G
F
D
L

GEOPHYSICAL FLUID DYNAMICS LABORATORY

ACTIVITIES – FY93
PLANS – FY94

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

DEPARTMENT OF COMMERCE · UNITED STATES OF AMERICA

GEOPHYSICAL FLUID DYNAMICS LABORATORY

ACTIVITIES - FY93

PLANS - FY94

OCTOBER 1993

GEOPHYSICAL FLUID DYNAMICS LABORATORY
PRINCETON, NEW JERSEY

UNITED STATES
DEPARTMENT OF COMMERCE

RONALD H. BROWN
SECRETARY OF COMMERCE

NATIONAL OCEANIC AND
ATMOSPHERIC ADMINISTRATION

D. JAMES BAKER
UNDERSECRETARY FOR OCEANS
AND ATMOSPHERE

ENVIRONMENTAL
RESEARCH
LABORATORIES

ALAN R. THOMAS
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 Princeton University affiliates, to interested offices of the National Oceanic and Atmospheric Administration, to other relevant government agencies and national organizations, and to interested individuals.

The organization of the document encompasses an overview, project activities and plans for the current and next fiscal year, 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; and 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; and Mesoscale Dynamics. 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 1993; 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 FY94; a listing of seminars presented at GFDL during Fiscal Year 1993; a list of seminars and talks presented during Fiscal Year 1993 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 1993 Annual Report was co-edited by John Lanzante and Betty M. Williams. Special thanks are due to Wendy Marshall for her patience and expertise in typing this report, and to Gail Haller for painstakingly proofreading the report.

September 1993

TABLE OF CONTENTS

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 describe the GFDL contributions to five major research areas that correspond to NOAA's mission in oceanography and meteorology.

HIGHLIGHTS OF FY93

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. The parentheses refer to references in GFDL Activities, FY93; Plans, FY94.

I. WEATHER SERVICE

GOALS

During the past two decades, weather forecasts extending out several days to a week have improved considerably, because of developments in computer models. These improved models include more of the physical processes of the atmosphere, represent those processes more realistically, and perform computations at locations which are located closer to one another. Successful forecasts for periods up to 5 days are now routine, and the limit to which these forecasts are theoretically possible has been extended to several weeks. However, the skill in forecasting the amount of precipitation has lagged behind other quantities. For smaller spatial scales, there has been considerable progress in determining the mechanisms that generate severe storms, in explaining how medium-scale phenomena interact with the larger-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/climate be predicted when averaged over periods of months to years? Are medium-scale weather systems and regional-scale precipitation patterns predictable, and if so, to what extent is the accuracy dependent on the prediction of the large-scale 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 persistent weather regimes.

ACCOMPLISHMENTS OVER THE PAST YEAR (FY93)

* Semi-operational hurricane prediction was carried out with a GFDL hurricane prediction system, with the forecast results being sent to the National Hurricane Center. Predictions in cases of well-developed storms were performed with revolutionary accuracy. Post-season evaluation of the system was made, followed by an intensive effort to improve the initialization scheme and upgrade the automation procedure. Operational capability of the automated GFDL hurricane prediction system was significantly increased in its 1993 version (6.1, 6.5).

* Understanding of the basic processes in tropical storm genesis has been significantly advanced through investigation of the sensitivity of storm formation to the conditions at the surface boundary and below. Two competing mechanisms involving the surface wind exist at the boundary between the atmosphere and the earth below. In one process, an enhancement of the surface wind leads to further enhancement due to warming; in the other, enhanced surface winds lead to their own reduction due to cooling. The difference in the available heat supply between the land and the upper

ocean makes a dramatic difference in the impact of the latter mechanism on the evolution of the storm (6.2, 6.4).

* A quantitative modeling study, the first of its kind, was made to evaluate the influence of Hurricane Gloria in 1985 on the larger-scale flow surrounding the hurricane. Analysis of the interaction between the hurricane and an approaching front suggests that accurate prediction of tropical cyclones can contribute substantially to the improvement of the forecast of large-scale features in the nearby environment (6.3).

* An idealized model was used to show that the existence of locally enhanced baroclinicity does not necessarily lead to enhanced eddy activity in the same area. Energy radiated by eddies which develop in this highly baroclinic region may trigger and sustain eddies (extending the storm track) in the downstream region, despite the lower baroclinicity (7.1.1). Analysis of observed data supports this conclusion by showing that this is a primary mechanism in the Pacific storm track (7.1.2).

* Preliminary simulations of the Blizzard of '93 using the GFDL LAHM model resulted in a well simulated storm track and central pressure, and showed that the period of explosive deepening began with strong convergence of geopotential fluxes. Sinking motion associated with cold advection contributed significantly to the subsequent baroclinic conversion (7.2.2).

* A novel mechanism responsible for the generation of orographic cyclones was found to be the interaction between the circulation of the front associated with the cyclone and the mountain. Simulations show that warm southerly flow ahead of the front is diverted westward by the mountain ridge, intensifying the strong hydrostatic pressure gradient, while cold northerly flow is diverted eastward as it approaches the mountain, producing the characteristic pressure dipole (7.3.1). In a related study, it was shown that when a front reaches a topographic ridge, cold postfrontal air at the surface decelerates and produces a high pressure anomaly on the windward slope. If this anomaly is strong enough, it accelerates air over the ridge peak in a shallow ageostrophic flow that possesses many features found in a gravity current (7.3.2).

* A numerical model has been used to obtain high-drag states consistent with slowly varying initial wind and static stability. Most of the drag enhancement is due to the pressure drop in the severe downslope windstorm. Contrary to a common assumption, the upstream influence is mostly due to an initial surge not directly related to wavebreaking. An empirical formula for the total drag has been obtained for use in wave-drag parameterizations for weather and climate models (7.3.3).

* An ensemble of seasonal forecasts provides not only the average forecast, but also the spread of a predicted variable. The spread is generally smaller in the tropics

than in the extratropics, suggesting that the tropics are more predictable. In comparing the spread of rainfall from two models having different resolution in space, the basic features are found to be very similar to each other, implying considerable robustness of the results (3.2.1, 3.4.2).

* While the overall spread of an ensemble of model seasonal predictions in the extratropics approaches that of natural climate variability (climatology), occasionally it becomes noticeably smaller. When an ensemble of 10 year precipitation time series over the U.S. was compared with observations, three droughts (1980, 1981 and 1988) and a heavy rainfall year (1983) were found to be well simulated (particularly over the southeast U.S.) (3.2.1, 3.4.2).

* Decadal series of ocean data assimilation have been completed using the recently arrived TOGA data. The assimilation results were compared with independent data or analyzed maps. In particular, the 10-year averages of the assimilation compared especially well with Levitus' (528) climatology (3.3.2).

* Pairs of thirteen month ENSO (El Nino-Southern Oscillation) forecasts have been made by a complex atmosphere-ocean model which uses initial conditions produced by two different schemes to incorporate observed ocean data. Better prognoses were produced using the oceanic analyses derived using a variational method than through use of a temperature nudging method. This study suggests that, while the initial heat content distribution in the equatorial Pacific is of considerable importance to the forecast problem, the atmospheric initial conditions are not so important (3.4.3).

SOME PLANS FOR FUTURE RESEARCH

* Ensemble techniques developed with simple models will be evaluated in model ensemble forecasts using about 300 perturbed initial conditions. As a reasonable way of stratifying the ensemble, two states of atmospheric circulation (*zonal* flow vs. *blocked* patterns) will be investigated.

* Experiments will be conducted using both simple models and comprehensive models to examine methods for reducing "climate drift" in extended simulations. Further analysis of the model's monthly mean cloud-radiation climatology will be performed. The refinement of other physics parameterizations for the uncoupled atmospheric model will continue, concentrating on: 1) prediction of marine stratiform clouds in the eastern Pacific; 2) surface solar radiation, aimed at improving sea-surface temperature simulations; and 3) making the cloud prediction scheme more consistent with the Arakawa-Schubert cumulus parameterization.

* Related to the systematic bias in the air-sea coupled model, the vertical resolution of the ocean model will be increased to examine its role in causing the climate drift in the model's thermocline structure.

* The initialization of soil moisture and snow cover for seasonal forecasts will be pursued. Nine decadal runs with the GFDL extended-range forecast model will be analyzed and reproducibility of forecasts will be studied. Comparison of the model's drought index with observations over the U.S. will be carried out further. A 40-year simulation using the revised sea-surface temperature data set supplied by the U.K. Meteorological Office will be started.

* Additional case studies, including the Blizzard of '93, will be evaluated to better understand the role of geopotential fluxes and baroclinic conversion in the development of cyclones. Explosively developing storms will be analyzed to identify the roles played by localized baroclinicity and the decay of upstream systems.

* The role of surface heat and momentum fluxes in atmospheric preconditioning and the intensification of extratropical cyclones will continue, particularly with respect to the new vertical mixing scheme incorporated into the LAHM model. New case studies will be performed to assess the impact of these processes on the development of both explosive and moderately strong cyclones.

* Investigation of topographic influences on mesoscale systems and large-scale flows will be continued, and mountain drag estimates will be extended to include more realistic mesoscale circulations. The role of gravity waves in mesoscale circulations will continue to be evaluated.

* Model development for the high resolution limited area models will emphasize two main aspects: a) improving the surface flux parameterizations and b) improving the accuracy of the numerical schemes.

II. CLIMATE

GOALS

The purpose of climate-related research at GFDL is two-fold: to describe, explain, and simulate mean climate and climate variability on time scales from seasons to millennia; and to evaluate the effect on climate of human activities such as the release of carbon dioxide (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 El Niño-Southern Oscillation (ENSO); 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 (FY93)

- Using a coupled ocean-atmosphere model, the multiple century response of climate to a doubling and quadrupling of atmospheric carbon dioxide (CO_2) was studied. Over 500 years, the global mean surface air temperature of the coupled model increases by 3.5 and 7°C, respectively, and sea-level rise is about 1 and 2 m respectively, due solely to the thermal expansion of sea water. It could be as much as five-times larger if the effect of ice sheet melting were taken into consideration. Furthermore, the dynamical as well as thermal structure of the oceans undergo marked changes. In particular, the thermohaline circulation almost disappears in the CO_2 quadrupling experiment (1.1.1).

- A statistical analysis of the 1000-year time series of global mean temperature of a coupled ocean-atmosphere model suggests that the long-term warming trend observed since the late 19th century may not be attributable to the natural variability of climate due to the interactions among the atmosphere, ocean, and land surface. Instead, it appears to represent the response of the coupled system to a thermal forcing such as the concentration of greenhouse gases (1.1.3).

- In a continued analysis of the sensitivity of continental hydrology to the water-holding capacity of soils, the role of atmospheric feedbacks was identified. An increased capacity leads, via increased evaporation, to increased precipitation and decreased potential evaporation. These feedbacks increase runoff; however, their net effect on evaporation is relatively small (1.2.1).

- A parameterization for convective systems for use in general circulation models has been developed. For the first time in such a parameterization, the effects of mesoscale updrafts are represented. The parameterization provides a basis for calculating the radiative properties of convective anvils and should be a valuable tool for studying interactions between convection and radiation in general circulation models. The heat and water budgets of the convective system agree well with those observed in field programs on tropical convection (1.3.2).

* Using a simplified three-dimensional model, baroclinic eddy heat fluxes have been shown to peak at the horizontal scale at which the inverse energy cascade to larger scales stops, rather than at the radius of deformation. This result has implications for estimates of subgrid scale mixing in ocean models (1.4.1.2).

* Benchmark calculations for the dry dynamical cores of atmospheric models have been designed that allow one to study the effects of the model numerics on climate without the complicating presence of realistic radiative, moist convective, and boundary layer processes. Comparisons have begun between the climates produced by spectral and by grid point models (1.6.1).

* Benchmark solar radiative transfer computations indicate that the spectral distribution of and the total near-infrared solar flux reflected at the top-of-the-atmosphere and that absorbed by water clouds depend on the vertical location of the cloud, whereas the surface flux is relatively insensitive to this factor (1.6.5.2).

* The new modular GFDL SKYHI model has been written in a form that is directly applicable to massively parallel processor (MPP) systems. This version has been released to the MPP vendor community for review and comment. The vendors have noted that the code is fair to the full range of MPP architectures and would be suitable as a benchmark in GFDL's planned supercomputer upgrade (2.2.1).

* The 1° latitude resolution version of the GFDL SKYHI model shows a number of impressive new simulation successes. Most notably, this high resolution version points to a much more plausible requirement for orographic drag parameterizations than employed in previous models of this type (2.2.2).

* A remarkable multi-year persistence has been found in the winter polar vortex structure of the SKYHI model. These low frequency variations in models with prescribed sea surface temperatures remain unexplained, but are very relevant as input to the interpretation of climate trend data (2.2.6).

* A simplified atmospheric model has been used to demonstrate some of the fundamental mechanisms responsible for the creation of relatively energetic motions in the mesoscale (10-1000 km) range. The interactions of planetary-scale motions act to create gravity wave motions that cascade into the mesoscale and "pile-up" there (2.2.9).

* Radiative-convective model studies indicate that increases in tropospheric aerosols, while counteracting the effects of the increases in the greenhouse gases with regards to surface warming, act in the same manner as CO_2 in causing a cooling of the lower stratosphere (2.3.3).

* High-spectral resolution radiative transfer computations reveal that the trapping ("greenhouse effect") of infrared radiation by many perfluorocarbons (PFCs) is comparable to chlorofluorocarbon-11. Since the PFCs are very long-lived, they are thus climatically important trace species (2.3.3).

* The radiative forcing induced by a change in the liquid water path of low clouds varies with latitude and month and is governed by the variations in insolation, solar zenith, surface albedo, and cloud cover. The latitudinal distribution of this forcing differs from that due to a doubling of CO_2 (2.3.5).

* The climatic effects due to an imposed global lower stratospheric ozone loss, such as that observed over the past decade, have been simulated in the SKYHI model. A substantial cooling occurs in the lower stratosphere at all latitudes that is consistent with the global decadal temperature trends inferred from upper air data records (2.3.5).

* An extensive set of atmospheric model experiments subjected to temporally varying sea-surface temperature (SST) anomalies at different maritime sites indicates that tropical Pacific SST anomalies play a primary role in forcing the midlatitude atmospheric circulation; however, the impact of extratropical SST anomalies on the overlying atmosphere is much weaker. The midlatitude atmospheric response to El Niño-Southern Oscillation (ENSO) episodes exerts considerable influence on the surface ocean outside the tropical Pacific. This "atmospheric bridge" thus contributes to the observed world-wide SST signals accompanying ENSO events occurring in the tropical Pacific (5.4.1).

* Analysis of satellite observations of cloudiness in conjunction with conventional meteorological data reveals well-defined spatial and temporal relationships between the atmospheric circulation and the occurrence of various cloud types. These relationships are consistent with the dynamical knowledge of such circulation systems as extratropical cyclones and near-equatorial Madden-Julian Oscillations (5.5.2).

SOME PLANS FOR FUTURE RESEARCH

* Analysis of the 1000-year time series from the coupled ocean-atmosphere model will continue. One of the goals of this analysis will be to study the role of the oceans in the temporal variation of climate on decadal to century time scales.

* An improved, coupled ocean-atmosphere model with higher computational resolution will be used to study the climate response to increasing CO_2 concentration in the atmosphere.

* Using the redesigned code for the non-hydrostatic moist model, a series of calculations will be performed to study the dependence of the radiative-convective

equilibrium on the size of the domain, resolution, and microphysical assumptions. A version of the model with a much higher upper boundary will be studied in order to better examine the model's wind oscillations. A preliminary three-dimensional version of the radiative-convective calculation will be attempted on a small domain.

* A study of the atmospheric ice clouds which integrates experimental results from field programs and global satellite observations with sensitivity studies using a complex atmospheric model, will be carried forward.

