperin, Effect of Rotation on Vertical Mixing and Associated Turbulence in Stratified Fluids, Journal of Geophysical Research, 94(C4):4843-4854, 1989.

(922) Hamilton, Kevin, Interhemispheric Asymmetry and Annual Synchronization of the Ozone Quasi-Biennial Oscillation, Journal of the Atmospheric Sciences, 46(7):1019-1025, 1989.

* (923) Galperin, B. and L. H. Kantha, A Turbulence Model for Rotating Flows, American Astrophysical and Aeronautical Journal, 27(6): 750-757, 1989.

* (924) Galperin, B., A. Rosati, L. H. Kantha, and G. L. Mellor, Modeling Rotating Stratified Turbulent Flows with Application to Oceanic Mixed Layers, Journal of Physical Oceanography, 19(7):901-916, 1989.

(925) Zhu, Xun, Radiative Cooling Calculated by Random Band Models with S^{-1}- Tailed Distribution, Journal of the Atmospheric Sciences, 46(4):511-520, 1989.

(926) Levy, Hiram II, and Walter J. Moxim, Influence of Long-Range Transport of Combustion Emissions on the Chemical Variability of the Background Atmosphere, Nature, 338(6213):326-328, 1989.

(927) Toggweiler, J. R., K. Dixon, and K. Bryan, Simulations of Radiocarbon in a Coarse-Resolution, World Ocean Model I: Steady-State, Pre-Bomb Distributions, Journal of Geophysical Research, 94(C6):8217-8242, 1989.

(928) Toggweiler, J. R., K. Dixon, and K. Bryan, Simulations of Radiocarbon in a Coarse Resolution World Ocean Model II: Distributions of Bomb-Produced ^{14}C, Journal of Geophysical Research, 94(C6):8243-8264, 1989.

* (929) Levy, Hiram II, and Walter J. Moxim, Simulated Global Distribution and Deposition of Reactive Nitrogen Emitted by Fossil Fuel Combustion, Tellus, (41B):256-271, 1989.

(930) Karoly, David J., Northern Hemisphere Temperature Trends: A Possible Greenhouse Gas Effect, Geophysical Research Letters, 16(5): 465-468, 1989.

(931) Levy, Hiram II, Tracers of Atmospheric Transport, Nature, 325(6107): 761-762, 1989.

(932) Levitus, Sydney, Interpentadal Variability of Temperature and Salinity at Intermediate Depths of the North Atlantic Ocean, (1970-74) versus (1955-59), Journal of Geophysical Research, 94(C5):6091-6131, 1989.

*In collaboration with other organizations

(933) Savijarvi, Hannu, and Huug M. van den Dool, On the Maintenance Mechanisms of Transient Large-Scale Variations in the Atmosphere, Part II: Motion Field, Scientific Report No. 88-37, Department of Meteorology, University of Maryland, College Park, MD., 1989.

(934) Pierrehumbert, R. T., An Essay on the Parameterization of Orographic Wave Drag. Proceedings of the ECMWF Seminars on Orographic Effects, July 1987. ECMWF Report, Reading, England, 1989.

* (935) Pierrehumbert, R. T., and J. T. Bacmeister, On the Realizability of Long's Model Solutions for Nonlinear Stratified Flow over an Obstacle, Proceedings of the Fourth International Symposium on Stratified Flow, California Technical Institute, August 1987. Elsevier, 1989.

(936) Toggweiler, J. R., Is the Downward Dissolved Organic Matter (DOM) Flux Important in a Carbon Transport? In Productivity of the Ocean: Present and Past, Dahlem Konferenzen, W. H. Berger, V. S. Smetacek, and G. Wefer, eds. John Wiley & Sons, Ltd. 65-83, 1989.

* (937) Ramaswamy, V., and V. Ramanathan, Solar Absorption by Cirrus Clouds and the Maintenance of the Tropical Upper Troposphere Thermal Structure, Journal of the Atmospheric Sciences, 46(14):2293-2310, 1989.

(938) Levy, Hiram, II, and Walter J. Moxim, Examining the Global Impact of Local/Regional Air Pollution: The Role of Global Chemical Transport Models, Proceedings of the 17th NATO/CCMS International Technical Meeting on Air Pollution Modelling and its Application, Cambridge, England, September 19-22, 1988, Plenum Publishing Co. 139-157, 1989.

(939) Kurihara, Yoshio and Morris A. Bender, On the Structure of Moving Tropical Cyclones, Proceedings of the 18th Conference on Hurricanes and Tropical Meteorology, 16-19 May, 1989, San Diego CA. American Meteorological Society, Boston, MA, 188-189, 1989.

(940) Levitus, Sydney., Interpentadal Variability of Salinity in the Upper 150 m of the North Atlantic Ocean, 1970-74 Versus 1955-59, Journal of Geophysical Research, 94(C7):9679-9685, 1989.

(941) Kantha, Lakshmi, and George L. Mellor, Application of a Two-Dimensional Coupled Ocean-Ice Model to the Bering Sea Marginal Ice Zone, Journal of Geophysical Research, 94(C8):10921-10935, 1989.

(942) Lin, Shiann-Jiann, The Instability Mechanism of Synoptic-Scale Eddies, Ph.D. Dissertation, Atmospheric and Oceanic Sciences Program, Princeton University, 1989.

*In collaboration with other organizations

(943) Chang, Ping, Oceanic Adjustment in the Presence of Mean Currents, Ph.D. Dissertation, Atmospheric and Oceanic Sciences Program, Princeton University, 1989.

(944) Nakamura, Noboru, Dynamics of Baroclinic Instability in Rapid Cyclogenesis, Atmospheric and Oceanic Sciences Program, Princeton University, 1989.

*In collaboration with other organizations

(iq) Derber, John C., Practical Data Assimilation for the Ocean, Proceedings of the Second WMO Workshop on Diagnostics and Prediction of Monthly and Seasonal Atmospheric Variations over the Globe Combined with the WMO Symposium on Ocean-Atmosphere, Toulouse, France, 15-19 June 1987.

(iz) Manabe, S., and T. Delworth, The Temporal Variability of Soil Wetness and its Impact on Climate, Climatic Change, October 1987.

(jq) Levitus, Sydney, Exploratory Data Analysis of Oceanographic Data: The Use of Frequency Distributions of Static Stability for Quality Control, Deep Sea Research, February 1988.

* (ka) McPhee, M. G., and L. H. Kantha, Generation of Internal Waves by Sea Ice, Journal of Geophysical Research, April 1988.

(kc) Mellor, George L., and Lakshmi H. Kantha, An Ice Coupled Model, Journal of Geophysical Research, May 1988.

* (kf) Pan, Yi Hong, and Abraham H. Oort, Correlation Analyses between Sea Surface Temperature Anomalies in the Eastern Equatorial Pacific and the World Ocean, Climate Dynamics, May 1988.

(kg) Bryan, Kirk, Climate Response to Greenhouse Warming: The Role of the Ocean, in "Climate and the Geosciences", D. Reidel, Publishing Co., June 1988.

(kh) Bryan, Kirk, The Design of Numerical Models of the Ocean Circulation, in "Ocean Circulation and Geochemical Transport", D. Reidel, Publishing Co., June 1988.

(kk) Murnane, R. J., and R. F. Stallard, Germanium/Silicon Fractionation During Biogenic Opal Formation, Journal of Paleo-Oceanography, June 1988.

* (ko) Sheng, Jian and Yoshikazu Hayashi, Observed and Simulated Energy Cycles in the Frequency Domain, Journal of the Atmospheric Sciences, July 1988.

* (kp) Sheng, Jian and Yoshikazu Hayashi, Estimation of Atmospheric Energetics in the Frequency Domain during the FGGE Year, Journal of the Atmospheric Sciences, July 1988.

(kr) Toggweiler, J. R., News and Views Column on Dissolved Organic Carbon in the Ocean, Nature, July 1988.

*In collaboration with other organizations

(kv) Derber, John, and Anthony Rosati, A Global Oceanic Data Assimilation System, Journal of Physical Oceanography, August 1988.

(kx) Galperin, B., and G. L. Mellor, A Time-Dependent, Three-Dimensional Model of the Delaware Bay and River System. Part 1: Description of the Model and Tidal Analysis, Journal of Physical Oceanography, September 1988.