* A series of climate-model experiments will be initiated, with the objective of understanding certain interactions between climate change and continental hydrology.

* Exploration of a new version of the GFDL SKYHI model that is more amenable to troposphere and lower stratosphere chemical problems will be underway.

* The modular, parallel version of SKYHI will be adapted for trial high-resolution calculations on the CM-5 computer at Los Alamos National Laboratories.

* The benchmark radiative transfer computations will continue to be used to diagnose the disposition of the radiative fluxes in the atmosphere and to test, develop and incorporate accurate parameterizations of the radiative effects due to several trace species in GFDL's atmospheric models.

* The sensitivity of climate to changes in the concentrations of greenhouse gases, ozone and aerosols, and to changes in the physical properties of clouds will be investigated using atmospheric models.

* Diagnostic analyses of key aspects of the atmospheric hydrologic cycle (*e.g.*, water vapor and clouds) and the global radiation budget will continue using several satellite observations. The satellite estimates will also be used to evaluate the computed estimates from GFDL's atmospheric models.

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. This involves attack on such central problems as: the transport of quasi-conservative trace gases; the biogeochemistry of climatically significant long-lived trace gases, such as CO_2, methane (CH_4), nitrous oxide (N_2O), and the chlorofluorocarbons (CFCs); the transport, sources, and sinks of aerosols; the chemistry of ozone and its regulative trace species, such as the families of reactive nitrogen, hydrogen, chlorine, and hydrocarbons; and the effects of clouds and aerosols on chemically important trace gases. Such research 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 (FY93)

* A new comprehensive ozone chemistry code has been prepared for use in the new modular GFDL SKYHI model. SKYHI's highly flexible coding structure allows for a very wide range of ozone and other chemical simulations in a computationally efficient manner on a variety of computer architectures (2.1.2).

* A long-term research effort to model and quantify all aspects of the tropospheric budgets of reactive nitrogen has now been completed. The various sources of reactive nitrogen contribute importantly in various locations and altitudes. These include: fossil-fuel combustion (21 tg N $year^{-1}$); biomass burning (8.5); biogenic emission (5.6); lightning (3); transport from the stratosphere (0.65); and subsonic aircraft emissions (0.45). These varied sources appear to close the reactive nitrogen budget and now allow for a quantitative attack on the global tropospheric ozone problem (2.1.3).

* A comprehensive model study of the reactive nitrogen subspecies peroxyacylnitrate (PAN) has revealed an intricate relationship between its thermal decomposition and its storage in the cold upper troposphere for later transport downward into remote regions normally low in reactive nitrogen (2.1.5).

SOME PLANS FOR FUTURE RESEARCH

* SKYHI transport studies will be performed with a suite of tracers: chlorofluorocarbon-11 to characterize the model's interhemispheric transport; reactive nitrogen compounds from fossil-fuel combustion emissions to test mid-latitude transport of tracers that undergo physical and chemical transformations and have surface sources; stratospheric ozone to test downward transport into the troposphere; and a biomass burning source of ozone to test tropospheric transport in the tropics.

* The SKYHI stratospheric ozone chemistry model will be extensively tested on a relatively simplified "nitrogen-only" system, including a chemically self-consistent troposphere.

* Tropospheric sulfate aerosols are believed to significantly affect the earth's radiation budget through their direct scattering of solar radiation, as well as indirectly

through their effect on the distributions of cloud condensation nuclei. Work will be initiated on box and one-dimensional chemical/microphysical models describing the cycling of biogenic sulfur compounds in the marine boundary layer. The goal of this work is to develop parameterizations for use in SKYHI and the GFDL/Global Chemical Transport Model.

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 (FY93)

* The sensitivity of oceanic uptake of anthropogenic CO_2 to various estimates of the natural carbon cycle, the carbonate equilibrium constants, numerical differencing schemes, and model physics was evaluated. Oceanic uptake estimates of order 2 GtC/yr for the last decade show only modest sensitivity of less than 20% to all these factors (4.5.1).

* Ecosystem model simulations of uptake of nitrate by organisms in the surface ocean have been completed. These models are being improved by an examination of the basic ecosystem structure, the application of sophisticated parameter estimation techniques, and assimilation of satellite ocean color observations. Work has been initiated on coupling a carbon-nitrogen ecosystem model into a global ocean model (4.5.2).

* An analysis of thorium, particulate organic carbon (POC), and particulate organic nitrogen (PON) data collected during the JGOFS North Atlantic Bloom Study was completed. Inverse techniques were used to estimate the rates of particle interactions and POC and PON remineralization at three continuous time intervals during the spring bloom. The results suggest that the rate of particle interactions increase dramatically through the course of the bloom (4.5.2).

* A new project to develop a model of the terrestrial carbon cycle was initiated during the last year. A major emphasis of research on the anthropogenic CO_2 budget during the last year has been to investigate the temporal and spatial distribution of the "missing sink", generally assumed to result from terrestrial processes (4.5.3).

* Oceanic measurements of the partial pressure of CO_2 (pCO_2), total carbon, and alkalinity were obtained in the Southeast Pacific. A study was initiated to develop an algorithm to predict the difference in pCO_2 between the ocean and atmosphere (delta pCO_2) from satellite and climatological data. Initial results using linear least squares models can predict North Atlantic summer delta pCO_2 values with a residual standard error of 15 microatmospheres (4.5.4).

* A simple biological parameterization has been employed to model the oceanic nitrous oxide cycle. This model, which is based on the observed correlation between apparent oxygen utilization and excess N_2O in the ocean, is able to reproduce the large-scale features of the observed N_2O distribution (4.6).

* The exchange of properties between the mixed layer and the permanent thermocline have been investigated with the aid of a numerical model of the North Atlantic Basin and in connection with modeling the distribution of tritium. The results clearly point to the horizontal transport of mass across sloping mixed layers as one of the main mechanisms for the ventilation of the thermocline, particularly in the Subpolar Gyre (4.7).

SOME PLANS FOR FUTURE RESEARCH

* The sensitivity studies of uptake of carbon by the ocean for the industrial period will be continued. A complete model of the carbon cycle including the solubility, biological, and calcium carbonate pumps will be used in an effort to bring together different results so far obtained using a perturbation model of carbon and a biology plus solubility pump model.

* A project is being initiated in collaboration with the Climate Dynamics group to calculate oceanic uptake of anthropogenic CO_2 in a coupled air-sea model of the climate response to increased atmospheric CO_2.

* Measurements of oceanic carbon distributions will be continued. Algorithms that relate observed ocean properties to delta pCO_2 (the difference between the ocean and atmosphere partial pressure of CO_2) will be developed using existing data bases and statistical techniques.

* The multiple chain ecosystem model development will be continued using the parameter estimation approach. The model will be placed in the GFDL ocean model.

Work on assimilating satellite color data will be continued. Work on placing the carbon-nitrogen model into the ocean model will continue.

* Simulation and analysis of an oceanic carbon cycle model that includes chemical, organic carbon, and inorganic carbon components will be completed. The river flux of dissolved carbon will be added to the ocean carbon cycle model.

* Studies of the spatial and temporal distribution of the terrestrial missing CO_2 sink will be completed and development of a terrestrial ecosystem model will continue.

* Research on the oceanic N_2O cycle will focus on improving the parameterization of the cycle by incorporating analysis of the available observational data sets for N_2O.

* Tracer modeling studies are being extended to the world ocean, in combination with analysis of the double diffusive processes and salt fingers instabilities as another possible mechanism for the ventilation of thermocline and Central Waters.

* The Ocean Tracers Laboratory will continue to participate in the WOCE Pacific Ocean measurement program. If current plans hold up, responsibility for processing ^{14}C and ^{228}Ra data from the Indian Ocean program will be assumed. Modeling work using both tracers will continue.

V. OCEAN SERVICES

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 phenomena.

ACCOMPLISHMENTS OVER THE PAST YEAR (FY93)

* Analyses of unstable, coupled ocean atmosphere modes in the tropics reveal that modes that are antisymmetrical about the equator are most unstable for the time mean itself. These modes are of central importance in climatic asymmetries relative to the equator (a northerly ITCZ in the eastern Pacific, for example) and in the seasonal cycle of the tropics (an annual cycle at the equator, where there is practically no annual variation in solar radiation) (4.1.1).

* Circulation models of the global atmosphere and tropical oceans have been coupled successfully and simulate the seasonal cycle over a ten-year period without appreciable climate drift even though no flux corrections are applied. Future efforts will focus on the improvements of the simulation in the region off the western coast of the Americas, where the absence of stratus clouds from the model causes conditions that are too warm (4.1.2).

* A study of the links between the tropical and extratropical oceanic circulations has established that winds over the eastern part of the subtropical gyre influence the structure of the equatorial thermocline, and hence could influence the time-scale of phenomena such as the Southern Oscillation (4.1.4).

* The sea level rise over the past 100 years has been calculated independently, showing good agreement with tide gauge data, and estimates of melting land ice. This is the first calculation of rising sea level using a complete ocean circulation model using the historical record of sea surface temperature as input (4.3.1).

* Sea level rise in response to enhanced greenhouse warming and the resultant thermal expansion of the ocean has been calculated from the output of the GFDL coupled ocean-atmosphere climate model. The study shows how large-scale internal waves redistribute mass within the ocean and give rise to a rather uniform rise in sea level, in response to a quite nonuniform input into the ocean by enhanced greenhouse warming (4.3.1).

* Forecast and nowcast skills have been demonstrated with a high resolution Gulf Stream ocean model and data assimilation scheme, using satellite altimetry and SST data. A coastal ocean prediction system for the U.S. east coast has been set in an operational environment for the first time; it will be coupled with an atmospheric model at the National Meteorological Center to produce experimental daily nowcasts and forecasts (4.4.1, 4.4.2).

SOME PLANS FOR FUTURE RESEARCH

* Extend the eddy resolving coastal ocean model to a basin-scale model in order to study climate change problems by modeling the Atlantic and the Arctic Oceans.

* Incorporate improvements in the coupled ocean-atmosphere TOGA model in order to properly simulate the seasonal cycle in the eastern tropical Pacific.

* Use the GFDL eddy-resolving model of the North Atlantic to design a monitoring system for the Atlantic thermohaline circulation.

* Study the "predictability" of changes in the North Atlantic thermohaline circulation, using "identical twin" experiments with the GFDL coupled atmosphere-ocean model.

PROJECT ACTIVITIES FY93

PROJECT PLANS FY94

1. CLIMATE DYNAMICS

GOALS

To construct mathematical models of the atmosphere and of the coupled 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 OCEAN-ATMOSPHERE INTERACTION

1.1.1 Multiple Century Response to Increasing CO_2

S. Manabe *R.J. Stouffer*

ACTIVITIES FY93

To speculate on the future change of climate over several centuries, three 500-year integrations of a coupled ocean-atmosphere model were performed. In addition to the standard integration in which the atmospheric concentration of carbon dioxide remained unchanged, two integrations were conducted (Fig. 1.1a). In one integration, the CO_2 concentration increased by 1% per year (compounded) until it reached four times the initial value at the 140th year and remained unchanged thereafter. In another integration, the CO_2 concentration also increased at the rate of 1% per year until it reached twice the initial value at the 70th year and remained unchanged thereafter. This study is an extension of an earlier study in which the response of the coupled ocean-atmosphere model to a gradual increase of atmospheric carbon dioxide concentration over the period of 100 years was reported (961, 1042, 1067).

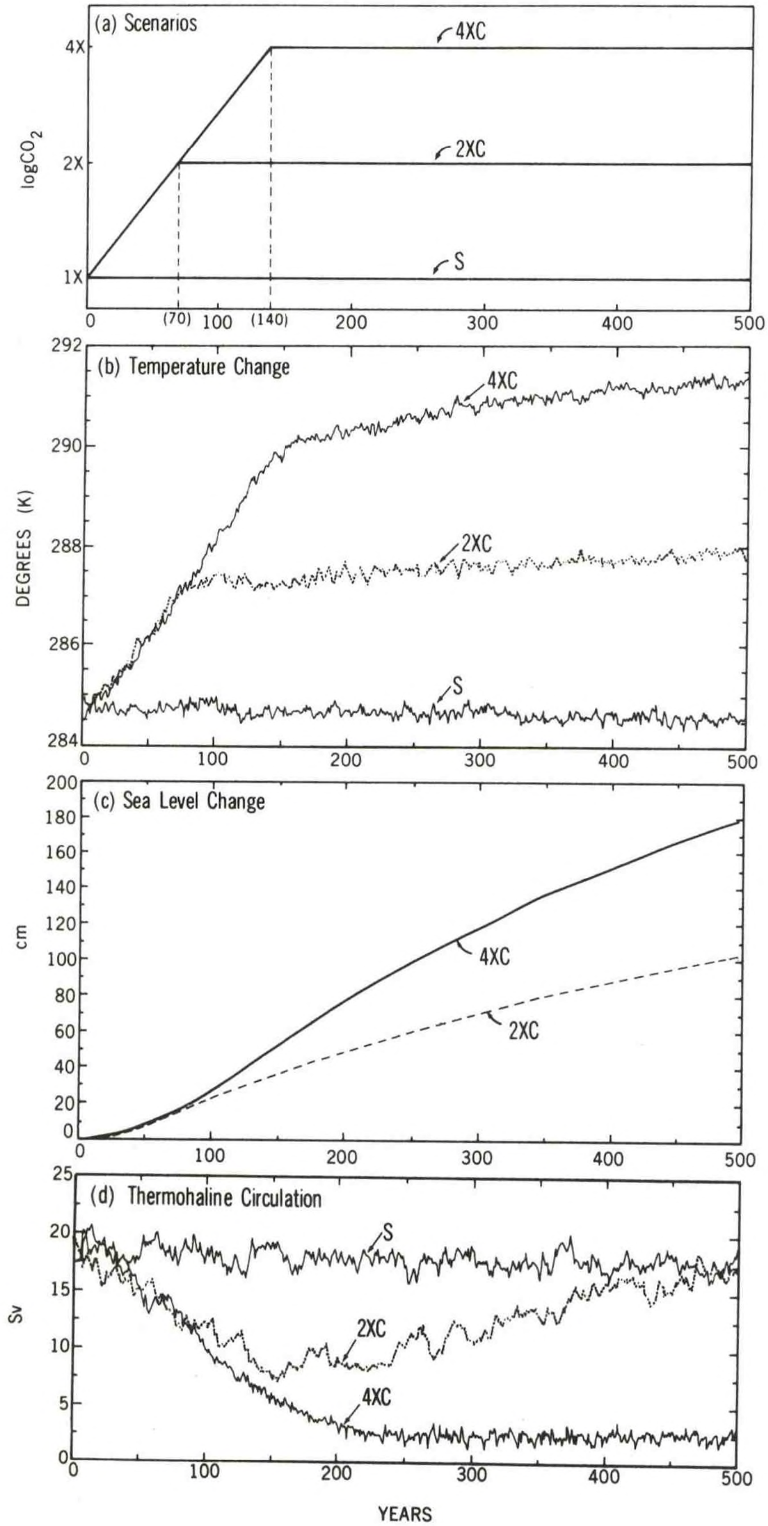


Fig. 1.1 Temporal variations of: (a) logarithm of atmospheric CO_2 concentration, (b) global mean surface air temperature (°K), (c) global mean increase of sea level (cm) due to thermal expansion, computed as the difference between the 4XC (quadrupled CO_2) and S (standard or control), and 2XC (doubled CO_2) and S integrations, and (d) the intensity of the thermohaline circulation in the North Atlantic Ocean. Here intensity is defined as the maximum value for the streamfunction representing the meridional circulation in the North Atlantic.

One of the most notable features of the CO_2-quadrupling integration is the gradual disappearance of thermohaline circulations in most of the model oceans during the first 250 year period, leaving behind only surface wind-driven cells. For example, the thermohaline circulation nearly vanishes in the North Atlantic during the first 200 years of the integration (Fig. 1.1d). In the Weddell and Ross Seas, the thermohaline circulation becomes weaker and shallower, thereby reducing the rate of bottom water formation and weakening the northward flow of bottom water in the Pacific and Atlantic Oceans. The weakening or near-disappearance of the thermohaline circulations described above is attributable mainly to the capping of the model oceans by relatively fresh water in high latitudes, where the excess of precipitation over evaporation increases markedly due to the enhanced poleward moisture transport in the warmer model troposphere.

In the CO_2-doubling integration, the thermohaline circulation weakens by more than a factor of two in the North Atlantic during the first 150 years, but almost recovers its original intensity by the 500th year. The increase and downward penetration of positive temperature anomaly in low and middle latitudes of the North Atlantic helps to increase the density contrast between the sinking and rising regions, contributing to this slow recovery. The recovery is aided by the gradual increase in surface salinity which accompanies the intensification of the thermohaline circulation.

During the 500-year period of the doubling and quadrupling experiments, the global mean surface air temperature increases by about 3.5°C and 7°C, respectively (Fig. 1.1b). The rise of sea level due to the thermal expansion of sea water is about 1 and 1.8 m, respectively (Fig. 1.1c), and could be as much as five times larger if the contribution of melt water from continental ice sheets were included.

According to the IPCC (Intergovernmental Panel on Climate Change), a quadrupling of the CO_2 could be realized if the Business-As-Usual scenario for the emission of greenhouse gases (which increases at a rate of about 1% per year) continued until the end of the 21st century. Draconian measures would probably be required to prevent the CO_2 equivalent of greenhouse gases from quadrupling (*e.g.*, Walker and Kasting, 1992[1]). Considering the possible overestimate of climate sensitivity by the present model, it may be reasonable to speculate that the CO_2-doubling and quadrupling experiments provide a probable range of future climate change.

---

1. Walker, J.C.G. and J.F. Kasting, 1992: Effect of Fuel and Forest Conservation of Future Levels of Atmospheric Carbon Dioxide. Paleoceanography, Paleoclimatology, Paleoecology (Global and Planetary Change Section), 97, 151-189.

PLANS FY94

The coupled model will continue to be used to study the long-term effects of increasing greenhouse gas concentrations in the atmosphere. A series of experiments are planned in which various scenarios for the rate of increase in CO_2 concentration will be studied.

1.1.2 Tropical Response to CO_2

T. Knutson *S. Manabe*

ACTIVITIES FY93

The impact of increasing atmospheric CO_2 concentration on the mean climate and low-frequency variability in the tropics is being investigated. The activities in FY93 have expanded on the preliminary results for the Walker Circulation and ENSO-like phenomena obtained in FY92.

1.1.2.1 CO_2-Induced Changes in the Time-Mean Walker Circulation

As discussed in A92/P93, as the model climate warms, enhanced radiative cooling in the upper tropical troposphere helps to offset much of the enhanced heating associated with moist convection and condensation. Further investigation has revealed that this enhanced radiative cooling is primarily due to the large fractional increase in moisture in the upper troposphere and to the tropospheric warming itself; these two effects are of comparable importance. An analysis of the atmospheric water budget indicated that the model's net moisture sink due to moist convection and condensation is enhanced in the upper troposphere, with this enhanced moisture sink being counterbalanced by enhanced moisture advection. Increased time-mean moisture gradients contributed to enhancing the moisture advection, whereas the time-mean circulation changes acted to slightly reduce the enhancement. Thus, the picture that emerges is that the CO_2-induced increase in precipitation in the model is related more to changes in the temperature and moisture distributions than to changes in the time-mean circulation. Consistent with this type of response, the model's time-mean Walker Circulation did not strengthen in the warmer climate, in spite of the increased precipitation over the western tropical Pacific.

1.1.2.2 CO_2-Induced Changes in ENSO-like Phenomena

In order to investigate the impact of CO_2-induced warming on ENSO-like fluctuations (1076) in the model, a long time-integration with a large CO_2 perturbation is desirable. An analysis has begun of ENSO-like phenomena in a 500-year control integration and in a 500-year simulation in which CO_2 increased at a rate of 1% per year to four times its initial level and then remained constant at that quadrupled level for another 360 years (1.1.1). During ENSO-like events in the CO_2-warmed climate, the amplitude of SST anomalies is slightly reduced in comparison to ENSO-like events in the control run (Fig. 1.2). In spite of the slightly reduced SST anomalies, both the ENSO-related enhancement of precipitation east of the dateline and the reduction of precipitation west of the dateline are intensified. A smaller fractional increase occurs in the surface westerly anomalies over the central Pacific. Investigation of the relationships between these phenomena is continuing.

PLANS FY94

The investigation of the ENSO response to increasing CO_2 will be completed in FY94. Attention will then turn to the response of higher-frequency "transient weather" phenomena in the tropics. Specifically, the response of the tropical storm climate in GCMs to a CO_2-induced warming will be investigated, following up on the earlier studies of Broccoli and Manabe (1009).

1.1.3 Detection of Global Warming

S. Manabe *K. Ya Vinnikov*
R.J. Stouffer

ACTIVITIES FY93

Since the late 19th century, the global mean surface air temperature has been increasing at the rate of about 0.5°C/century. However, a poor quantitative understanding of low frequency natural climate variability has made it very difficult to prove that the observed warming trend is attributable to a thermal forcing, such as the enhanced greenhouse effect (IPCC, 1990[2], 1992[3]). In this study, the observed warming trend is evaluated based upon the results from a 1000-year integration of the coupled ocean-atmosphere model (1.1.1, 1.1.2).

The time series of the globally averaged, annual mean temperature obtained from the 1000-year integration mentioned above is shown in Fig. 1.3a. It has a small cooling trend of 0.023°C/century, which is much less than the observed warming trend of 0.52°C/century from the time series of observed, global mean surface air

---

2. Climate Change, The IPCC Scientific Assessment, WMO-UNEP (Cambridge Univ. Press, 1990).
3. Climate Change 1992, The Supplementary Report to the IPCC Scientific Assessment, WMO-UNEP (Cambridge Univ. Press, 1992).

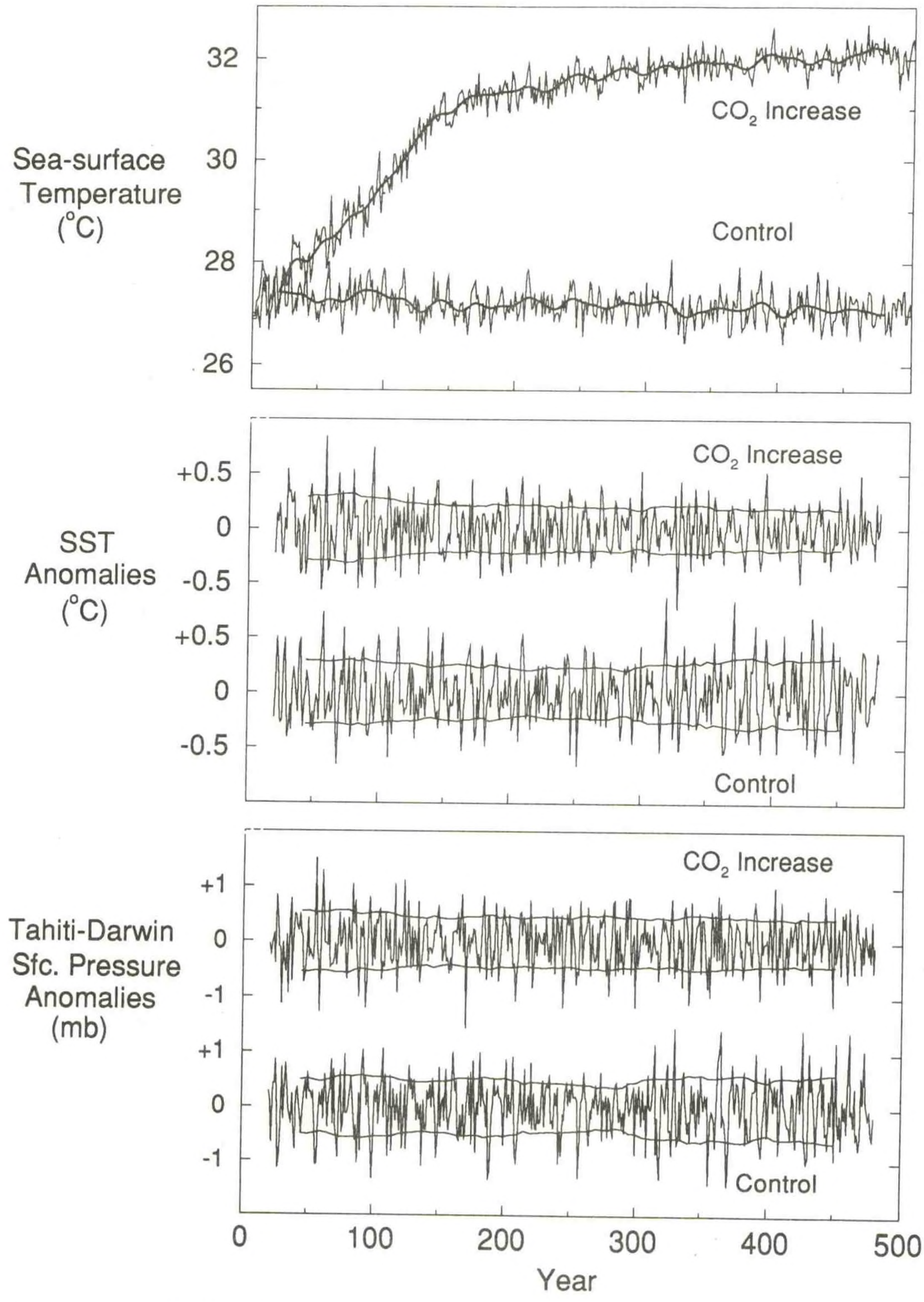


Fig. 1.2 Annual mean sea surface temperature (top panel), SST anomalies (middle), and Tahiti-Darwin surface pressure anomalies (bottom) from both the $4XCO_2$ perturbation experiment and the control experiment (see text for details). "Anomalies" are the residuals from the low-pass (> 25 year) filtered data (*e.g.*, dark line, top panel). The "variability envelopes" in the middle and bottom panels are based on +/- one standard deviations for 50-year segments of anomalies. Sea surface temperatures are for the region 7N-7S, 172.5E-120W.

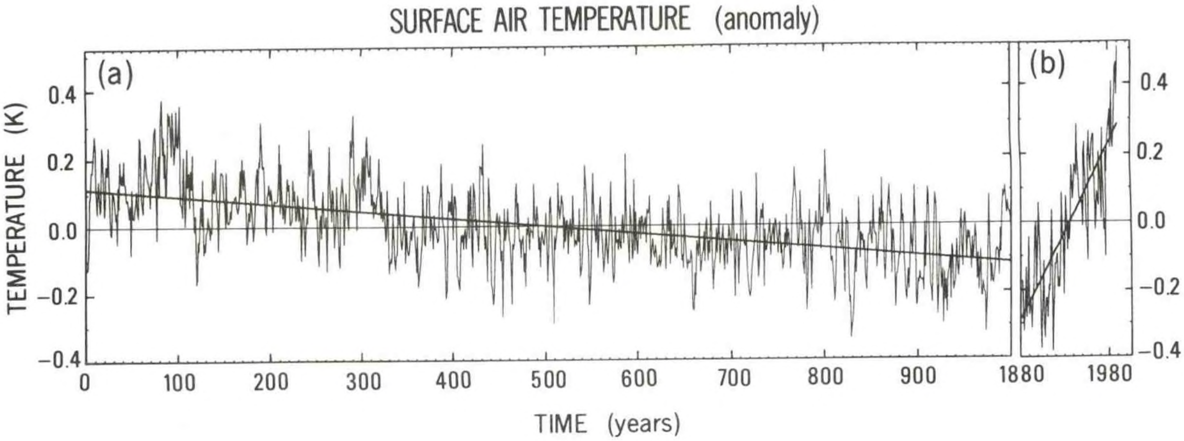


Fig. 1.3 Time series of globally averaged, annual mean surface air temperature anomaly from a long term mean (°K) for: (a) 1,000-year integration of the coupled ocean-atmosphere model and (b) Observations compiled by Jones and Wigley (1991).

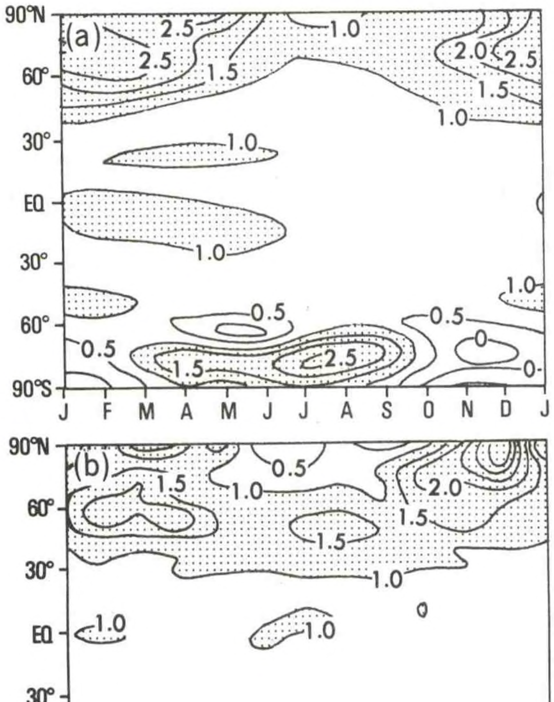
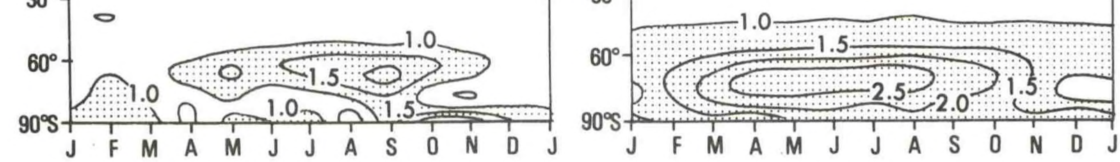


Fig. 1.4 Zonal-seasonal distribution of the regression coefficient between globally averaged, annual mean and zonally averaged monthly mean surface air temperature.
(a) Estimates for observed interannual variations in temperature (1881-1991).
(b) Estimates for modelled unforced natural variations in temperature (700 year control run of the GFDL coupled model).
(c) Equilibrium response of zonal mean surface air temperature (°K) of the atmosphere-mixed layer model to CO_2 doubling. The response has been normalized (divided) by the change in global mean surface air temperature.



temperature over the period 1880-1990 (Fig. 1.3b) obtained by Jones et al., (1991[4]). The inspection of the 1000-year time series indicates that the model successfully mimics the observed variability of the global mean surface air temperature on decadal and interdecadal time scales.

In the time series from the coupled model, one notes that there are periods during which the warming trend is as large as 0.5°C/century. However, these periods last only a few decades.

A statistical analysis of the time series suggests that it is not likely that the long-term warming trend observed since the late 19th century is attributable to the natural variability of climate resulting from interactions among the atmosphere, ocean, and land surface. Instead, it appears to represent the response of the coupled system to a thermal forcing, such as the changes in the concentration of greenhouse gases and the loading of aerosols in the atmosphere. This conclusion would be stronger if it were possible to test the model's capability to simulate century-scale variability. Unfortunately, the required observations over hundreds of years do not exist.

PLANS FY94

During the next year, the role of the oceans on the interdecadal variability of climate will be investigated using the 1000-year integration of the coupled ocean-atmosphere model.