(ky) Galperin, B., and G. L. Mellor, A Time-Dependent, Three-Dimensional Model of the Delaware Bay and River System, Part 2: Three-Dimensional Flow Fields and Residual Circulation, Journal of Physical Oceanography, September 1988.

(lc) Thiele, Gerhard, and J. L. Sarmiento, Towards a Framework for the Interpretation of Transient Tracer Observations, Journal of Geophysical Research, October 1988.

(ld) Karoly, David J., The Role of Transient Eddies in Low Frequency Zonal Variations of the Southern Hemisphere Circulation, Tellus, Series A, Dynamical Meteorology, October 1988.

(lh) Schwarzkopf, M. Daniel and Stephen B. Fels, The Simplified Exchange Method Revisited: An Accurate, Rapid Method for Computation of Infrared Cooling Rates and Fluxes, Journal of Geophysical Research, November 1988.

(lj) Derber, John., A Variational Continuous Assimilation Technique, Monthly Weather Review, December 1988.

(ll) Oort, Abraham H., Angular Momentum Cycle in the Atmosphere - Ocean - Solid Earth System, Bulletin of the American Meteorological Society, January 1989.

* (lm) Feldstein, Steven, and Isaac Held, Barotropic Decay of Barotropic Waves in a Two-Layer Beta-Plane Model, Journal of the Atmospheric Sciences, January 1989.

* (ln) Chang, Ping, and S. G. H. Philander, Quasigeostrophic Oceanic Adjustment in the Presence of Mean Currents, Dynamics of Atmospheres and Oceans, January 1989.

(lo) Philander, S. G. H., N. C. Lau, R. C. Pacanowski, and M. J. Nath, Two Different Simulations of the Southern Oscillation and El Niño with Coupled Ocean-Atmosphere General Circulation Models, Phil. Trans. Royal Society of London, January 1989.

* (lp) Kalnay, E., M. Kanamitsu, J. Pfaendtner, J. Sela, M. Suarez, J. Stackpole, J. Tuccillo, L. Umscheid, and D. Williamson, Rules for Interchange of Physical Parameterizations, Bulletin of the American Meteorological Society, January 1989.

*In collaboration with other organizations

* (lq) Bard, E., M. Arnold, J. R. Toggweiler, P. Maurice, J.-C. Duplessey, Bomb ^{14}C in the Indian Ocean Measured by Accelerator Mass Spectrometry: Oceanographic Implications, Radiocarbon, January 1989.

(lr) Held, Isaac M. and Peter J. Phillipps, A Barotropic Model of the Interaction between the Hadley Cell and a Rossby Wave, Journal of the Atmospheric Sciences, February 1989.

(ls) Lau, Ngar-Cheung and Mary Jo Nath, A General Circulation Model Study of the Atmospheric Response to Extratropical SST Anomalies Observed in 1950-79, Journal of Climate, February 1989.

(lt) Karoly, David J., and Imre Szeredi, Low Frequency Variations of the Southern Hemisphere Circulation: I. Observed Structure, Journal of Climate, February 1989.

(lu) Moxim, Walter J., Simulated Transport of NOy to Hawaii during August: A Synoptic Study, Journal of Geophysical Research, February 1989.

* (lv) Fyfe, John and Isaac M. Held, The "Two-Fifths" and "One-Fifth" Rules for Rossby Wave Breaking, Journal of the Atmospheric Sciences, February 1989.

* (lw) Kurihara, Yoshio, Christopher Kerr, and Morris A. Bender, An Improved Numerical Scheme to Treat the Open Lateral Boundary of A Regional Model, Monthly Weather Review, February 1989.

(lx) Karoly, David J., and Imre Szeredi, Low Frequency Variations of the Southern Hemisphere Circulation: II. Further Diagnostics and Possible Mechanisms, Journal of Climate, February 1989.

(ly) Karoly, David J., R. Alan Plumb, and Mingfang Ting, Examples of the Horizontal Propagation of Quasi-Stationary Waves, Journal of the Atmospheric Sciences, March 1989.

(lz) Levitus, Sydney, Interpentadal Variability of Temperature and Salinity in the Deep North Atlantic, 1970-74, Versus 1955-59, Journal of Geophysical Research - Oceans, March 1989.

(ma) Levitus, Sydney, Interpentadal Variability of Steric Sea Level and Geopotential Thickness of the North Atlantic Ocean, 1970-74 Versus 1955-59, Journal of Geophysical Research - Oceans, March 1989.

(mb) Cox, Michael, An Idealized Model of the World Ocean: Part I: The Global-Scale Water Masses, Journal of Physical Oceanography, March 1989.

(mc) Delworth, Thomas and Syukuro Manabe, The Influence of Soil Wetness on Atmospheric Variability, Journal of Climate, March 1989.

*In collaboration with other organizations

* (md) Ramaswamy, V., and S. M. Freidenreich, Solar Radiative Line-by-Line Determination of Water Vapor Absorption and Water Cloud Extinction in Inhomogeneous Atmospheres: I. Techniques, Journal of Geophysical Research, March 1989.

(me) Hamilton, Kevin, A Look at the Recently Proposed Solar-QBO-Weather Relationship, Journal of Climate, March 1989.

(mf) Thiele, G., and J. L. Sarmiento, Tracer Dating and Ocean Ventilation, Journal of Geophysical Research, April 1989.

* (mg) Held, Isaac and Mingfang Ting, Orographic Versus Thermal Forcing of Stationary Waves: The Importance of the Mean Low-Level Wind, Journal of the Atmospheric Sciences, May 1989.

(mh) Manabe, Syukuro, Kirk Bryan, and Michael J. Spelman, Transient Response of a Global Ocean-Atmosphere Model to a Doubling of Atmospheric Carbon Dioxide, Journal of Physical Oceanography, May 1989.

(mi) Karoly, David J., and Denise S. Graves, On Data Sources and Quality for the Southern Hemisphere Stratosphere, NATO ARW, Vol. Dynamics, Transport and Photochemistry in the Middle Atmosphere, June 1989.

* (mj) Nakamura, Noboru, and Isaac M. Held, Nonlinear Equilibration of 2-D Eady Waves, Journal of Atmospheric Sciences, June 1989.

(mk) Mahlman, J. D., Mathematical Modeling of Greenhouse Warming: How Much Do We Know? Proceedings of the NRC Forum on Global Change and Our Common Future, 2-3 May, 1989, Washington, DC

* (ml) Wetherald, R. T., S. Manabe, and V. Ramaswamy, A Simulation of High Cloud Cover by a General Circulation Model of the Atmosphere, Climate Dynamics, June 1989.

(mm) Lau, Ngar-Cheung, GCM Simulations of the Influences of Tropical and Extratropical SST Changes on the Atmospheric Circulation, Proceedings of Bureau of Meteorology Research Center (BMRC) Workshop on the Impact of SST Specification in NWP and Climate Simulation, 11-12 July 1989, Melbourne, Australia

* (mn) Lau, Alexis Kai-Hon, and Ngar-Cheung Lau, Observed Structure and Propagation Characteristics of Summertime Synoptic-Scale Disturbances over the Tropical Western Pacific, Proceedings of International Conference on East Asia and Western Pacific Meteorology and Climate, July 6-8, 1989, Hong Kong.

(mo) Stouffer, R. J., S. Manabe, and K. Bryan, On The Climate Change Induced by a Gradual Increase of Atmospheric Carbon Dioxide, Nature, June 1989.

*In collaboration with other organizations

(mp) Zhu, Xun, CO_2 15 um Band Cooling Rates in the Upper Middle Atmosphere Calculated by Curtis Matrix Interpolation, Journal of the Atmospheric Sciences, June 1989.

(mq) Philander, George, El Niño and La Niña, Interannual Climate Fluctuations Caused by Air-Sea Interactions, American Scientist, June 1989.

(mr) Cook, Kerry H., The Atmosphere's Response to the Ice Sheets of the Last Glacial Maximum, Annals of Glaciology, July 1989.

(ms) Bryan, K., A Review of "Mathematical Modelling of Ocean Circulation" by G. I. Marchuk and A. S. Sarkisyan, Springer-Verlag, Bulletin of Meteorology, American Meteorological Society, July 1989.

(mt) Sirutis, J., and K. Miyakoda, Sub-grid Scale Physics in One-Month Forecasts, Part I: Experiment with Four Parameterization Packages, Monthly Weather Review, July 1989.