1.1.4 Polar Amplification of Surface Air Temperature Anomalies

S. Manabe *K. Ya Vinnikov*
R.J. Stouffer

ACTIVITIES FY93

A linear statistical method has been used to study the correspondence between global and zonal mean surface air temperature anomalies. The seasonal-latitudinal distribution of the regression coefficient between the annual mean, global surface air temperature and the zonal mean temperature has been computed for both the observed climate variations and for modeled, unforced natural climate variations. Updated observed surface air temperature (Jones et al., 1991; Vinnikov et al., 1990[5])

---

4. Jones, P.D., T.M.L. Wigley, and G. Farmer, 1991: Marine and Land Temperature Data Sets: A Comparison and a Look at Recent Trends. In: Greenhouse-Gas-Induced Climatic Change: A Critical Appraisal of Simulations and Observations, M.E. Schlesinger (Ed.), Elsevier Science Publishers B.A., Amsterdam, pp. 153-172.
5. Vinnikov K.Ya., P.Ya. Groisman, and K.M. Lugina, 1990: Empirical data on contemporary climate change (temperature and precipitation). Journal of Climate, 3, 662-677.

and 700 years of surface air temperature data from the unforced integration of the GFDL coupled ocean-atmosphere model (1.1.3) were used. The results were also compared with the equilibrium response of surface air temperature obtained from an atmosphere-mixed layer ocean model in which the CO_2 concentration in the atmosphere was doubled.

The estimates of zonal-seasonal distribution of this regression coefficient for the observed (1881-1991) interannual variability of the annual mean, global mean surface air temperature are presented in Fig. 1.4a. The polar-winter amplification for surface temperature is shown in this figure by the relatively large values (2.5) during the winter months in high latitudes of both hemispheres. A similar distribution of the regression coefficient estimates for interannual unforced natural climate variations in the 700 year model integration are presented in Fig. 1.4b. The estimates for the model also reach values of 2-2.5 for the winter months in high latitudes of both hemispheres. Therefore, both the modeled and observed distributions show a polar-winter amplification of surface temperature.

By comparing the regression coefficient patterns described above for the observed and modeled unforced natural fluctuations in the mean global temperature (Fig. 1.4 a, b) with the normalized surface air temperature response due to greenhouse global warming in an atmosphere-mixed layer ocean model (Fig. 1.4c), it can be easily seen that to a first approximation the patterns are very similar. This suggests that the detection of greenhouse warming is difficult because of natural variability.

1.1.5 Atlantic Variability

T.L. Delworth *R.J. Stouffer*
S. Manabe

ACTIVITIES FY93

Interdecadal variations in the intensity of the thermohaline circulation (THC) in the North Atlantic Ocean have been studied in the coupled ocean-atmosphere model described in preceding sections. The objectives of the project are to ascertain the characteristics and mechanisms of interdecadal variability in this model, to examine how such variability can affect the atmosphere, and to compare model variability to the variability observed in the real climate system. The coupled ocean-atmosphere model used in this study has a global computational domain, realistic geography, seasonally varying insolation, and predicted cloudiness.

As previously reported, detailed analyses of a 1000-year integration have demonstrated substantial amounts of variance at decadal and longer time scales. In particular, the model THC has substantial variability on interdecadal time scales which are largely attributable to changes in the large-scale density structure in the model Atlantic. Anomalously dense water between approximately 50°N and 75°N in the North Atlantic, combined with negative density anomalies at lower latitudes, is associated with an unusually intense THC. The salt and heat anomalies which determine the anomalous density structure are strongly influenced by anomalous horizontal transports of heat and fresh water. The horizontal circulations are related geostrophically to anomalies of dynamic height, which are in turn generated by variations in the intensity of the THC, thereby forming a cycle. Shown in Fig. 1.5 are the circulation and dynamic height anomalies at times when the THC is intensifying (Fig. 1.5, top), at its maximum (Fig. 1.5, middle), and weakening (Fig. 1.5, bottom). The anomalous circulations result in a convergence of salt (Fig. 1.5, top) or fresh water (Fig. 1.5, bottom) into the sinking region, thereby amplifying or weakening the intensity of the THC. At the time of maximum THC (Fig. 1.5, middle), there is a zonal gradient of dynamic height across the Atlantic Basin which supports an enhanced northward geostrophic flow in the upper layers.

There are also anomalous surface fluxes of heat and fresh water associated with these variations in the THC, but their relative importance on the vertically-averaged salt budget appears smaller than the horizontal transport terms. As previously discussed (A92/P93), the SST variations associated with these fluctuations bear an encouraging resemblance to observational results.

PLANS FY94

The analysis of low frequency variability in the coupled model of the atmosphere-ocean system will be continued. Decadal variability in the Labrador Sea will be compared to observational analyses.

1.2 CONTINENTAL HYDROLOGY AND CLIMATE

1.2.1 Sensitivity of Global Water Cycle to Water-Holding Capacity of Land

*K.A. Dunne ** *P.C.D. Milly **

** U.S. Geological Survey*

ACTIVITIES FY93

A study of the sensitivity of the global water cycle in a climate model to the water-holding capacity of soil (1129) was extended (tx). The direct surface hydrologic sensitivity was separated from atmospheric feedbacks by running a series of stand-alone simulations of surface water and energy balances. Combined analysis of these

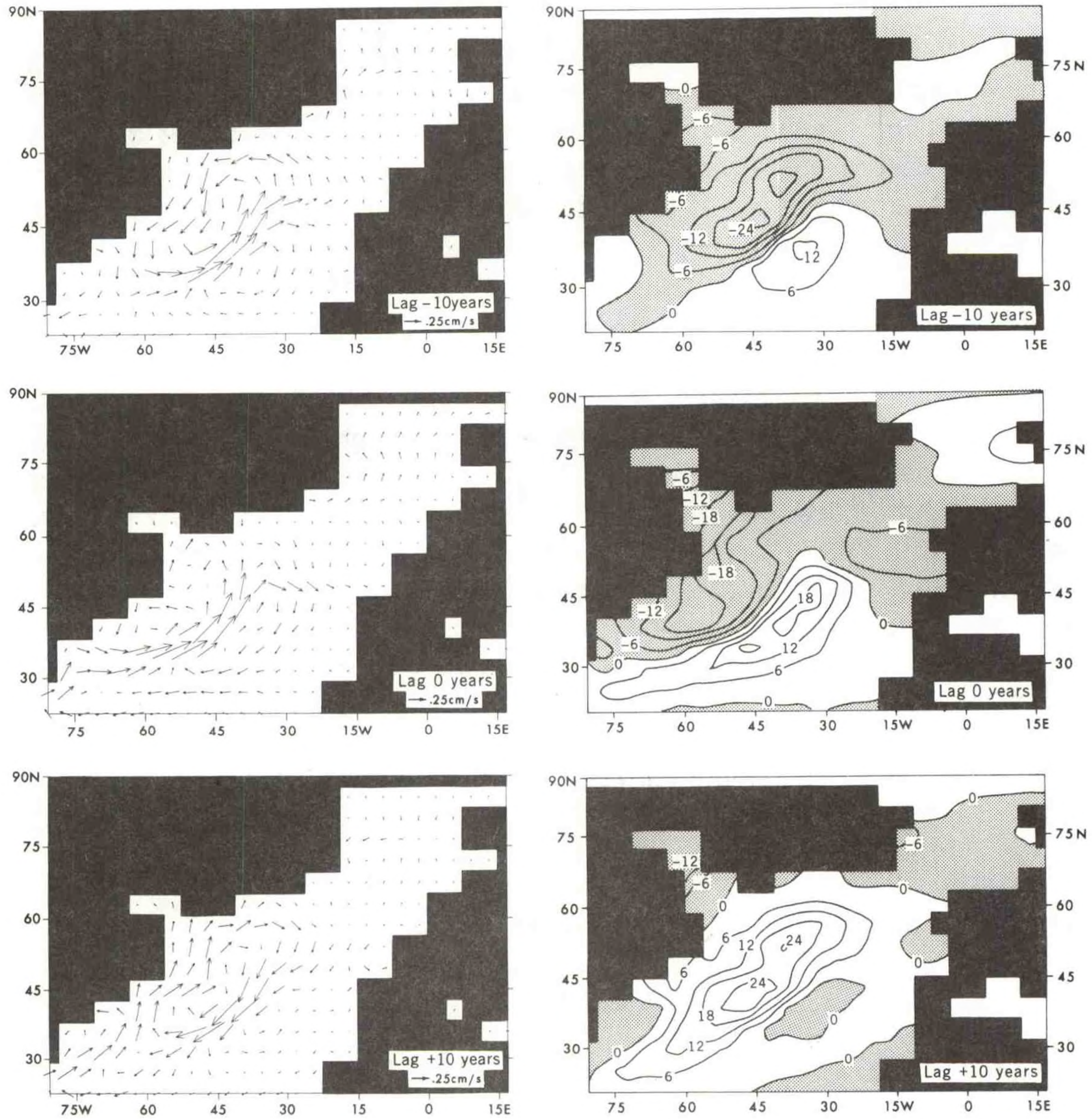


Fig. 1.5 Linear regression coefficients between various quantities and the THC (thermohaline circulation) intensity, denoting changes in circulation and dynamic height related to variations in the THC intensity. The left column denotes regressions for currents at 170 m depth in the ocean versus the intensity of the THC. At each grid point, regression coefficients were computed between the zonal and meridional components of the ocean current versus a time series of the intensity of the THC. These regression coefficients are then plotted at each grid point in vector form, such that the length of the arrow in the zonal (meridional) direction denotes the magnitude of the regression coefficients between the zonal (meridional) component of the current and the THC. In the right column are shown the regressions between anomalies of dynamic height and the THC. Dynamic height was computed from the surface to 915 decibars. Units are 10^2 cm^2s^{-2}. Values less than zero are stippled. Top row: Regressions for lag -10 years (*i.e.*, the time series of dynamic height and currents led the time series of the THC by 10 years in the regression calculations). These may be interpreted as the anomalous conditions 10 years prior to a maximum in the THC (of magnitude 1 Sv). Middle row: Regressions for lag 0 years. These may be interpreted as the anomalous conditions at a maximum in the THC (of magnitude 1 Sv). Bottom row: Regressions for lag 10 years. These may be interpreted as the anomalous conditions 10 years after a maximum in the THC (of magnitude 1 Sv).

and the earlier coupled climate simulations indicated that an increase in water-holding capacity leads, via increased evaporation, to increased precipitation and decreased potential evaporation. The effect of both of these is to increase runoff from the continents. For evaporation, in contrast, these feedbacks are generally in opposition. Furthermore, the direct effects of a change in storage capacity are, in general, significantly larger than the feedbacks.

PLANS FY94

The sensitivity studies recently completed led to the formulation of hypotheses about effects of human water use on climate, effects of greenhouse warming on continental hydrology, and land-surface biophysical feedbacks to greenhouse warming. These hypotheses will be explored in future numerical experiments. Work in the immediate future will focus on the development of a hydrologically realistic control simulation for use in those experiments. Canopy resistance to surface vapor flux will be incorporated into the existing land-surface parameterization, and global data sets on soils and vegetation will be used to estimate the geographic variability of all land-surface parameters.

1.2.2 A Storage Theory of Continental Water Balance

*P.C.D. Milly **

** U.S. Geological Survey*

ACTIVITIES FY93

Parameterizations of land hydrology for GCMs should be based on an understanding of the physical processes that govern the land-surface water balances on seasonal time scales and on regional space scales. In order to improve understanding in this area, a water-balance study was initiated in FY93 using a simple model of soil-water storage (sk). The ability of such a model to describe the accumulation of soil water during rainfall events and the subsequent depletion of soil water by evaporation between storms was investigated. When the alternating supplies (precipitation) and demands (potential evaporation) are viewed as random variables, it follows that soil-water storage, evaporation, and runoff are also random variables. Under a reasonable set of assumptions about the random nature of the supply and demand, it is possible to derive the asymptotic distributions of storage, evaporation, and runoff analytically. A particular result is that the fraction of rainfall converted to runoff is given by $(1-R^{-1})/\{\exp[\alpha(1-R^{-1})]-R^{-1}\}$, in which R is the ratio of mean potential evaporation to mean rainfall and α is the ratio of soil water-holding capacity to mean storm depth. A simple application of the results of this analysis suggests that random, intraseasonal fluctuations of precipitation cannot by themselves explain the observed dependence of the annual water balance on annual totals of precipitation and potential evaporation.

PLANS FY94

The analysis of continental water balances using a simple storage model of soil water will continue. The model will be generalized to include seasonality of climatic forcing and spatial variability of soil available water-holding capacity. The hypotheses underlying this generalized model will be tested by comparing model predictions with observational data from a large part of North America.

1.2.3 Global Distribution of Soil Water-Holding Capacity

*K.A. Dunne *　　　P.C.D. Milly **

** U.S. Geological Survey*

ACTIVITIES FY93

Realistic representation of hydrology on regional scales in climate models requires knowledge of the geographic variability of the soil water-holding capacity. A study is underway to estimate the spatial distribution of this parameter for use in GCM modeling studies of hydrology-climate interactions. For each cell of a 0.5° x 0.5° grid, the capacity is estimated as the integral, over the depth of the plant root zone, of the difference between the volumetric water content of freely-drained soil ("field capacity") and the volumetric water content of soil at the permanent wilting point of the vegetation. Where vegetation is absent, the water-holding capacity is presently estimated as the integral of the field capacity over an arbitrary depth (order of one meter). Field capacity, wilting values, and rooting depths are estimated from available global data sets on soil texture, soil organic content, and vegetation types. The estimated global mean storage capacity is about 11 cm. High values (>15 cm) occur in arid regions and some agricultural regions (central North America, Europe). Significant areas of small values (<5 cm) are found in the tropics and at high latitudes. Uncertainty in plant rooting depths and effective soil depths for storage under bare surfaces lead to great uncertainty (possibly a factor of two) in estimates of soil water-holding capacity.

PLANS FY94

Dynamic estimates of field capacity will be derived using soil physical theory. The importance of upward liquid flow from beneath the root zone will also be estimated. An attempt will be made to develop an objective way to define the water-holding capacity of bare soil. The results of this project will be incorporated into ongoing climate simulations.

1.2.4 Water and Heat Fluxes in Desert Soils

*P.C.D. Milly **

** U.S. Geological Survey*

ACTIVITIES FY93

An understanding of water and heat movement in desert soils is needed for the formulation of models of land-atmosphere interactions and for the interpretation of climatic signals appearing in the soil profiles of water and heat storage. A collaborative study with the University of Texas has been using a detailed numerical model of soil water and heat flow to interpret an extensive set of data collected in the Chihuahuan Desert of western Texas (ub). Remarkable consistency was found between computed and measured water potentials and temperatures. Attenuation and phase shift of the seasonal cycle of water potentials below a shallow subsurface active zone (0-0.3 m depth) were robustly similar to those of temperatures, suggesting that water-potential fluctuations are driven primarily by well-understood temperature changes. Sensitivity analyses indicated that the predominantly upward liquid water fluxes below a depth of 0.2 m were very sensitive to uncertainties in the representation of hydraulic conductivity. The relatively insensitive direction and magnitude of modeled net downward water vapor fluxes were consistent with observed differences in depth of penetration of volatile ^{3}H and nonvolatile ^{36}Cl.

PLANS FY94

The analysis of water flow in desert soil led to the formulation of a hypothesis on the character of vertical water flow in arid environments. The hypothesis is that there exist equal and opposite net downward vapor and net upward liquid fluxes, whose magnitudes decay exponentially with depth. In FY94 an attempt will be made to describe this situation using simple analytic descriptions of the relevant physics.

1.2.5 Project for Intercomparison of Land-Surface Parameterization Schemes

*K.A. Dunne **   *P.C.D. Milly **

** U.S. Geological Survey*

ACTIVITIES FY93

The international Project for Intercomparison of Land-Surface Parameterization Schemes (PILPS) has the objective of identifying the essential differences among the many parameterization schemes used to characterize water and energy exchange at land surfaces in GCMs. GFDL and USGS are participating by assisting in experimental design and analysis and by providing simulation results for one scheme. Initial comparisons have been made on the basis of a first set of simulations, in which all schemes were run with identical forcing. It has been suggested that the differences among the results may be explained mostly by unintentional differences in effective mean values of water-holding capacity, albedo, canopy resistance, and drag coefficient; and that differences in level of complexity of schemes may be relatively unimportant.

PLANS FY94

A second round of simulations is being planned, with experiments designed to identify how much of the scatter in response can be attributed to each of several subparameterizations. These simulations will be carried out and analyzed.

1.2.6 Recycling of Water Vapor

T.L. Delworth

ACTIVITIES FY93

One of the measures of the importance of land-surface processes to climate is the degree to which evaporation from a continental region affects precipitation over that same region. Precipitation recycling is defined as "*the fraction of precipitation falling over a region which is attributable to evaporation from that same region*" (*i.e.*, the moisture is recycled). The larger this fraction, the greater the potential role that land surface processes may play in this region.

The degree of precipitation recycling in the GFDL climate model was investigated by incorporating water vapor tracers as additional prognostic variables within the model. These tracers undergo the same physical and numerical processes that total water vapor undergoes, including condensation and precipitation, with the exception that the flux of a water vapor tracer from the surface into the atmosphere is set equal to the total evaporation rate only over the specified source region for that tracer. Outside the source region, the flux of that tracer from the surface to the atmosphere is set to zero. As an example, one water vapor tracer could have as its source region all continental locations. Using this technique, the total precipitation falling at any grid point in the model can be decomposed into fractions from various source regions.

Shown in Fig. 1.6 are the percentages of the total precipitation attributable to evaporation from all continental regions for JJA (top) and DJF (bottom). Note that in the interior of Asia during JJA greater than 80% of the moisture precipitating was last evaporated from a continental surface, thereby emphasizing the critical role that land surface processes play. In contrast, during DJF this percentage falls sharply in those same locations. The much smaller insolation during Northern Hemisphere winter restricts the amount of moisture evaporated into the atmosphere and thus available for precipitation. In addition, generally colder conditions over land areas (compared to oceanic regions at similar latitudes) result in a greater reduction in evaporation from land regions than from oceanic regions, thereby decreasing the fraction of precipitation attributable to continental evaporation.

PLANS FY94

The water vapor tracer capability will be used in studies of hydrologic variability, with particular regard to assessing the importance of interactions between the land surface and the atmosphere.

1.2.7 CO_2-Induced Mid-Continental Summer Dryness

S. Manabe *R.T. Wetherald*

ACTIVITIES FY93

In order to identify and elucidate the mechanisms responsible for CO_2-induced summer dryness, several integrations were performed using the R15 version of a GCM with idealized geography. The separate experiments conducted were: interactive soil moisture and snow cover, prescribed snow cover, prescribed soil moisture, and both prescribed snow cover and soil moisture together. The response to a quadrupling of CO_2 by each version of the model was then determined and evaluated.

In the subtropics to middle latitudes, carbon dioxide and atmospheric water vapor increase, thereby increasing the downward flux of terrestrial radiation and making more energy available for both sensible and latent heating at the ground

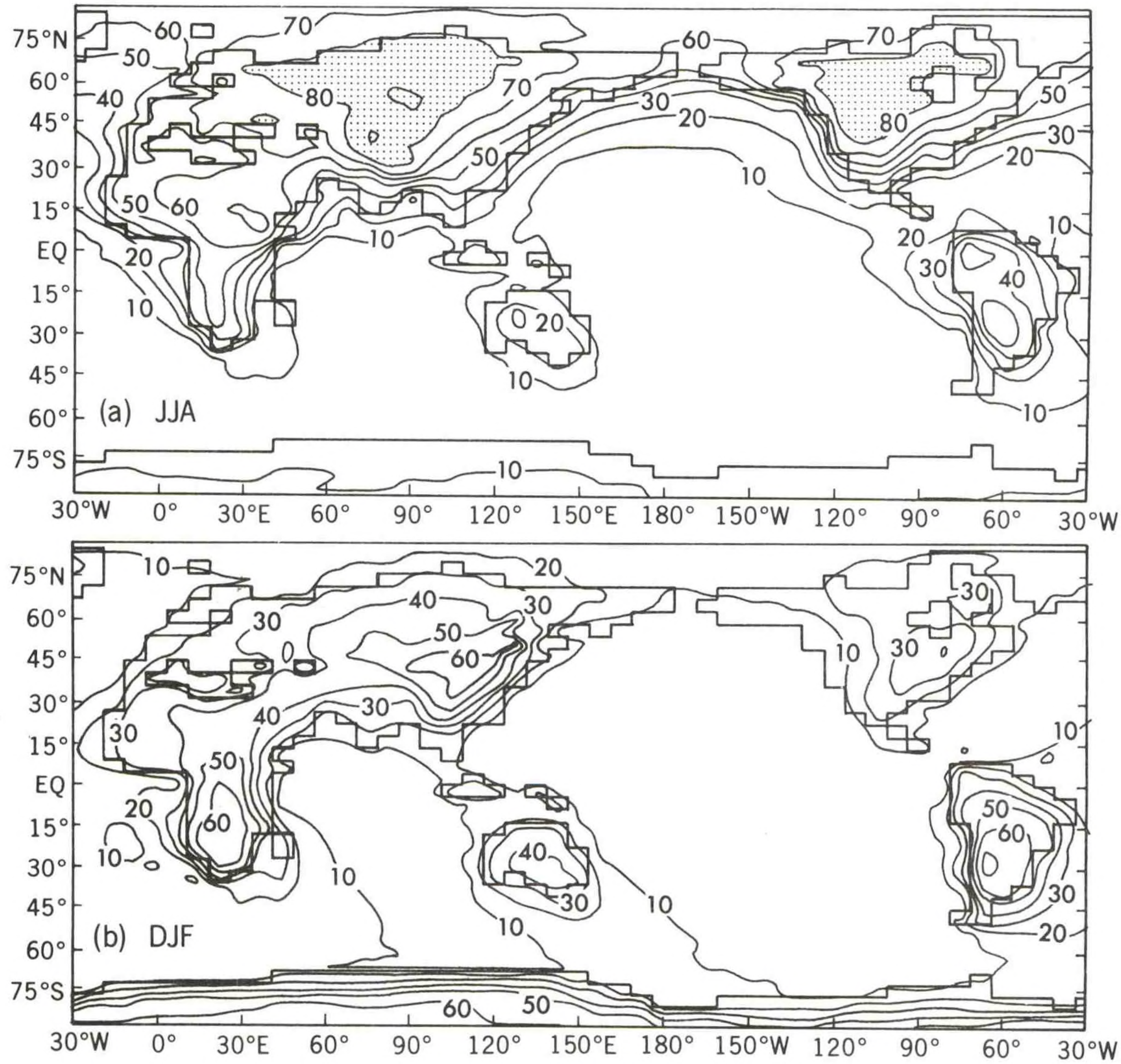


Fig. 1.6 Percentage of the precipitation at each grid point which is attributable to evaporation from all continental regions. Contour interval is 10%. A value of 20% means that 20% of the moisture falling as precipitation at that grid point was last evaporated from a land point, while 80% of the moisture falling as precipitation at that point was last evaporated from an ocean point. Values greater than 80% are stippled. (a) JJA, (b) DJF.

surface. Since the saturation vapor pressure increases almost exponentially with temperature, a larger fraction of this increased radiative energy is realized as latent heat (and therefore evaporation) rather than sensible heat. Because of this, evaporation increases more than precipitation over the land surface in the equatorward half of the middle latitude rainbelt, where evaporation exceeds precipitation during late spring and early summer, and initiates the drying out of the soil surface there. As the summer season progresses and soil moisture is reduced, evaporation decreases in the equatorward half of the rainbelt when the soil moisture becomes too dry to maintain increased amounts of evaporation. This, in turn, causes a corresponding decrease of precipitation during summer and results in a poleward shift of the middle latitude rainbelt and an earlier rainy season during spring, creating a longer drying period throughout the summer. These factors all combine to further enhance the reduction of soil moisture during the entire summer season over continental regions in middle latitudes.

The reverse is true during the winter season in middle latitudes. Although there is also additional radiative energy available at the surface during this season (due to the increase in CO_2), a greater fraction of this energy is realized as sensible heat rather than latent heat due to the colder surface temperature. This, in turn, causes precipitation to increase more than evaporation, thereby contributing to an increase of soil moisture. It should be noted, however, that since the soil moisture is nearly saturated during the winter season, most of this additional moisture occurs as runoff.

In high latitudes, there is also a tendency for increased summer dryness, although it is not as large as it is in middle latitudes. An analysis of this latitude region indicates that this feature is initiated by both an earlier snow melt season and increased evaporation over precipitation, which combine to lengthen the drying period there during summer. These two regions of summer dryness are illustrated by Fig. 1.7, which shows the changes of soil moisture in response to the quadrupling of CO_2 for both the fully interactive soil moisture and snow cover experiment and the prescribed snow cover experiment, respectively.

To summarize, it was found in this study that mid-latitude summer dryness was not caused by a poleward shift of the middle latitude jet stream or a reduction of eddy kinetic energy, but by an excess of evaporation over precipitation followed by a feedback between temperature, soil moisture, and precipitation as outlined above. Also, snow melt was not a significant factor in causing summer dryness except at high latitudes.

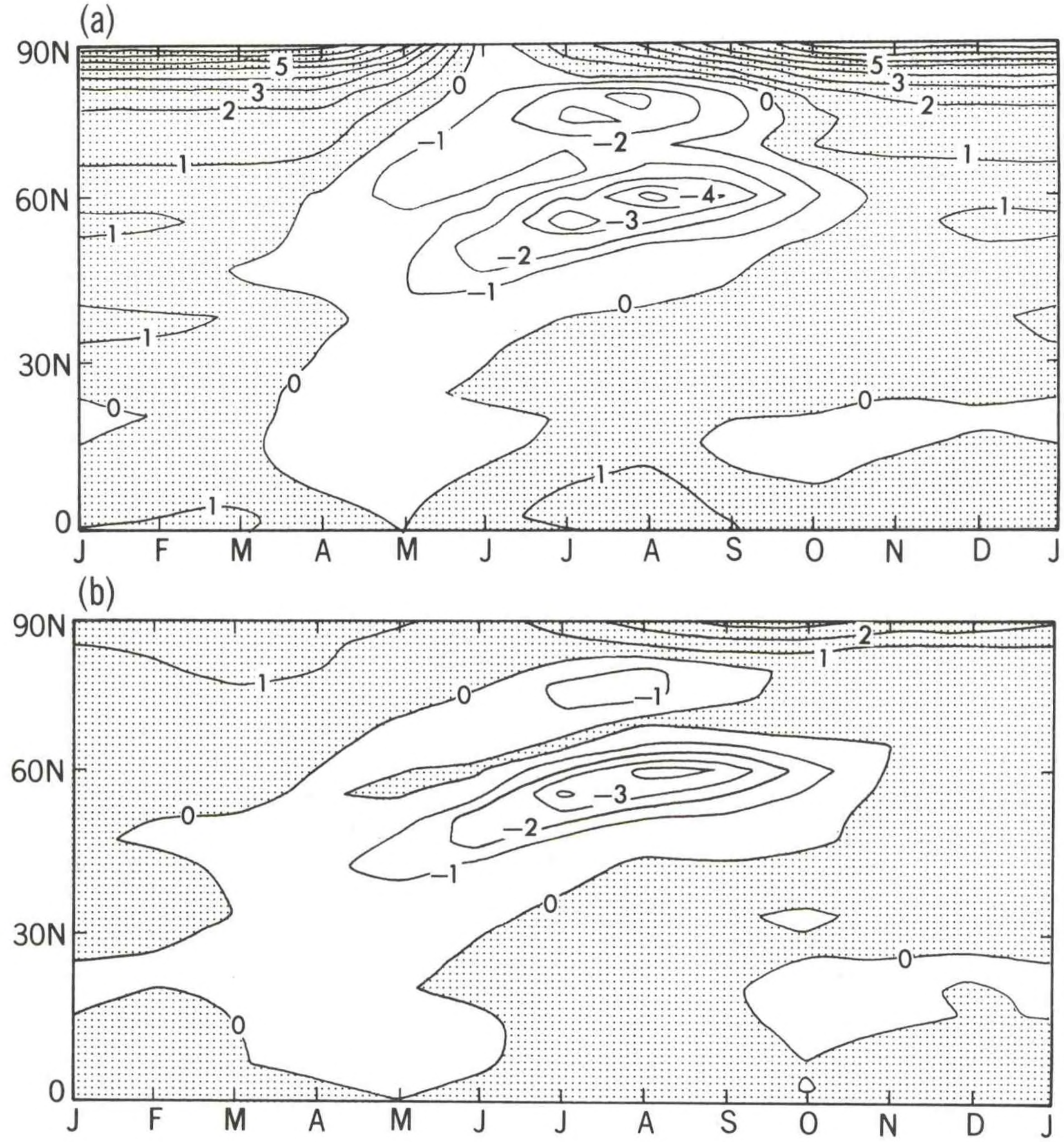


Fig. 1.7 Latitude-time distributions of zonal mean soil moisture difference (*i.e.*, response to quadrupling CO_2) obtained from: (a) the fully interactive soil moisture experiment, and (b) the prescribed snow cover experiment. Clear portions denote regions of negative soil moisture differences and the units are in cm.

PLANS FY94

Plans call for a completion of the analysis of the various mechanisms responsible for the CO_2-induced hydrologic changes and the preparation of a manuscript summarizing the results.

1.3 CONVECTION-RADIATION - CLIMATE INTERACTIONS

1.3.1 Explicit Radiative Moist-Convective Equilibrium

I.M. Held *V. Ramaswamy*
R.S. Hemler *D.-Z. Sun*

ACTIVITIES FY93

Analysis continues of the statistical equilibrium achieved through the balance between radiative forcing and moist convection in an explicitly resolved two-dimensional nonhydrostatic model. The model is nonrotating, periodic in the horizontal dimension, and is forced by a prescribed uniform surface temperature. The clouds produced by the model are fully interactive with the radiative transfer. A paper has been prepared for publication (sv) describing (1) the QBO-like oscillation generated in the model stratosphere, (2) the tendency, when the zonal mean flow is constrained to vanish, for the convection to organize itself into a stationary "wet-spot", (3) the horizontally homogeneous convection resulting from the imposition of a small vertical shear in the zonal mean winds, and (4) the sensitivity of the resulting model to the surface temperature. The model with fixed vertical shear produces a planetary albedo that decreases with increasing surface temperature (over the range 25°C to 30°C examined to date), implying a strong positive cloud feedback (*i.e.*, increased solar absorption).

The FORTRAN code for this nonhydrostatic cloud model is in the process of being totally revised, to simultaneously make it more user friendly and more readily transferrable to parallel computing architectures. The revised SKYHI code is being used as a guide for this transformation. The radiative model has also been considerably streamlined.

The model's oscillatory stratospheric winds have been analyzed to show that QBO-like dynamics (the interplay between the momentum fluxes in vertically propagating gravity waves and the mean zonal flow) are active. However, the model's oscillation extends into the troposphere, where convective momentum fluxes also seem to be playing a role.

A hydrostatic radiative-convective two-dimensional model has also been constructed, in which the effects of differing parameterizations of moist convection on this equilibrium can be studied and compared with the resolved convection model. Preliminary calculations with a moist convective adjustment are underway.