(mu) Miyakoda, K., and J. Sirutis, Sub-grid Scale Physics in One-Month Forecasts, Part II: Systematic Error and Blocking Forecasts, Monthly Weather Review, July 1989.

(mv) Murnane, R. J., J. L. Sarmiento, and M. P. Bacon, On the Use of Trace Metal and Sediment Trap Observations to Develop Nutrient and Trace Metal Cycling Models, Journal of Geophysical Research, August 1989.

(mw) Manabe, S., and A. J. Broccoli, Mountains and Arid Climates of Middle Latitudes, Science, August 1989.

(mx) Hakkinen, S., and G. L. Mellor, One Hundred Years of Arctic Ice Cover Variations as Simulated by a One-Dimensional, Ice-Ocean Model, Journal of Geophysical Research, August 1989.

(my) Galperin, B., and G. Mellor, The Effects of Streamline Curvature and Spanwise Rotation on Turbulent Boundary Layers, Journal of Fluid Mechanics, August 1989.

(mz) Hakkinen, S., Models and Their Applications to Polar Oceanography, in Polar Oceanography, (ed. W. Smith), August 1989.

*In collaboration with other organizations

BIBLIOGRAPHY

1984-1989

CROSS-REFERENCE BY AUTHOR

APPENDIX C

Computational Support

Computational Support

The computational support at GFDL comprises three Control Data CYBER computers:

CY1, a 170/730 with 256K words of memory;
CY2, a 205 supercomputer, with 4 million words of memory; and
CY4, another 205, with 4 million words of memory.

During FY89 a new release of the NOS 2 operating system was installed on the CYBER 170, featuring automatic migration of disk files to tape and improved TCP/IP support. Negotiations were initiated with Control Data Corporation to extend maintenance services for the CYBER system beyond the end of the current contract in December, 1989.

Sun-3/50 workstations were installed in the offices of fifty scientists during FY89. The workstations provide a variety of terminal emulations for accessing the CYBER system. The graphics terminal emulation features a laser printer hardcopy capability. Local use of the workstations supports source editing, program debugging, and data analysis using the NCAR graphics software. Electronic mail to the Internet, Bitnet, and Omnet networks is provided via a secure "uucp" link to the Princeton University network.

Installation of six additional Sun-3/50 workstations, software for scientific document preparation, and a T1 communication link from a standalone host to the NSFNET network is expected by the end of FY89. A memory upgrade to the existing workstations and installation of color workstations, disk servers, and additional printers is expected during FY90.

A draft RFP for a Class VII supercomputer system was reviewed by supercomputer vendors during FY89.

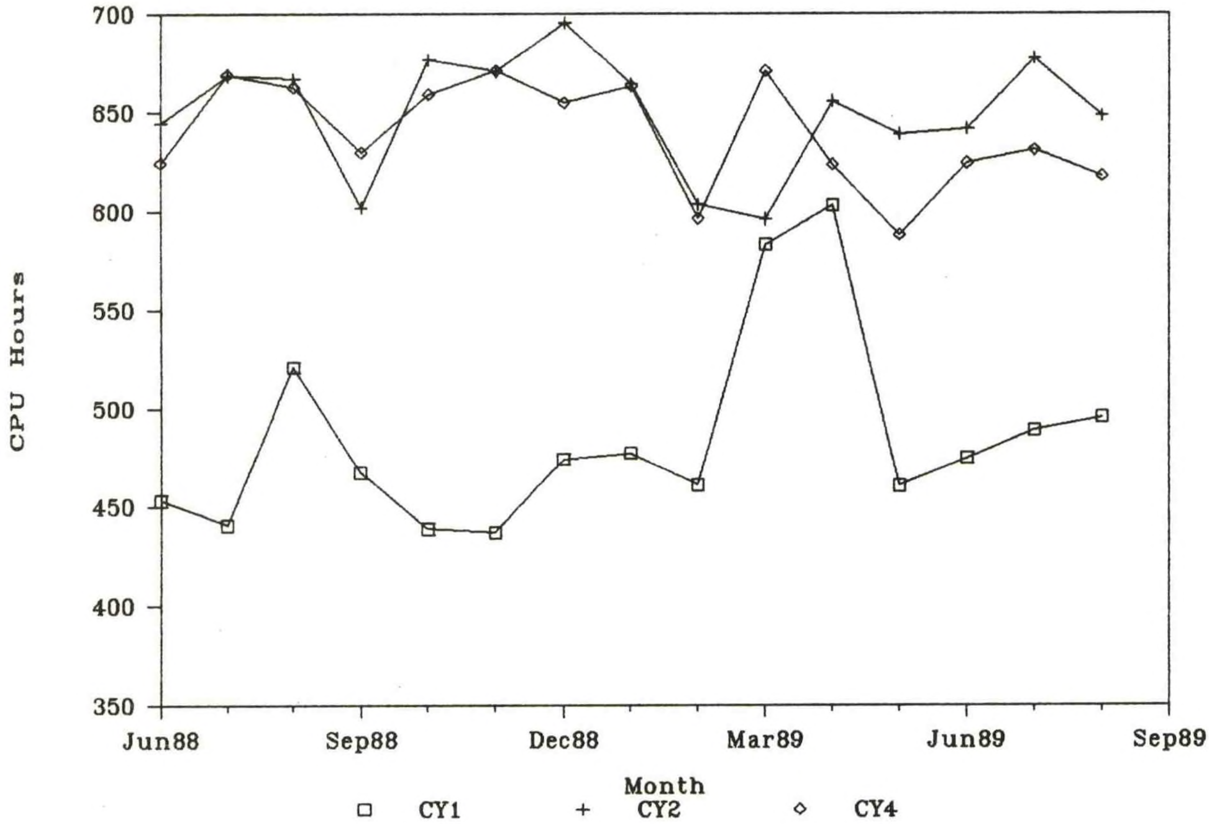
The following table and figure show how many CPU hours were achieved on each machine during the period of this report.

Table C-1. Achieved CPU Hours for GFDL Machines

Month	CY1	CY2	CY4	CY2+CY4
Sep 88	467	602	630	1232
Oct 88	439	676	659	1336
Nov 88	437	671	671	1342
Dec 88	474	696	655	1351
Jan 89	477	665	663	1328
Feb 89	461	604	597	1200
Mar 89	583	596	671	1267
Apr 89	603	656	624	1279
May 89	460	639	588	1227
Jun 89	475	642	625	1266
Jul 89	489	677	631	1308
Aug 89	496	648	618	1266
Sep 89	**	**	**	**

** Not available at press time.

CYBER CPU Hours



APPENDIX D

Seminars Given at GFDL

During Fiscal Year 1989

20 September 1988	"Fair Weather Convection and Light Aircraft, Helicopter and Glider Accidents" by Dr. Dale Hess, Bureau of Meteorology Research Center, Melbourne, Australia
22 September 1988	"The Role of Numerical Advection Schemes in General Circulation Models" by Dr. Ruediger Gerdes, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
26 September 1988	"Southern Hemisphere Sea-Level Climatology in the General Circulation Models of NCAR, GFDL, Canada and the European Centre for Medium Range Forecasting" by Dr. H. von Storch, Max Planck Institute Hamburg, Germany
27 September 1988	"Southern Hemisphere Temperature Trends - A Possible Greenhouse Signal?" by Dr. David Karoly, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
4 October 1988	"The Effects of Removing the Baroclinic Eddies from the Initial State of a Numerical Forecast" by Dr. Yochanan Kushnir, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
6 October 1988	"Low Frequency Variations of the Southern Hemisphere Troposphere Structure and Forcing" by Dr. David Karoly, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
11 October 1988	"Minimal Modelling of the Atmospheric General Circulation" by Dr. Enda O'Brien, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
18 October 1988	"Gravity Waves - the Untold Story" by Dr. Kevin Hamilton, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
20 October 1988	"Maximum Amplitude of Baroclinic Waves" by Dr. Noburo Nakamura, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
21 October 1988	"Review of CO_2 Uptake Modeling Studies" by Dr. U. Siegenthaler, Universitat of Bern, Bern, Switzerland
21 October 1988	"Strategy for Developing a World Ocean Model of Fossil Fuel CO_2 Uptake" by Dr. Jorge Sarmiento, Princeton University, Princeton, NJ
21 October 1988	"Annual Mean Phosphate Model of World Ocean" by Dr. R. Najjar, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ

21 October 1988	"Brief Review of Progress on Reanalyzing GEOSECS Nutrient Data" by L. Anderson, Princeton University, Princeton, NJ
21 October 1988	"Freon Uptake Experiments in a World Ocean Model" by Keith Dixon, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
21 October 1988	"Features and Flaws of Annual Mean World Ocean Pertinent to CO_2 Uptake" by Dr. J.R. Toggweiler, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
25 October 1988	"A Case of Nonlinear Wave Growth and Decay in the Southern Hemisphere Stratosphere" by Dr. David Karoly, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
25 October 1988	"Atmospheric Carbon Dioxide Variations Related to El Nino" by Dr. Uli Siegenthaler, Universitat Bern, Switzerland
27 October 1988	"The Sensitivity of Stationary Waves to Variations in the Basic State Zonal Flow" by Dr. Sumant Nigam, Meteorology Department, University of Maryland, College Park, MD
8 November 1988	"Global Ocean-Atmosphere Climate Models" by Dr. U. Cubasch, Max Planck Institute for Meteorology, Mainz, Federal Republic of Germany
17 November 1988	"The Airborne Antarctic Ozone Experiment, 1987" by Dr. Adrian Tuck, Aeronomy Laboratory, Boulder, CO
18 November 1988	"Applying the Adjoint Method to the Oceanic Steady Circulation Problem: QG Model Simulations" by Dr. Eli Tziperman, Weizmann Institute, Rehovat, Israel
22 November 1988	"Seasonal and Mesoscale Variability in the Mediterranean Sea" by Dr. Nadia Pinardi, Harvard University and the the University of Bologna, Italy
2 December 1988	"Non-Separable Baroclinic Instability and Cyclogenesis" by Dr. G. W. Kent Moore, Physics Department, University of Toronto, Toronto, Canada
6 December 1988	"The Seasonal Cycle of Southern Hemisphere Planetary Waves" by Dr. Alan Plumb, Department of Earth, Atmosphere, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA
6 December 1988	"The "1/5 th" Rule: A Criterion for Rossby Wave Breaking" by Dr. John Fyfe, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ

13 December 1988	"Comparison of 30-Day GCM Predictions With and Without Interactive Clouds" by Dr. Tony Gordon, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
20 December 1988	"Three-Dimensional Effects in Nonlinear Flow Over Mountains" by Dr. Sigurdur Thorsteinsson, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
22 December 1988	"Numerical Solution of the Primitive Equations on the Connection Machine" by Dr. James Tuccillo, National Meteorological Center/NWS, World Weather Building, Washington, DC
13 January 1989	"Climate Stability and Cloud Optical Thickness Feedback" by Dr. Richard Somerville, Scripps Institute of Oceanography, La Jolla, CA
31 January 1989	"On the Benthic Boundary Layer Associated with the Cold Filament of the Western North Atlantic" by Mr. Tal Ezer, Department of Oceanography, Florida State University, Tallahassee, FL
31 January 1989	"The Influence of Soil Wetness on Atmospheric Variability" by Mr. Tom Delworth, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
2 February 1989	"Spectral Optimum Interpolation" by Dr. David Parrish, National Meteorological Center, Washington, DC
9 February 1989	"Large-Scale Surface Heat Flux Variations Over the Northern Ocean" by Mr. Dan Cayan, Climate Research Group, Scripps Institute of Oceanography, La Jolla, CA
16 February 1989	"Satellite Oceanography: Scatterometer Results" by Dr. David L. T. Anderson, Department of Meteorology, Oxford University, Oxford, England
17 February 1989	"Observing System Experiments using Summer Monex Data" Dr. Mohan Ramamurthy, Department of Atmospheric Sciences, University of Illinois, Urbana, IL
23 February 1989	"Low Frequency Structures in the Presence of Stationary Waves" by Dr. Grant Branstator, National Center for Atmospheric Research, Boulder, CO
24 February 1989	"Seasonal Variations in Models of the North Atlantic and North Pacific" by Prof. Richard Greatbach, Physics Department, Memorial University, Newfoundland, Canada

2 March 1989	"Formation and Maintenance of Cirrus: Observations and Simulations" by Dr. David O'C Starr, NASA, Goddard Space Flight Center, Greenbelt. MD 20771
9 March 1989	"The NMC Quasi-Lagrangian Hurricane Model" by Dr. M. Mathur, World Weather Building, National Meteorological Center, Washington, DC
13 March 1989	"Low Frequency Oscillation Induced by Mesocale Eddies" by Prof. Dan Seidov, Shirshov Institute, USSR Academy of Science, Moscow, USSR
14 March 1989	"The Next Generation of GFDL Longwave Codes" by Mr. Dan Schwarzkopf, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
16 March 1989	"Lakewood Quaternary Water Level Fluctuation in the Northeastern United States" by Dr. Robert Webb, Geology Department, Brown University, Providence, RI
21 March 1989	"The Drake Passage and Ice Age CO_2" by Dr. J. R. Toggweiler, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
28 March 1989	"SGS Physics in One Month Forecasts" by Mr. J. Sirutis and Dr. K. Miyakoda, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
28 March 1989	"On the Dynamic Estimation of Relative Weights For Observation and Forecast in Numerical Weather Prediction" by Prof. Grace Wahba, Yale University, New Haven, CONN
4 April 1989	"Systematic Error and Blocking Forecasts" by Dr. K. Miyakoda and Mr. J. Sirutis, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
5 April 1989	"The Dynamical Balance of the Antarctic Circumpolar Current Studied with an Eddy-Resolving QG-Model" by Dr. Joerg-Olaf Wolff, Max Planck Institute of Meteorology, University of Hamburg, Hamburg, Germany
7 April 1989	"Design, Development and Testing of the ETA ("Storm") Limited Area Model" by Dr. Fedor Mesinger, World Weather Building, National Meteorological Center/NOAA, Washington, DC
11 April 1989	"El Niño" by Dr. G. Philander, Dr. N.-C. Lau, Mr. R. Pacanowski, and Ms. M.J. Nath, Geophysical Fluid Dynamics Laboratory, Princeton, NJ

14 April 1989	"Cloud Variations Measured by a Global System of Satellites in ISCCP" by Dr. William Rossow, Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025
18 April 1989	"Cirrus Clouds and the Tropical Upper Troposphere" by Dr. V. Ramaswamy, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
19 April 1989	"Patterns of Low Frequency Temperature Variation Near The Ocean Surface" by Dr. Christopher Folland, Climate Analysis Center, National Meteorological Center, Washington, DC
20 April 1989	"Nested Wind Analyses of Several Atlantic Hurricanes (1982-1987)" by Dr. Stephen J. Lord, Development Division, National Meteorological Center, Washington, DC
21 April 1989	"Can Chaos and Intransitivity Lead to Interannual Variability?" by Prof. Edward Lorenz, Department of Earth, Atmospheric, Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139
25 April 1989	"Can We Detect the Horizontal Propagation of Stationary Rossby Waves out of the Tropics Using Observations"? by Dr. David Karoly, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
28 April 1989	"Cloud-Radiative Forcing and Climate: Insights from The Earth Radiation Budget Experiment" by Dr. V. Ramanathan, The University of Chicago, Department of Geophysical Sciences, Chicago, IL
2 May 1989	"Orographic vs. Thermal Stationary Waves: The Importance of the Mean Low Level Flow" by Dr. I. Held and Ms. M. Ting, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
4 May 1989	"Forecast Skill, Predictability, and Sensitivity of Monte Carlo Ensemble Integrations from a T31 General Circulation Model" by Dr. David P. Baumhefner, National Center for Atmospheric Research, Boulder, CO
9 May 1989	"Experimental Prediction of Hurricane Gloria" by Y. Kurihara, B. Ross, R. Tuleya, and M. Bender, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
12 May 1989	"Combining High Resolution Global and Regional Model for Hurricane Forecasting" by Prof. T. N. Krishnamurti, The Florida State University, Tallahassee, FL
19 May 1989	"Planetary Waves in the Atmospheres of Jupiter and Saturn" by Dr. Michael Allison, Goddard Institute for Space Studies, 2880 Broadway, New York, NY

26 May 1989	"Sea-Ice and Mixed Layer Models in the Weddell Sea" by Dr. Peter Lemke, Institute fur Meeriskunde, Bremerhaven, W. Germany
30 May 1989	"Anomalous Stationary Waves as a Model for Persistent Anomalies" by Dr. A. da Silva, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
1 June 1989	"Large-Scale Influences on Atlantic Tropical Storm Activity" by Dr. Lloyd Shapiro, Hurricane Research Division, Atlantic Oceanographic & Meteorological Laboratory, Miami, FL
6 June 1989	"Two-Dimensional Turbulence" by Dr. David Dritschel, Cambridge University, Department of Applied Mathematics & Theoretical Physics, Cambridge, UK
6 June 1989	"The Effects of Orography on the Distribution of Dry Climates in the Northern Hemisphere" by Mr. Tony Broccoli and Dr. Syukuro Manabe, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
7 June 1989	"Vorticity Dynamics of Simplified Squall Line Models" by Dr. Steve Garner, Department of Meteorology, University of Reading, Reading, UK
13 June 1989	"Bucket Hydrology" by Dr. Christopher Milly, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
16 June 1989	"The Three-Dimensional Structure of the Wind-Driven Circulation" by Dr. R. X. Huang, Woods Hole Oceanographic Institution, Woods Hole, MA
19 June 1989	"Sensitivity of Cloud Amount and Moist Processes to Model Resolution in the NCAR Community Climate Model" by Dr. Jeffrey Kiehl, National Center for Atmospheric Research, Boulder, CO
20 June 1989	"The Atmospheric Response to Orbital Parameter Variations" by Dr. Isaac Held and Mr. Peter Phillipps, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
21 June 1989	"Topographic Influence on wind Driven Stratified Flow in a Beta-Plane Channel" by Dr. Anne-Marie Tregiuer, National Center for Atmospheric Research, Boulder, CO
22 June 1989	"Greenhouse Climate Change Fingerprint Detection" by Dr. David Karoly, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ

27 June 1989	"Is CISK Alive" by Dr. Y. Kurihara, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
11 July 1989	"A Multi-Layer Model of Geostrophic Turbulence" by Dr. E. O'Brien, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
24 July 1989	"Influence of SST in the Surface Winds in the Eastern Tropical Pacific Ocean" by Dr. S. Hayes, Pacific Marine Environmental Laboratories, Seattle, WA
28 July 1989	"Weather Forecasting Through Analogues" by Dr. Huug van den Dool, Department of Meteorology, University of Maryland, College Park, MD
28 July 1989	"The Costa Rica Dome and the Seasonal Cycle of the Eastern Tropical Pacific" by Dr. T. Yamagata, Kyushu University, Azasakamoto, Oazakasuga, Kasuga, Japan

APPENDIX E

Talks, Seminars, and Papers Presented Outside GFDL

During Fiscal Year 1989

19 September 1988	Mr. William F. Stern "Systematic Errors in GFDL's Extended Range Prediction GCM" Workshop on Systematic Errors in Models of the Atmosphere, sponsored by World Meteorological Organization and World Climate Research Program, Toronto, Canada
19 September 1988	Dr. Hiram Levy II "Combustion Nitrogen Emissions: A Numerical Simulation of their Regional and Global Transport and Deposition" Seventeenth NATO International Technical Meeting on Air Pollution Modeling, Cambridge, England
19 September 1988	Mr. Joseph J. Sirutis "Systematic Bias in Predictions with the GFDL Coupled Air-Sea Model" Workshop on Systematic Errors in Models of the Atmosphere, sponsored by World Meteorological Organization and World Climate Research Program, Toronto, Canada
19 September 1988	Dr. Kikuro Miyakoda "Systematic Errors in an Air-Sea Coupled Model" Workshop on Systematic Errors in Models of the Atmosphere, sponsored by World Meteorological Organization and World Climate Research Program, Toronto, Canada
29 September 1988	Dr. Kerry Cook "Policy Conference on the Environment: Modeling Greenhouse Warming" Woodrow Wilson School of Public Policy, Princeton University, Princeton NJ
3 October 1988	Dr. Jack J. Katzfey 1) "The Importance of Low Level Baroclinicity During GALE IOP-2" and 2) "Sensitivity of Model Simulations for GALE IOP-2" GALE/CASP Workshop, Val Morin, Quebec
5 October 1988	Dr. Jerry D. Mahlman "The Case for Dynamical Extended Range Forecasting" National Research Council Climate Research Committee Meeting, Washington, DC
7 October 1988	Dr. Jerry D. Mahlman "Class VII Supercomputing at GFDL for Weather and Climate Research" Office of Management and Budget, Washington, DC

10 October 1988	Dr. Gareth P. Williams 1) "The General Character of Global Atmospheric Circulations" 2) "The Stability and Genesis of Jovian Vortices" Fifth International Workshop on Cosmic Gas Dynamics (Planetary Fluid Dynamics) organized by the Institute for Problems in Mechanics of the U.S.S.R. Academy of Sciences, Moscow, USSR
18 October 1988	Dr. Kirk Bryan "Bjerknes Theory of North Atlantic Climate Variations" ERL Planning Conference - An Air-Sea Interaction Initiative, Boulder, CO
18 October 1988	Dr. Syukuro Manabe "Drought and Greenhouse Warming: What is the Relation?" Board on Atmospheric Sciences and Climate of the National Research Council/National Academy of Sciences, Washington, DC
20 October 1988	Dr. D. Karoly "Low Frequency Variations of the Southern Hemisphere Circulation-Structure and Forcing" University of Maryland, College Park, MD
20 October 1988	Dr. Kikuro Miyakoda "A Seasonal Forecast Experiment with an Air-Sea Coupled Model" University of Missouri, Columbia, MI
20 October 1988	Dr. J. D. Mahlman "Atmospheric Ozone Changes: How Much do We Understand?" Sigma Xi, Johnson & Johnson Chapter, New Brunswick, NJ
25 October 1988	Dr. Kerry Cook "Natural and Anthropogenic Climate Change" Center for Energy and Environmental Sciences, Princeton University, Princeton, NJ
1 November 1988	Dr. Jerry D. Mahlman "Predicting Climate Change: How Good is the Science?" Joint Council on Food and Agricultural Sciences Meeting, Washington, DC
2 November 1988	Mr. Richard T. Wetherald "Summer Dryness and Winter Wetness Due To An Increase of Atmospheric CO_2" Michigan State University, Lansing, Michigan
3 November 1988	Dr. Y. Kushnir "Frequency Dependence of Teleconnection Patterns" 13th Annual Climate Diagnostic Workshop, Boston, MA

4 November 1988	Mr. R. Najjar "Simulations of the Distributions of Phosphate and Oxygen in an Ocean GCM" AGU Meeting, San Francisco, CA
14 November 1988	Dr. Kirk Bryan "North Atlantic Climate Variability" STACS Meeting on North Atlantic Monitoring Atlantic Oceanographic and Meteorological Laboratory/NOAA, Key Biscayne, FL
14 November 1988	Dr. Abraham H. Oort "On The Unity and Diversity in the Climatic System" Victor Starr Memorial Lecture, Massachusetts Institute of Technology, Cambridge, MA
15 November 1988	Dr. Syukuro Manabe "Future Climate Change Induced by Greenhouse Gases" Department of Physics and Astronomy, University of Maryland, College Park, MD
15 November 1988	Dr. Kikuro Miyakoda "Experimental Seasonal Forecasts with an Air-Sea Model" Symposium on Western Pacific Air-Sea Interactions, Beijing, China
24 November 1988	Dr. Syukuro Manabe "Studies of Global Change: Role of Japan" Symposium "Japanese Role in the Research on Global Change" Tokyo, Japan
25 November 1988	Dr. Syukuro Manabe "Issues in the Study of Future Climate Change" National Institute of Environmental Studies, Tsukuba, Japan
26 November 1988	Dr. Syukuro Manabe "Overview of the Research Activities: Future Climate Change due to Greenhouse Gases" Japanese Environmental Agency, Tokyo, Japan
28 November 1988	Dr. Jerry D. Mahlman "How To Know If You Are In A Greenhouse" Third Annual Congressional and Scientific Forum on Global Earth Studies, Santa Fe, NM
5 December 1988	Mr. William J. Hurlin "Sensitivity of GCM to Mixing and Heat Flux Parameterizations" American Geophysical Union 1988 Fall Meeting. San Francisco, California