PLANS FY94

Using the redesigned code, a series of additional calculations will be conducted to study the dependence of results obtained to date on the size of the domain, resolution, and microphysical assumptions. A version of the model with a much higher upper boundary will be studied, in order to better examine the QBO-like oscillation. A preliminary three-dimensional version of the radiative-convective calculation will be attempted on a small domain. The analysis of the hydrostatic model with different convective parameterizations will continue.

1.3.2 Cumulus Parameterization

L.J. Donner

ACTIVITIES FY93

Interactions between cumulus convection and atmospheric radiation represent a difficult and important problem in the study of climate and climate change. Cumulus convection interacts with atmospheric radiation through several processes; among the most significant are the controls on the vertical distribution of water vapor exerted by cumulus convection and feedbacks involving clouds in convective systems with both short-wave and long-wave radiation. To address these problems in the context of general circulation models (GCMs), a parameterization for cumulus convection, which provides a physical basis for treating radiative interactions, has been developed (1133). The vertical momentum profiles for an ensemble of cumulus elements are parameterized, in addition to the ensemble's mass fluxes. The microphysical properties of the cumulus elements and the associated stratiform anvil depend strongly on the vertical momentum profiles. From the microphysical properties, radiative transfer associated with the convective system can be evaluated. Comparison of (1) the thermodynamic and moisture forcing predicted by the parameterization with forcing diagnosed in field programs, and (2) the basic predicted and observed microphysical and radiative properties, demonstrated that the parameterization behaves reasonably for tropical convection when the ensemble's vertical-velocity profiles are realistic. The stratiform anvils were found to modify strongly the thermodynamic and moisture forcing produced by the cumulus-scale updrafts and downdrafts and to dominate the radiative properties of the convective system.

The water budget treated by the cumulus parameterization (Fig. 1.8) permits the calculation of the ice contents of the stratiform anvils associated with convective systems. A comparison of these predicted ice contents with very limited observational data available shows good agreement and indicates that the parameterization can be used to address issues regarding the interaction between convection and radiation in GCMs.

PLANS FY94

Issues related to implementing the cumulus parameterization in GCMs will be studied, including optimal methods for closing the parameterization and computational simplifications. Initial studies of the sensitivity of GCMs to the parameterization are planned.

1.3.3 Cumulus Ensemble Models

L. Donner *C. Seman*
R. Hemler

ACTIVITIES FY93

The processes treated by the cumulus parameterization (1.3.2) are under study using the Lipps-Hemler (885) cumulus ensemble model (CEM). Many of the dynamic, thermodynamic, microphysical, and radiative properties central to the parameterization are difficult to observe or have been observed only in limited synoptic situations. The CEM, in three-dimensional, semi-prognostic mode, predicts these properties without requiring the hypotheses and assumptions in the cumulus parameterization and can be used to assess the validity of the parameterization hypotheses. Present studies focus on the region in the east Atlantic studied during the GATE [GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment] and are examining the agreement between CEM integrations and field observations. Analysis is currently focused on the distribution of cumulus vertical velocities and the microphysical properties of the cumulus cells and stratiform anvils simulated by the CEM, since the treatments of these processes represent unique aspects of the cumulus parameterization described above and are critical for studying interactions between cumulus convection and radiation.

PLANS FY94

The emphasis of the CEM studies will shift to focus on testing the cumulus parameterization (1.3.1) in various synoptic contexts. Particular attention will be directed toward interactions involving radiative transfer.

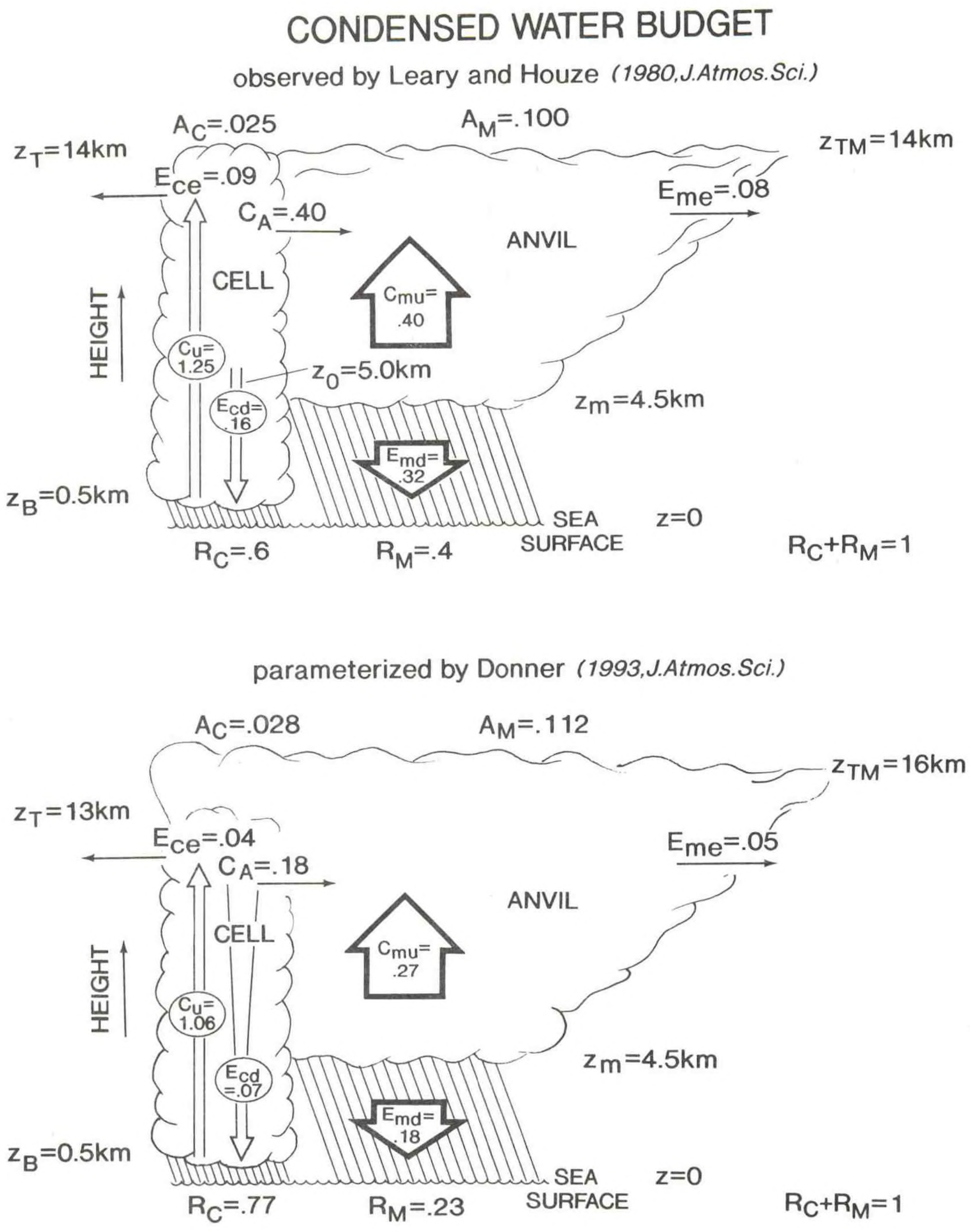


Fig. 1.8 Condensed water budget for a convective system, parameterized as discussed in 1.3.2 and compared with a budget diagnosed from observations for a similar system by Leary and Houze (*J. Atmos. Sci.*, 37, 784-796, 1980). The height of the cumulus cloud base is z_B; the anvil base is z_m, the top of the deepest cumulus element is z_T, and the anvil top is z_{TM}. The fractional area of the cumulus updrafts is A_C, and the fractional area of the mesoscale anvil is A_M. The sum of rain from the cumulus updrafts R_C and the mesoscale anvil R_M is normalized to 1. The other terms in the water budget, whose typical units are mm/day, are: E_{ce}, evaporation from the cumulus updrafts; C_A, transfer of condensed water from cumulus cells to mesoscale anvil; C_u, condensation in cumulus cells; E_{cd}, evaporation in downdrafts associated with cumulus cells; C_{mu}, condensation in mesoscale updraft; E_{md}, evaporation in mesoscale downdraft; and E_{me}, evaporation from mesoscale updraft.

1.3.4 Atmospheric Ice Clouds

L. Donner *J. Warren*
B. Soden

ACTIVITIES FY93

To develop further understanding of the role in climate of atmospheric ice clouds, a parameterization for their ice content (Heymsfield and Donner, 1990)[6] has been incorporated into a GCM. This project represents an ongoing collaboration with the National Center for Atmospheric Research, and the parameterization has been incorporated experimentally in Community Climate Model-1. The parameterizations for both (1) ice clouds, in which deposition from vapor to ice and gravitational settling are in equilibrium, and (2) subsaturated layers below ice clouds, in which settling ice sublimates, have been incorporated. Further, the parameterization has been linked to the hydrological cycle in the GCM. Unlike many cloud parameterizations, very little of the ice reaches the surface as precipitation; most of the ice in a given cloud eventually sublimates, and the ice clouds can persist across model time steps.

The parameterization has also been linked to both solar and longwave radiative transfer in the GCM. Variations in ice-particle sizes are parameterized based on field observations. Preliminary results indicate that large-scale variations in both ice content and particle sizes are important for regional variations in cloud albedo and emissivity.

The parameterization has been used to produce global ice distributions using European Centre for Medium-Range Weather Forecasts analyses. The resulting radiative properties of the ice clouds have been compared with several types of satellite data for the same time periods. These results of the parameterization are in reasonable agreement with observations for most regions.

The roles of the variables which control the parameterization and account for its behavior as measured against aircraft observations of ice in field programs have been studied. Temperature and vertical velocity appear to be primary controls. There are indications that the role played by these variables differs as horizontal scale varies from those typically studied in field programs to those resolved in GCMs and reported in satellite cloud climatologies.

6. Heymsfield, A.J., and L.J. Donner, 1990: A scheme for parameterizing ice-cloud water content in general circulation models. J. Atmos. Sci., 47, 1865-1877.

PLANS FY94

The implications of the parameterized ice distributions for radiative transfer and climate-cloud feedbacks will be studied. The parameterized ice contents will be used to calculate albedos and emissivities for radiative transfer in the GCM. The sensitivity of simulated climate to ice clouds in GCM integrations will be examined.

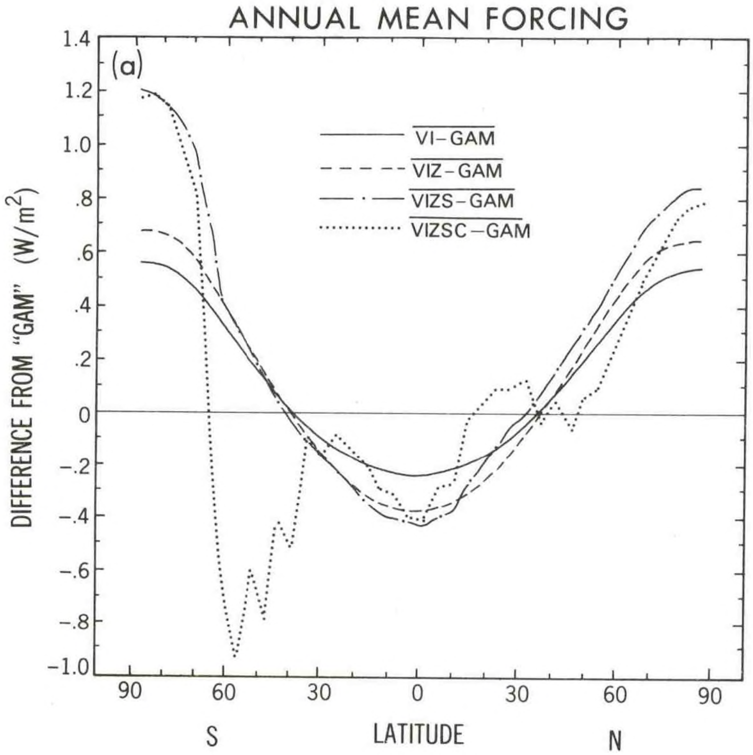
The comparison of the parameterization with satellite observations, driven by analyzed data sets, will be assessed in light of revised interpretations of some of the satellite observations, which have resulted from recently completed field studies of satellite cloud-property retrievals. The dependence of the behavior of the parameterization on horizontal scale will continue to be studied, including the development of simple conceptual models to explain the dependence.

1.3.5 Global Forcing Due to Cloud Radiative Properties

C.-T. Chen *V. Ramaswamy*

ACTIVITIES FY93

The global radiative forcing due to changes in the liquid water content of low clouds was investigated using the radiative transfer scheme of the R15 GCM. One important modification was made to the scheme regarding cloud radiative properties. These were computed using the delta-Eddington approximation and cloud single-scattering parameters that depend explicitly on liquid water path (LWP). The motivation for this study is the Somerville-Remer hypothesis in which cloud LWPs increase in a warmer climate, leading to an increase in the albedo (negative forcing). High, middle and low cloud amounts are prescribed and held fixed, as are water vapor and temperature, for the purpose of determining the radiative forcing. The "control" value of the LWPs is different for the three cloud levels. Only spatially and temporally uniform changes in the low cloud LWP were considered in this study. Two types of computations were performed - in one, the forcing was computed using globally-and-annually-averaged atmospheric and surface conditions (termed "GAM"), while in the second, the actual monthly and latitudinally varying forcings were computed using appropriate atmosphere and surface conditions. For the second category of experiments, a systematic analysis was conducted to examine the effects due to the introduction of the space-time variations in insolation ("VI"); then, in addition, the effects of the variations in the solar zenith angle ("VIZ") upon cloud radiative properties; and finally, in addition, the variations in the surface albedo ("VIZS"). Another experiment ("VIZSC") was conducted, similar to VIZS, but in which the low cloud amount was substantially greater in the midlatitudes of the Southern Hemisphere. Fig. 1.9(a) illustrates the zonal, annual mean difference between the VI, VIZ, VIZS, VIZSC experiments and the GAM value (-1 W/m^2) for a 10% increase in



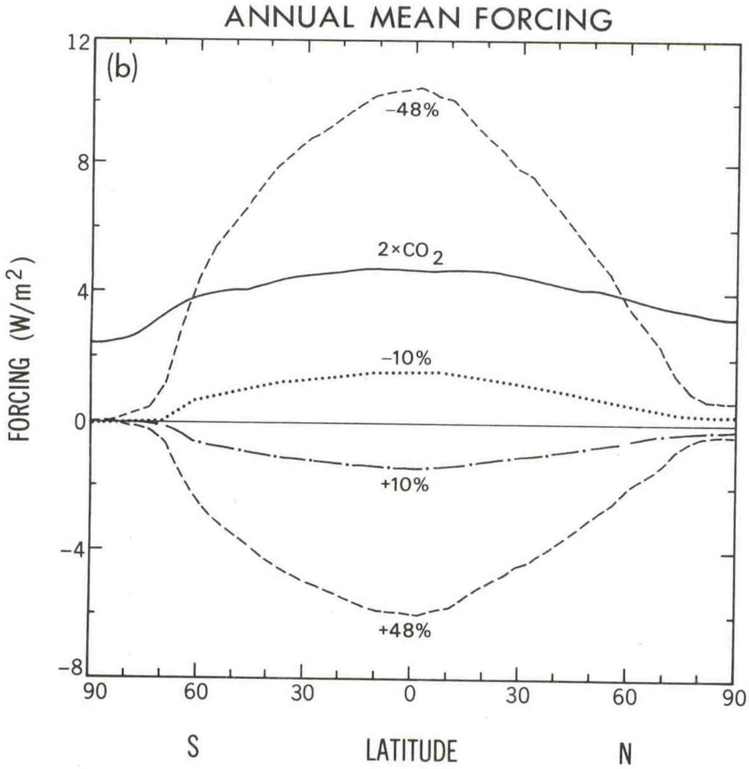


Fig. 1.9 (a) Departure of the zonal radiative forcing induced by a 10% global increase in the liquid water path of low clouds for various experiments, when compared with a reference experiment (GAM). The GAM result (-1 W/m^2) is obtained using global, annual mean conditions. The other experiments consider explicitly the latitude-month variations in the relevant parameters (see text). (b) Zonal forcing due to doubling of CO_2, and that due to increase/decrease of low cloud liquid water path by 10 and 48%, respectively.

the low cloud LWP. The forcing is larger (*i.e.*, more negative) than GAM at the lower latitudes for all experiments and at the southern hemisphere midlatitudes for the VIZCS experiment. At latitudes poleward of 30°, the annually-averaged result becomes progressively less than GAM in magnitude (except for the VIZCS experiment).The results demonstrate the nonuniformity of the forcing over the globe, even when the "control" LWP and the LWP changes are the same everywhere.