13 December 1988	Dr. Samuel George Philander "Interannual Oscillations in a Coupled Ocean-Atmosphere Model" Meeting on Coupled Ocean Atmosphere Models sponsored by the Royal Society and Committee on Climate and Ocean Change, London, England
14 December 1988	Dr. Jerry D. Mahlman "GFDL and NOAA: Answers for a Changing Environment" U.S. Senate Committee in Commerce, Science, and Transportation, Washington, DC
15 December 1988	Dr. Jerry D. Mahlman "Ocean Prediction" presented at OAR, Oceans/Great Lakes Pre-Retreat, Washington, DC
15 December 1988	Dr. Kerry Cook "CO_2 - Induced Climate Change" Graduate Student Conference on Science and Policy, Woodrow Wilson School of Public Policy, Princeton University, Princeton, NJ
17 January 1988	Dr. R. Gerdes "The Role of Numerical Advection Schemes in General Circulation Models" Workshop on Parameterization of Small Scale Processes, Honolulu, HI
19 January 1989	Dr. D. Karoly "Southern Hemisphere Circulation Features Associated with El Niño Southern Oscillation Events" Seminar at Pennsylvania State University, State College, PA
20 January 1989	Mr. Richard Wetherald "Recent Results on CO_2-Induced Changes of Hydrology" Goddard Institute for Space Studies, New York, NY
21 January 1989	Dr. Jerry D. Mahlman "The Fragile Ozone Layer" Smithsonian Institute, Washington, DC
25 January 1989	Dr. Syukuro Manabe "Climate Changes Induced by Greenhouse Gases" Princeton University Plasma Physics Laboratory, Princeton, NJ
26-27 January 1989	Dr. Isaac Held "New Perspectives on the Theory of the Tropospheric General Circulation" and "Stationary Eddies in Linear Models and GCM's" Texas A & M, College Station, TX
30 January 1989	Dr. Kikuro Miyakoda "Systematic Error and Blocking Prediction" Lecture, Goddard Space Flight Center, Greenbelt, MD

31 January 1989	Dr. Kikuro Miyakoda "Seasonal Forecast Experiment with an Air Sea Model" Lecture, University of Maryland, College Park, MD
1 February 1989	Dr. Kikuro Miyakoda "Reanalysis of FGGE" Ad-hoc Panel on Reanalysis of TOGA, University of Maryland, College Park, MD
7 February 1989	Dr.Ngar-Cheung Lau "Coupled Ocean-Atmosphere Modeling at GFDL" EPOCS Council Meeting, Miami, FL
7 February 1989	Dr. Kirk Bryan "Bjerknes Theory of North Atlantic Climate Variability" GEWEX Meeting, Pasadena, CA
9 February 1989	Dr. Jerry D. Mahlman "Scientific Uncertainties in Climate Change Predictions" Hearing on Global Change of the House Appropriations Committee, Washington, DC
16 February 1989	Dr. Hiram Levy II "Global Distribution and Deposition of Reactive Nitrogen" AER, Cambridge, MA
17 February 1989	Ms. M. Ting "Stationary Wave Response to a Tropical SST Anomaly in an Idealized GCM" Massachusetts Inst. of Technology, Cambridge, MA
20 February 1989	Mr. Richard Wetherald "Latest Results on CO_2-Induced Hydrologic Change" Task Force Meeting at IIASA, Laxenburg (Vienna) Austria
21 February 1989	Dr. D. Karoly "Low Frequency Variations of the Southern Hemisphere Circulation" National Center for Atmospheric Research, Boulder, CO
21 February 1989	Dr. Jerry D. Mahlman "Scientific Uncertainties in Climate Change Predictions" House of Representatives Hearing, Washington, DC
6-9 March 1989	Dr. Bruce B. Ross "Four-Dimensional Data Assimilation Experiments Using Fraternal-Twin Models" 2nd Workshop on Regional Data Assimilation, Norman, OK

13 March 1989	Dr. Jerry D. Mahlman "The Role of Greenhouse Gases in Global Chemical-Dynamical Processes" Tenth Session of the Joint Scientific Committee of the World Climate Research Programme (WCRP), Sillefranche-sur-Mer, France
13 March 1989	Mr. Anthony Broccoli "The Greenhouse Effect" New Jersey Energy and Facilities Management Exposition 1989, The Meadowlands Hilton, Secaucus, NJ
17 March 1989	Dr. D. Karoly "Low Frequency Variations of the Southern Hemisphere Circulation: Observed Structure and Possible Mechanisms" Massachusetts Inst. of Technology, Cambridge, MA
22 March 1989	Dr. Syukuro Manabe "Modeling Study of Climate Change Induced by Greenhouse Gases" Lecture, Geography/Ecology Seminar Series, University of North Carolina, Chapel Hill, NC
22 March 1989	Dr. George Philander "Oceanic Adjustment in the Presence of Mean Currents" University of California, Los Angeles, CA
23 March 1989	Dr. Kerry Cook "Global Climate Change" Princeton Corridor Rotary, Princeton, NJ
31 March 1989	Dr. Kerry Cook "Modeling Global Climate" Lectures, Hunter College, New York, NY
4 April 1989	Dr. John R. Toggweiler "Dissolved Organic Carbon and the Global Carbon Cycle" Lecture, Dalhousie University, Halifax, Nova Scotia, Canada
4 April 1989	Mr. Richard T. Wetherald "Changes of Hydrology and Temperature Caused by an Increase of Atmosphere Carbon Dioxide as Obtained from a General Circulation Model" Lecture, Petawawa National Forestry Institute, Chalk River, Ontario
6 April 1989	Dr. Yoshio Kurihara "Some Problems on the Hurricane Analysis" NMC Annual Meeting on Tropical Cyclone Analysis and Prediction, Washington, DC
6 April 1989	Dr. Yoshio Kurihara "Experimental Prediction of Hurricane Gloria" Seminar, National Meteorological Center, Washington, DC

10 April 1989	Dr. Isaac Held "Stationary Waves in GCM's with Idealized Topography" Waves and Stability Conference, San Francisco, CA
10 April 1989	Mr. Richard T. Wetherald "Changes of Hydrology and Temperature Causes by an Increase of Atmosphere Carbon Dioxide as Obtained from a General Circulation Model" Lecture, Massachusetts Institute of Technology, Cambridge, MA
10 April 1989	Dr. V. Ramaswamy "Uses of Aerosol Climatology for GCM-Based Studies" Workshop on Aerosol Climatology, Norfolk, VA
11 April 1989	Dr. Jerry Mahlman "Dynamical Effects of the Antarctic Ozone Hole: A 3-D Model Experiment" 7th Conference on the Meteorology of the Middle Atmosphere, San Francisco, CA
12 April 1989	Dr. D. Karoly "A Case Study of Nonlinear Wave Growth and Decay in the Southern Hemisphere Stratosphere" AMS Conference, San Francisco, CA
13 April 1989	Dr. Kirk Bryan "The Role of the Oceans in Greenhouse Warming" John C. Ludwick Lecture, Old Dominion University, Norfolk, VA
14 April 1989	Mr. R. Saravanan "The Role of Waves and Mean Motions in the Quasi-Biennial Oscillation: A Simple Multi-Wave Model" AMS Conference, San Francisco, CA
15 April 1989	Dr. D. Karoly "On Data Sources and Quality for Southern Hemisphere Troposphere and Stratosphere" AMS Conference, San Francisco, CA
19 April 1989	Dr. John R. Toggweiler "Dissolved Organic Matter and the Ocean's Carbon and Nutrient Cycles" Lecture, University of Delaware, Lewes, DE
24-25 April 1989	Mr. Richard T. Wetherald "CO_2-Induced Changes of Temperature and Hydrology as Obtained from GCM's" Symposium on Global Climate Change, New York State Museum, Albany, NY
27 April 1989	Dr. Kirk Bryan "Report on Atlantic Variability Meeting at GFDL" 18-19 April, 1989, NOAA Global Change Panel Meeting, Alexandria, VA