Figure 1.9(b) illustrates the spatial dependence of the annual mean forcing due to a doubling of CO_2 ($2xCO_2$) and compares it with that due to a +10%, -10%, +48% and a -48% change, respectively, in the low cloud LWP. The 48% increase in LWP yields a global radiative forcing that is identical, but opposite to that due to $2xCO_2$. The meridional forcing pattern due to LWP changes differs from that due to $2xCO_2$. The asymmetry in the forcing between the increase and decrease in LWP of identical magnitudes is due to the nonlinear relationship of the albedo to the water path.

PLANS FY94

The cloud radiative formulation in the GCM will be improved. GCM experiments will be conducted to examine the sensitivity of the simulated climate to the forcing due to changes in cloud physical properties.

1.4 PLANETARY WAVE DYNAMICS

1.4.1 Quasi-Geostrophic Dynamics

S. Garner	*V. Larichev*
F. Hansen	*V. Pavan*
I.M. Held	*J. Zhang*

ACTIVITIES FY93

1.4.1.1 Moist Baroclinic Instability in a Two-Layer Model

Work has continued on the analysis of the effects of latent heat release on baroclinic eddy fluxes, using a two-layer quasi-geostrophic model. Since the effects of latent heating will increase in a warmer climate, the analysis of this idealized model may suggest new ways of analyzing GCM simulations of the climatic response to increasing greenhouse gas concentrations.

The behavior of this model is strongly controlled by two parameters: the reduction in static stability in regions of saturated ascent; and the degree of enhancement of the poleward energy flux due to moisture transport. The former effect is closely tied to the advection of moisture by the ageostrophic component of the wind, and tends to increase eddy amplitudes; the latter is tied to advection by the geostrophic component of the winds, and tends to reduce eddy amplitudes. In the (unrealistic) limit in which the evaporation rate is so large that the atmosphere can be thought of as being saturated everywhere, the total effect of latent heat release can be explained by these two effects, and an equivalent dry model can be constructed. With a realistic evaporation rate producing saturation in only a small fractional area of the domain, the net effect of latent heating is not cleanly separable into these two parameters, but qualitatively, the importance of the moisture transport parameter is enhanced at the expense of the reduction in stability.

1.4.1.2 Two-Dimensional Turbulence

The radius of deformation plays an important role in atmospheric and oceanic dynamics, partly because it is the scale at which baroclinic instability occurs. It is often assumed, as a consequence, that eddy fluxes of heat, momentum, potential vorticity, etc., will be dominated by eddy fluxes on this scale. But quasi-geostrophic flows also "reverse" cascade energy to larger scales until this cascade is halted by dissipation, the beta-effect, or some other process. Should one expect the eddy energies and the eddy fluxes to be dominated by eddies at the scale at which the cascade has been halted, rather than the radius of deformation? Simulations in baroclinically unstable flows with sufficient scale separation between the radius of deformation and the scale to which the energy reverse cascade extends are needed to address this issue. A first study has been completed using a two-layer quasi-geostrophic, doubly-periodic model. The result is that it is clearly the scale at which the reverse cascade halts, and not the radius of deformation, that dominates the fluxes.

This result has implications for basic understanding of the atmosphere (eddies with the scale of the radius of deformation are important only because the reverse energy cascade does not extend over a significant range of scales). However, it has greater practical implications for ocean models; it implies that closure schemes for mesoscale eddies must implicitly or explicitly account for the reverse energy cascade, and cannot rely on the radius of deformation as the dominant scale, or "mixing length".

1.4.1.3 Dry Quasi-Geostrophic Models of Baroclinically Unstable Jets

Work is continuing on several fundamental problems related to finite-amplitude baroclinic instability. The dependence of the eddy heat and potential vorticity fluxes on horizontal temperature gradients is being studied as a function of the number of levels in the model, in order to relate the numerous studies with two-layer models (upon which many of the current ideas about eddy flux closure theory are based) to quasi-geostrophic models of higher vertical resolution. These models are also being used to study the relative importance of upper and lower tropospheric temperature gradients for the eddy amplitudes and fluxes. Particular attention has been placed on a transition that occurs in baroclinically unstable jets as the strength of the jet is increased. The state prior to the transition is characterized by a flow in which the mixing by eddies is confined to the two sides of the jet, with relatively little mixing across a sharp jump in potential vorticity that forms at the jet. Subsequent to the transition there is flow with substantial mixing across the jet, accompanied by cutoff high and low formation. The former, more weakly unstable case bears some resemblance to the storm track in the Southern Hemisphere, particularly during summer, while the latter is more analogous to that in the Northern Hemisphere winter.

1.4.1.4 Surface Geostrophic Dynamics

In collaboration with R. Pierrehumbert (U. of Chicago), studies have continued on "surface geostrophic" dynamics, which describes the evolution of a quasi-geostrophic flow in a semi-infinite atmosphere with uniform interior potential vorticity, which is, therefore, induced entirely by the temperature distribution at the surface. Work has been completed that describes turbulence simulations with these equations, and supports the claim that turbulence of this type, although formally still two-dimensional, is very distinct from that in classical two-dimensional (2D) flows, being much more prone to "secondary instabilities" producing "little whorls" within "big whorls" (sz). As examples of this unfamiliar type of dynamics, a series of idealized initial value problems are being examined: the evolution of an elliptical warm spot, the start-up vortex resulting from the development of flow over a circular bump, the finite-amplitude instability of a temperature filament, and the development of the Eady edge-wave critical layer. In each case, remarkably intricate small-scale structures of a fractal character develop, as illustrated in Fig. 1.10.

PLANS FY94

Various aspects of finite-amplitude baroclinic instability, storm track structure, and geostrophic turbulence will be studied using a hierarchy of idealized models.

1.4.2 NOAA/University Joint Study of the Maintenance of Regional Climates and Low-Frequency Variability in GCMs

I.M. Held	*M.J. Nath*
N.-C. Lau	*P. Phillipps*

ACTIVITIES FY93

The collaboration between scientists at GFDL and NOAA/CMDL with a consortium of researchers at several universities (Washington, Illinois, MIT, Chicago, and Columbia) has continued to be active in designing and analyzing GCM experiments. A variety of studies of the low-frequency variability, Lagrangian transport

Fig. 1.10 An example of surface geostrophic dynamics. The flow is quasi-geostrophic in a semi-infinite domain over a flat surface, with uniform potential vorticity in the interior. The initial surface temperature distribution (upper panel) is $\exp(-x^2 - 4y^2)$, which is balanced by a surface cyclone. The remaining panels show how surface temperatures evolves in time.

properties, and regional climates of the climate group's GCM are underway. A new 30-year integration with a 14-level R30 model has been added to the list of integrations made available to outside researchers on Exabyte cartridges.

The response to SST anomalies in an R15 model has been re-examined, but using a flat all-ocean boundary with idealized SST distribution, in an attempt at generating a cleaner and more understandable response. The results are cleaner and are similar to those obtained earlier (985) by perturbing a zonally symmetric climate. The response in this case is qualitatively similar to that expected from the linear response to shallow extratropical heating, with a low in the vicinity and downstream of a warm SST anomaly. The response that has been obtained in some other models (a high in the vicinity of the warm anomaly, presumably due to a redistribution of storm track vorticity fluxes) was not observed. Neither was there a strong asymmetry in the response to warm and cold anomalies, as claimed in other studies.

A new set of integrations with idealized boundary conditions have also been initiated, using the 14-level R30 model, to study nonlinearity in the response to orography and the interaction between latent heating, storm tracks, and orography. The elements are an idealized midlatitude continent (similar to Eurasia), an idealized orographic feature (roughly the size of Tibet), and the prescribed temperature distribution over the ocean. The goal is to increase understanding of the interaction between the SST gradient across the Pacific, extratropical heating asymmetries, and the Tibetan plateau in maintaining the subtropical jet off the Asian coast. Experiments with and without the orographic feature, and with and without SST gradients in the tropics are in preparation. A control experiment with all of these features present has been completed.

PLANS FY94

Work will continue on both idealized and realistic GCMs, in collaboration with several university scientists.

1.4.3 Tropical Oscillations

D. Golder *Y. Hayashi*

ACTIVITIES FY93

Interactive numerical and theoretical studies are being conducted to examine tropical oscillations including intraseasonal oscillations, Kelvin waves, and mixed Rossby-gravity waves. To examine the generation of tropical oscillations, a series of controlled experiments have been carried out with a nine-level spectral GCM and the 40-level SKYHI model, both having convective adjustment. Several effects being examined include condensational heating, the feedback between moisture and wind convergence, and the feedback between the surface fluxes of latent and sensible heat and the low-level winds. To theoretically study the generation of these oscillations, the parameterization of convective adjustment was analytically reformulated. The analytical scheme allows an explicit determination of the moistening and heating due to convective adjustment, after it is switched on, as a function of the other terms in the temperature and moisture equations, such as moisture convergence, adiabatic cooling, and the surface fluxes of latent and sensible heat. The analytical scheme is useful not only for theoretical studies, but also for interpreting the results of numerical experiments with the original scheme of convective adjustment.

According to preliminary numerical results, when condensational heating was eliminated in one of the experiments, tropical oscillations remained with their amplitude greatly reduced. These oscillations disappeared when the feedback between the surface flux of sensible heat and the low-level winds was further eliminated from the dry model. This result suggests that, even in the absence of condensational heating, tropical oscillations can be generated in part by the heating due to dry convective adjustment, which is induced by the sensible-heat flux interacting with surface-wind fluctuations. This interpretation was found to be consistent with the "sensible heat-wind feedback instability" predicted in the analytical scheme of convective adjustment. With condensation, the analytical scheme also allows a possible "switch-on" instability due to moist convective adjustment, which differs from wave-CISK and evaporation-wind feedback instabilities. This possibility is presently being examined both numerically and theoretically.

PLANS FY94

Interactive numerical and theoretical studies of tropical oscillations with the use of the idealized GCM and the analytical scheme of convective adjustment will be continued.

1.5 PLANETARY ATMOSPHERES

G.P. Williams

ACTIVITIES FY93

Earth's atmospheric circulation, although its behavior is well simulated and its components are well defined, still lacks a comprehensive global theory. Long standing questions, such as those concerning the basic state upon which eddies develop and the scale and number of the jets, remain unanswered.

Fortunately atmospheres exist on other planets that allow study of such circulation problems by generalizing them. By altering the scale, strength and mix of the various components - the jets, cells and eddies - insight is gained into how they arise and interact. Given their widely diverse configurations, the planets can be used to explore and test circulation theory in parametric regions unreached by Earth. Thus Jupiter tests circulation theory at high rotation rates, Mars at high obliquity, Venus at low rotation rates, while Titan exemplifies axisymmetric states at low rotation rates and high obliquity.

To improve the definition and understanding of the global circulations of the planets, a hierarchy of numerical models is being used to simulate various planetary-scale processes. Of immediate concern - given the imminent monitoring by the Galileo spacecraft - are the multiple jets and vortices of the Jovian planets, as well as the super-rotation of Venus and the easterly jet of Mars. These are the primary phenomena requiring an explanation in planetary fluid dynamics and involve fields ranging from turbulence to coherence to wave propagation. By defining the range and parametric variability of planetary circulations, the terrestrial problems are seen in a broader perspective. Thus the planets still represent the ultimate - but barely perceived - meteorological frontier.

1.5.1 Coherent Structures

Long-lived vortices occur in Earth's oceans, particularly in the Gulf Stream, and, for longer periods and perhaps more simply, in between jets in the Jovian atmospheres. These vortex studies are attempting to solve two problems: 1) to define what dynamical processes are involved in vortex production and maintenance, and 2) to discover what atmospheric environments favor such highly predictable phenomena.

The conditions under which planetary vortices form and persist have been found from solutions with a 3-D process model. These solutions also suggest what vertical forms the temperature and wind fields might take on Jupiter. Such forms have also been used in a preliminary study with a more general GCM to examine the vortex genesis problem.

1.5.2 Global Circulations

The global circulations of deep atmospheres are being studied using GCMs to try to simulate the Jovian circulations. The conditions under which multiple midlatitude jets and a super-rotating equatorial jet occur have been found. The GCM used was set up with a variety of high resolutions to resolve the small eddies of large rapidly rotating planets and with a variety of heating and vertical structures. Attempts have also been made to reconcile these conditions with those under which vortices persist. Studies have been complicated by a numerical instability that is peculiar to the spectral model in the Jovian parameter range. This instability has been isolated and ways of avoiding it have been developed.

1.5.3 Model Development

The initial phase of vortex and circulation study has yielded some idea of the character of deep atmospheric circulations. For the final calculations, the process model and the analysis/graphics programs have been completely rewritten. The process model was reprogrammed to simplify I/O procedures to include a new formulation of the nonlinear terms that eliminates ambiguities in the vertical velocity. This should lead to the faster computation of more predictable phenomena.

The graphics programs were reprogrammed using the high-level Matlab language to produce both simpler analysis and animation packages. These Matlab routines are run on the workstation in parallel with the model running on the Cray computer. They produce publication quality figures. Explorer scripts for 3-D graphics have also been developed.

PLANS FY94

A final round of calculations will be made with the process model to examine the influence of environment on the stability and genesis of 3-D planetary vortices. New methods for analyzing the dynamics will be implemented.

The high resolution GCM will be reprogrammed and a final set of circulation states generated to define the possible forms of deep atmospheric motions.

1.6 MODEL DEVELOPMENT

1.6.1 Benchmark Calculations for the Dry Dynamical Cores of GCMs

K. Hamilton *B. Wyman*
I.M. Held

ACTIVITIES FY93

In collaboration with M.J. Suarez (NASA/Goddard), a series of benchmark calculations for the dry dynamical cores of atmospheric GCMs has been designed. The first calculation in this series has been used for a detailed comparison of a spectral, semi-implicit model and an explicit C-grid finite-difference model in use at Goddard (which uses fourth-order accurate differencing for the terms responsible for the advection of vorticity). The model atmosphere has a flat lower boundary and is forced by linear damping back to a prescribed radiative equilibrium temperature distribution, while linear damping of the flow near the surface provides the dissipation. Both models have been integrated to statistical equilibrium at a variety of resolutions (from T21 to T63 in the spectral model, and from 6 x 7.5 to 2 x 2.5° (latitude x longitude) in the grid model). "Comparable" resolutions of the two models are defined as those which produce the same level of eddy kinetic energy, since this quantity is sensitive to resolution. The differences between comparable grid and spectral models are found to be subtle, and much smaller than the changes that occur as the resolution is changed (see Fig. 1.11). Comparable grid and spectral models also require similar amounts of CPU time.

Preliminary comparisons have also been made with the N30 SKYHI model and the E-grid model developed by the Experimental Prediction Group. The differences with the spectral solutions are somewhat larger in these cases.

PLANS FY94

The sensitivity to vertical resolution and sub-grid scale mixing schemes will be investigated, and calculations will begin on the next in this series of planned benchmarks, in which an idealized mountain is placed in midlatitudes.