1 May 1989	Dr. D. Karoly "Low Frequency Variations of the Southern Hemisphere Circulation" National Meteorological Center, Washington, DC
1 May 1989	Dr. Jerry D. Mahlman "NRC Forum on Global Change and Our Common Future" Washington, DC
2 May 1989	Dr. D. Karoly "Can We Detect the Propagation of Quasi-Stationary Rossby Waves Out of the Tropics?" Goddard Laboratory, Greenbelt, MD
4 May 1989	Mr. Richard T. Wetherald "CO_2-Induced Changes of Temperature and Hydrology as Obtained from GCM's" Lecture, EPA Department, University of Cincinnati, Cincinnati, OHIO
7-12 May 1989	Mr. Anthony J. Broccoli "Simulation of Cyclonic Tropical Disturbances in Climate Models" AGU Spring Meeting, Baltimore, MD
8 May 1989	Dr. Syukuro Manabe "Transient Response of a Coupled Ocean-Atmosphere Model to CO_2 Forcing" DOE Workshop on Greenhouse-Gas-Induced Climate Change, University of Massachusetts, Amherst, MA
8-12 May 1989	Dr. Kirk Bryan "North Atlantic Decadal Climate Variability" Liege Symposium, Liege, Belgium
8-12 May 1989	Mr. Sydney Levitus "Temporal Variability of Sea Surface Salinity in the North Atlantic Ocean" DOE Workshop on Greenhouse-Gas-Induced Climate Change, Amherst, MA
10 May 1989	Dr. Kerry Cook "Continents and Climate in an Idealized General Circulation Model" AGU Spring Meeting, Baltimore, MD
10 May 1989	Dr. Hiram Levy II "Simulated Global Deposition of Reactive Nitrogen Emitted by Fossil Fuel Combustion" AGU Spring Meeting, Baltimore, MD
10 May 1989	Dr. John R. Toggweiler "The Drake Passage and Ice Age CO_2" AGU Spring Meeting, Baltimore, MD

11 May 1989	Mr. Keith W. Dixon "Simulating Chlorofluoromethane Distributions in Numerical Models of the World Ocean" AGU Spring Meeting, Baltimore, MD
16 May 1989	Dr. V. Ramawamy "Radiative Transmission Characteristics of the New Fluorocarbons" Conference of Experts-Alternative Fluorocarbons Environment Study, Boulder, CO
16 May 1989	Mr. Morris A. Bender "The Simulation of Mature Tropical Storms using a High Resolution Multiply Nested Movable Mesh Model" Conference on Hurricane and Tropical Meteorology, San Diego, CA
16 May 1989	Dr. Yoshio Kurihara "On the Structure of Moving Tropical Cyclones" AMS Conference on Hurricane and Tropical Meteorology, San Diego, CA
17 May 1989	Dr. Syukuro Manabe "Climatic Change Due to Greenhouse Gases" ILP Symposium on Global Change, Massachusetts Institute of Technology, Cambridge, MA
22 May 1989	Mr. Christopher Kranz "Site Report: Networking and Operations", Meteorological Supercomputer Users Group Meeting sponsored by NCAR, Boulder, CO
22 May 1989	Mr. William T. Yeager "Site Report: Class VII Computer Procurement" Meteorological Supercomputer Users Group Meeting sponsored by NCAR, Boulder, CO
31 May 1989	Mr. Sydney Levitus "Temporal Variability of the Thermohaline Structure of the North Atlantic Ocean" Lamont-Doherty Geological Observatory, Palisades, NY
31 May 1989	Dr. Syukuro Manabe 1) "Past and Future Climatic Changes Due to Greenhouse Gases" 2) "Transient Response of Coupled Ocean-Atmosphere Model to the Gradual Increase in Atmospheric CO_2" University of California, Los Angeles, Department of Atmospheric Sciences, Los Angeles, CA
2 June 1989	Mr. Richard Wetherald "Climate Change and the Greenhouse Effect" Bedminster Elementary School, Bedminster, NJ

5 June 1989	Dr. Jerry D. Mahlman "Mathematical Modeling of Environmental Systems" Joint U.S. - U.S.S.R. National Academy of Science Committee on Global Ecology, Moscow, USSR
13 June 1989	Dr. Jerry D. Mahlman "Climate and Chemical Change: Implications for Future Energy Production" Chemical Manufacturer's Association Meeting on Energy and Environment, Washington, DC
14 June 1989	Mr. Richard Wetherald "Climate Change and the Greenhouse Effect" Parsons Elementary School, North Brunswick, NJ
28 June - 2 July 1989	Dr. John R. Toggweiler "The Drake Passage and Ice Age CO_2" SPECMAP Conference, Edinburgh, U.K.
3 July 1989	Dr. Hiram Levy II "The Global Climatology of Reactive Nitrogen: A Numerical Study" International Conference on the Generation of Oxidants on Regional and Global Scales, Norwich, England
5 July 1989	Dr. Abraham H. Oort "The Energy Cycle of the Ocean-Atmosphere System" University of Washington, Department of Atmospheric Sciences, Seattle, WA
9 July 1989	Dr. Ngar-Cheung Lau "The Structure and Propagation of Summertime Synoptic Scale Disturbances over the Western Pacific" International Conference on East Asia and Western Pacific Meteorology and Climate, Hong Kong, China
10 July 1989	Dr. S. Rintoul "Inverse Models of the Circulation and Property Fluxes of the North Atlantic" WOCE Workshop, London, England
10 July 1989	Mr. James G. Welsh "Supercomputing in the 21st Century" Environmental Research Laboratory, Boulder, CO
10 July 1989	Dr. Charles T. Gordon "Comparison of One-Month Integrations of a GCM With and Without Interactive Clouds" FIRE (Phase 1) Annual Meeting, Monterey, CA

10 July 1989	Mr. Sydney Levitus "Temporal Variability of the Thermohaline Structure of the North Atlantic Ocean" Sixteenth Stanstead Seminar on "High Latitude Climatic Processes with Special Emphasis on Large-Scale Air-Ice-Sea Interactions" Bishops University, Lennoxville, Canada
12 July 1989	Dr. Ngar-Cheung Lau "The Response of Model Atmospheres to Observed Tropical and Extratropical SST Anomalies" Workshop on Impact of SST Specification in NWP and Climate Simulation, Melbourne, Australia
13 July 1989	Dr. Isaac M. Held "Orographic versus Thermally-Forced Stationary Waves: The Importance of the Low-Level Mean Winds" Massachusetts Institute of Technology, Cambridge, MA
13-21 July 1989	Dr. Ngar-Cheung Lau 1) "Variability of the Observed Midlatitude Storm Tracks in Relation to Low-Frequency Changes in the Circulation Pattern" 2) "Structure and Propagation Characteristics of Observed Synoptic-Scale Summertime Disturbances in the Tropics" 3) "Simulation of ENSO Phenomena with Ocean-Atmosphere Coupled GCM's at GFDL" Seminar Series at Bureau of Meteorology Research Center, Melbourne, Australia.
17 July 1989	Dr. Samuel George Philander "The Air-Sea Interactions in the Tropics" The Institute of Geophysics, Lima, Peru
23 July 1989	Mr. Sydney Levitus Temporal Variability of Basin Modes in the Thermohaline Structure of the North Atlantic Ocean" Meeting on Long Term Monitoring of Deep Ocean by Tomography Techniques, Washington, DC
24 July 1989	Dr. Syukuro Manabe "Study of the Contrast between the Glacial and Interglacial Climates by use of Coupled Ocean-Atmosphere Models" 1989 Global Change Institute: Explaining Records of Past Global Change, Snowmass, CO
25 July 1989	Dr. Kirk Bryan "Air-Sea Interaction in the North Atlantic- Purpose of the Meeting" NOAA/Climate Change Program on North Atlantic Variability, Lamont-Doherty Geological Observatory, Palisades, NY

25 July 1989	Dr. Samuel George Philander "Operational Ocean Models" NOAA Atlantic Meeting, Palisades, New York
31 July 1989	Dr. Isidoro Orlanski "Extratropical Cyclones in the Southern Hemisphere" IAMAP 89 - Mesoscale Processing in Extratropical Cyclones, Reading, England
1 August 1989	Dr. Kevin Hamilton 1) "Dissipation of Equatorial Waves in the GFDL "SKYHI" Mesophere-Stratosphere-Troposphere General Circulation Model", 2) "Properties of Stratospheric Gravity Waves Deduced from Rocket Soundings of Wind and Temperature" Fifth Scientific Assembly of the International Association of Meteorology and Atmospheric Physics, Reading, England
1 August 1989	Mr. Thomas L. Delworth "The Influence of Soil Wetness on Atmospheric Variability" Symposium on Global Energy and Water Fluxes - International Association of Meteorology and Atmospheric Physics, Fifth Scientific Assembly, Reading, England.
4 August 1989	Dr. Y. Kushnir "Geophysical Distribution, Structure and Time-Scale Dependence of Northern Hemisphere Low-Frequency Variability" IAMAP Conference, Reading, England
7 August 1989	Ms. M. Ting "The Stationary Response to Tropical SST Anomaly in an Idealized GCM" IAMAP Conference, Reading, England
7 August 1989	Dr. Kikuro Miyakoda "Essay on 10 Years After FGGE: Extended Range Forecasts" IAMAP 89 Conference, Reading, England
7 August 1989	Dr. Syukuro Manabe "Climate Change Induced by a Gradual Increase of Atmospheric CO_2" National Center for Atmospheric Research, Boulder, CO
7 August 1989	Dr. Isaac M. Held "The Transition to Equatorial Super-Rotation in General Circulation Models" IAMAP 89 Conference, Reading, England
14 August 1989	Dr. R. Gerdes "Seasonal Variability in Two Models of the North Atlantic" University of British Columbia, Vancouver, BC

14 August 1989	Dr. John R. Toggweiler "Dissolved Organic Matter and the Cycline of Carbon and Nutrient Elements in the Sea" Gordon Research Conference on Chemical Oceanography, Kimball Union Academy, Meriden, NH
22 August 1989	Dr. John R. Toggweiler "Organization of the Ocean's Chemical Distributions by the Flow through Drake Passage, at Ice and Climate" "Ice and Climate" Symposium, University of Washington, Seattle, WA
22 August 1989	Dr. Kerry Cook "The Response of the Atmosphere to the Ice Sheets of the Last Glacial Maximum" Ice and Climate Conference, Seattle, WA
22 August 1989	Dr. Kerry Cook "Stationary Waves and North Atlantic Cooling during the Last Glacial Maximum" ERL/NOAA Climate Research Division, Boulder, CO
22 August 1989	Dr. Kirk Bryan "Air-Sea Interaction in the North Atlantic-Purpose of the Meeting" "Ocean Tracer" Conference, University of Washington, Seattle, WA
22 August 1989	Dr. Steven Rintoul "Adjoint Methods and Tracer Modeling" SAVE Meeting, Seattle, WA
22 August 1989	Dr. R. Gerdes "Outflow from Marginal Seas in Large-Scale GCM's" SAVE Meeting, Seattle, WA
22 August 1989	Mr. J. Orr "Oceanic Uptake of Fossil CO_2 in a 3-D Non-Seasonal World Ocean Model" SAVE Meeting, Seattle, WA
23 August 1989	Dr. Syukuro Manabe "Transient Response of a Coupled Ocean-Atmosphere Model to a Gradual Increase of Atmospheric Carbon Dioxide" Meeting of Long Term Monitoring of Deep Ocean by Tomography Techniques, Washington, DC
27 August 1989	Dr. S. Hakkinen "One Hundred Years of Arctic Ice Cover Variations as Simulated by a One-Dimensional Coupled Ice-Ocean Model" Oceanography Society Meeting, Monterey, CA

27 August 1989	Dr. E. O'Brien "Topical Issues in the Atmospheric Sciences" NASA sponsored Workshop, Williamsburg, VA
28 August 1989	Mr. Sydney Levitus "Temporal Variability of the Thermohaline Structure of the North Atlantic Ocean" U. S. Naval Postgraduate School, Monterey, CA
28 August 1989	Dr. V. Ramaswamy "Modeling of Aerosol Effects on Climate" US-USSR Symposium on Aerosols and Climate, Moscow, USSR
28 August 1989	Dr. Steven Rintoul "Mass Heat and Nutrient Fluxes and Budgets in the North Atlantic Ocean" Oceanography Society Meeting, Monterey, CA
28 August 1989	Dr. Isaac M. Held 1) "The Tropospheric General Circulation: New Perspectives" 2) "Stationary Planetary Waves: Linear Models and GCM's" 3) "Developments in the Theory of Low Frequency Variability", Workshop on Topical Issues in the Atmospheric Sciences, Williamsburg, VA
31 August 1989	Dr. Yoshio Kurihara "Model Initialization Method at GFDL/NOAA" Workshop on Data Assimilation for Tropical Cyclone Studies, Naval Postgraduate School, Monterey, CA
11 September 1989	Dr. Syukuro Manabe "Assessment of Current State of Scientific Knowledge; Present and Future" Tokyo Conference on Global Environment and Human Response Towards Sustainable Environment, Tokyo, Japan
11 September 1989	Dr. Kerry H. Cook "Effects of a Continent on the Tropical Circulation in a GCM with Idealized Boundary Conditions" International Conference on Modeling of Global Climate Change and Variability, Hamburg, Federal Republic of Germany.
11 September 1989	Dr. Abraham H. Oort "The Current State of the Ocean/Atmosphere/Ice System" International Conference on "Modeling of Global Climate Change and Variability" Hamburg, Federal Republic of Germany.
13 September 1989	Dr. V. Ramaswamy "Comparison of Cirrus Cloud Simulation by a GCM" International Conference on Modeling of Global Climate Change, Hamburg, Germany

14 September 1989 Dr. Syukuro Manabe
"Current Status of the Research on Future Climate Change and Strategy for Adaptation" New Energy and Industrial Technology Development Organization, Tokyo. Japan

APPENDIX F

ACRONYMS

ACRONYMS

A2,E2,E4, F,M	Five physical parameterization packages in use at GFDL, in increasing order of sophistication. E4 physics includes a high-order closure scheme for subgrid turbulence, F physics includes Arakawa-Schubert convective parameterization, and M physics include envelope orography
CDC	Control Data Corporation
CIMA	Center of Ocean and Atmospheric Research, Buenos Aires, Argentina
COADS	Comprehensive Ocean-Atmosphere Data Set
ECMWF	European Centre for Medium-Range Weather Forecast
ENSO	El Niño - Southern Oscillation
ERBE	Earth Radiation Budget Experiment
FGGE	First GARP Global Experiment- Dec.1978 - Nov.1979 IIIb - Data set analyzed on a spatial grid. 4D- Analysis system taking into account both space and time variation of the data. SOP1 - First Observing Period, Jan.5 - Mar.5,1979 SOP2 - Second Observing Period May 1 - June 30, 1979
GALE/IOP	Genesis of Atlantic Lows Experiment, Intensive Observational Period
GARP	Global Atmospheric Research Program
GCM	General Circulation Model
GCTM	Global Chemical Transport Model
GEOSECS	GE Chemical Oceans SEC Time Study
GFDL	Geophysical Fluid Dynamics Laboratory
GFDL A88/P89	Geophysical Fluid Dynamics Laboratory Annual Report FY88, Plans FY89
HIBU	Federal Hydrological Institute and Belgrade University
ISCCP	International Satellite Cloud Climatology Project
ICRCCM	Intercomparison of Radiation Codes in Climate Models

ITCZ	Intertropical Convergence Zone
LAHM	Limited Area HIBU Model
MAC/BES	Meso-Alpha Coarse Model/Meso-Beta Scale Model
Meso α, β, or γ,	Three classes of mesoscale atmospheric motion, in descending order of spatial scale.
MMM	Multiply Nested Movable Mesh
MOODS	Master Oceanographic Observations Data Set
N60L18	60 points between pole and equator, 18 vertical levels
NCDS	National Climate Data Center
NODC	National Oceanographic Data Center
NMC	National Meteorological Center (USA)
PSC	Polar Stratospheric Clouds
PU	Princeton University
R15, (R30)	Rhomboidal truncation at wave numbers 15(30) with corresponding grid of 4.5°(2.25°) latitude by 7.5°(3.75°) longitude
SAVE	South Atlantic Ventilation Experiment
SESAME	Severe Storms & Mesoscale Experiment
SIB	Simple Biosphere
SKYHI	The GFDL Troposphere-Stratosphere-Mesosphere GCM
SST	Sea Surface Temperature
T30	Triangular truncation at wave number 30 with corresponding grid of 3.75° latitude by 3.75° longitude
UNEP	United Nations Environmental Program
USGS	United States Geological Survey
WGNE	Working Group on Numerical Experimentation
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment

☆U.S. GOVERNMENT PRINTING OFFICE:1989 -630 -169/ 00064