1.6.2 Coupled Ocean-Atmosphere Model

K. Dixon *M. Spelman*
S. Manabe *R.J. Stouffer*

ACTIVITIES FY93

The project to construct an ocean-atmosphere model having higher computational resolution was continued in FY93. The model will be used to study the transient response of climate to gradually increasing concentration of atmospheric CO_2. This project is an important component of the GFDL participation in the next IPCC (Intergovernmental Panel on Climate Change) study.

The high resolution atmospheric model (R30, 14 levels) was constructed and a time integration of the model for 20 years was completed, to generate surface boundary data for the ocean component of the coupled model. A major effort was made to improve the simulation of the atmospheric model. The vertical resolution was increased from 9 to 14 levels, resulting in improved simulation of quasi-stationary waves in the winter atmosphere. The gravity wave drag parameterization was tuned to yield realistic zonal winds in the troposphere. Rayleigh drag was imposed at the top finite difference level to avoid excessive intensification of zonal winds in the winter stratosphere. As a result of these modifications, the time step in the model was

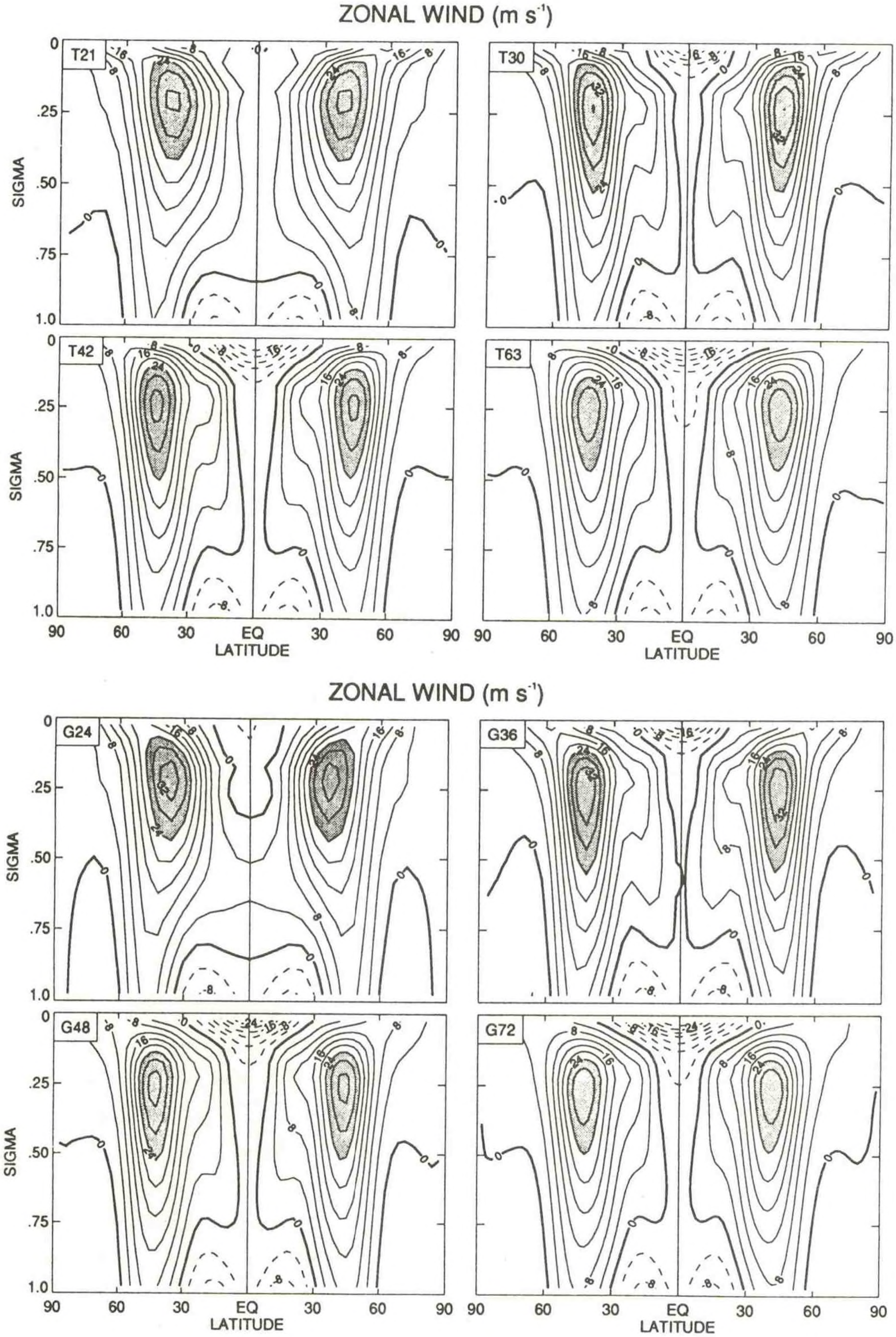


Fig. 1.11 The time-averaged, zonally-averaged zonal winds obtained from 1000 day integrations with a series of spectral and grid point GCM dynamical cores. The forcing is symmetric about the equator, so differences between hemispheres are a measure of sampling error. Contour interval is 4 m/s, with negatives contours dashed and values above 24 m/s shaded. The vertical coordinate is σ = pressure/(surface pressure). The upper four panels show the results from T21, T30, T42, and T63 spectral models, the lower panels from 6 x 7.5 (G24), 4 x 6 (G32), 3 x 4.25 (G48), and 2 x 3 (G72) grid models.

increased, resulting in a 50% reduction in the amount of computer time needed for the time integration. A special technique was developed to remove two grid point ripples in the model topography without significantly altering its large scale features. This smoothing resulted in marked improvement in the distribution of precipitation (1.6.3). In addition, the new soil moisture parameterization of C. Milly was included in the model, reducing the tendency of the model to generate unrealistically dry soil in summer.

The high resolution oceanic model (1.8° longitude, 2.2° latitude, 18 levels) was constructed by modifying and adapting the MOM (Modular Ocean Model) ocean code. The model integration for several centuries is being conducted to generate the initial condition and surface flux adjustments for the coupled model. Additional modifications of the ocean model are being tested to improve the simulation of temperature and salinity in the deep ocean.

PLANS FY94

Development of the high resolution ocean-atmosphere model will continue. The simulation of the high resolution ocean model will be improved. The coupled ocean-atmosphere model will be constructed and time integrations with normal and increased atmospheric CO_2 will be started.

1.6.3 Improvement of Atmospheric GCM

A.J. Broccoli *C.R. Lindberg*

ACTIVITIES FY93

The first of the two major atmospheric model development projects active during FY93 has been the installation of a new scheme for boundary layer diffusion. Based on the work of John Garratt at CSIRO (Commonwealth Scientific and Industrial Research Organization), this scheme utilizes mixing coefficients that depend on the Richardson number. In addition to the coding of this scheme, a series of tests was conducted to examine its performance in a low resolution climate model. Reasonable agreement between simulated and observed profiles of temperature and relative humidity was obtained by prescribing a minimum value for the adjustment to the mixing coefficients, representing a "background diffusion" that is not Richardson number-dependent. The availability of the Garratt boundary layer diffusion scheme will make it possible to study the sensitivity of boundary layer phenomena (such as polar inversions) to climate change.

Efforts were also underway to develop improved representations of global topography for use in the climate model. Since the representation of topography as a truncated set of spherical harmonics creates spurious "ripples" (akin to the Gibbs oscillations in a truncated Fourier series) with undesirable consequences for the simulated climate (uk), these efforts focused on developing topographies that reduce the magnitude of these oscillations without too much distortion of the height or extent of major topographic barriers. Many topographies have been developed and several have been tested in R30 climate model integrations. Work is currently underway to identify representations of topography that satisfy the above criteria and improve the fidelity of the simulated precipitation. Preliminary results indicate the existence of several techniques that can produce topography with these characteristics.

PLANS FY94

An integration will be initiated using the R30 climate model with increased vertical resolution (20 levels) that incorporates the Garratt boundary layer scheme and the improved representation of topography. The results from this integration will be carefully examined to prepare for its intended use in a number of climate sensitivity studies.

1.6.4 Effect of Parameterized Gravity-Wave Drag on Transient Disturbances

D. Golder *Y. Hayashi*

ACTIVITIES FY93

To evaluate the simulation of extratropical transient disturbances and the effects of a parameterized orographical gravity-wave drag on these disturbances, a statistical analysis was made of nine years of data from a nine-level R30 spectral GCM, with and without gravity-wave drag, and the ECMWF four-dimensional analysis data set. It was found that the extratropical transient eddy kinetic energy simulated without gravity-wave drag was somewhat deficient in both the Northern and Southern Hemispheres, probably due to insufficient horizontal resolution in the model. In the Northern Hemisphere, this deficiency became serious when gravity-wave drag was incorporated. It is suggested that the horizontal resolution of the model should be increased to improve the transient-eddy kinetic energy, while the vertical resolution should also be increased, so that the model requires a weaker gravity-wave drag to realistically simulate the mean state.

PLANS FY94

The effect of increased horizontal resolution on extratropical transient disturbances simulated with and without gravity-wave drag will be examined.

1.6.5 Solar Radiative Transfer

S.M. Freidenreich M.D. Schwarzkopf
V. Ramaswamy

ACTIVITIES FY93

1.6.5.1 Benchmark Results

The benchmark algorithm for radiative transfer in absorbing-scattering atmospheres can now be deployed for performing the computations at any arbitrary solar zenith angle instead of at the Gaussian quadrature angles employed in earlier years. A direct comparison became possible to some earlier doubling-adding results for a pure scattering layer; the agreement was excellent. Comparisons were also attempted with an earlier ozone-Rayleigh scattering calculation performed with the successive scattering technique and which has been widely used as a standard; again, excellent agreement was attained. "Exact" computations have now been performed to account for the solar radiative effects due to H_2O, CO_2, O_3, and Rayleigh scattering. Rayleigh scattering is considered only between 9700 and 50000 cm^{-1}, since this accounts for more than 99% of the scattered flux and reduces the burden of the line-by-line + doubling-adding computations. For frequencies less than 18000 cm^{-1} (wavelength of 0.55 μm.), the computations are line-by-line, while above 18000 cm^{-1}, owing to the absence of molecular line spectra, the computations are for every 1 cm^{-1}. These computational results will be useful in evaluating the accuracy of commonly used approximations in GCMs.

1.6.5.2 Overcast Sky Flux Analyses

The near-infrared benchmark results derived earlier for overcast skies (A92/P93) were further analyzed. Specifically, the reflected flux at the top of the atmosphere, the absorbed flux in the atmosphere, and the transmitted flux at the surface were examined. Fig. 1.12 illustrates the spectral distribution of the three fluxes for a high (180-200 mb) and a low (800-900 mb) cloud, respectively, located over a nonreflecting surface. Both clouds have a drop optical depth of 10 and water saturation is assumed at the cloud location. The solar zenith angle is 3° while the solar insolation in the 0-18000 cm^{-1} spectrum considered here is 966 W/m^2. The high cloud case causes more flux to be reflected than the low cloud case. This occurs because the bands in which water drops can scatter and absorb also happen to be water vapor absorption regimes. Thus, in the low cloud case, the water vapor column between the top of the atmosphere and the low cloud absorbs radiation that would otherwise have been scattered by the cloud. This leads to a greater amount of solar flux absorbed within the atmosphere in the low cloud case. The surface flux in any spectral region is insensitive to the location of the cloud, just like for the total flux (A92/P93). Comparing

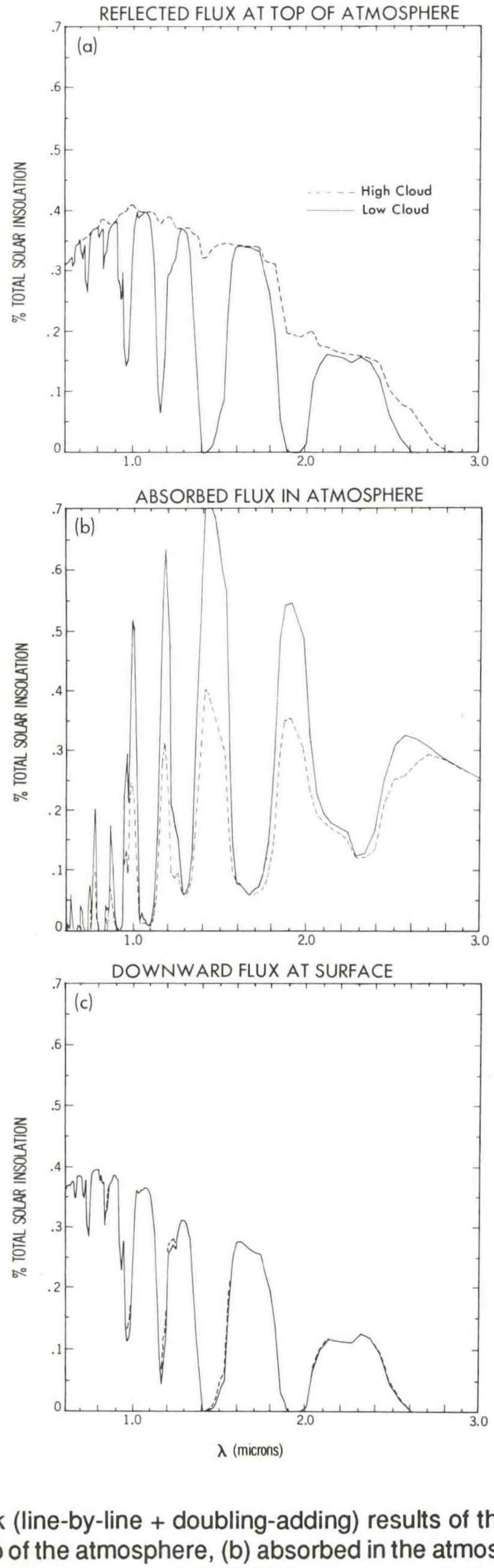


Fig. 1.12 Benchmark (line-by-line + doubling-adding) results of the spectral distribution of the flux (a) reflected at the top of the atmosphere, (b) absorbed in the atmosphere, and (c) at the surface for a high (180-200 mb) and a low cloud (800-900 mb), respectively. Both clouds have identical water drop single-scattering parameters (optical depth = 10). Results are for a solar zenith angle of 3° and are expressed as a function of the total solar insolation in the midlatitude summer atmosphere.

the two cloud cases, the reflected and the absorbed fluxes exhibit complementary variations in each spectral interval such that the surface flux is invariant. The absorbed flux in an overcast atmosphere is sensitive to the location of the cloud and cannot be considered to be invariant. Also, the surface and the top-of-the-atmosphere flux cannot a priori be assumed to bear a simple relation to one another. This conclusion is in contrast to the case of a vapor-only atmosphere, where there is indeed a simple linear relationship, and the atmospheric absorption is relatively insensitive to the details of the water vapor profile.

1.6.5.3 Parameterization

With the extensive benchmark solutions now available, efforts are underway to develop a parameterization that departs from the single interval broadband concept traditionally employed to represent the near-infrared radiative transfer in models. The goal of the present efforts is to reduce the monochromatic frequencies over which the radiative transfer is performed to far less than what is required in the benchmark computations, while retaining the identity of the near-infrared spectrum and not compromising too much on the accuracy of the results. The procedure adopted is to subdivide the near-infrared spectrum into a number of bands, within each of which the transmission by H_2O, the major clear-sky absorber, is fitted by a weighted sum of exponentials. Absorption by CO_2 is incorporated by retaining the same weights, but modifying the exponent so as to agree with the appropriate benchmark results. For the visible and UV regions, where absorption is essentially a continuum, the ozone and the Rayleigh optical depths are averaged over broad spectral regions. With this scheme, the number of bands and the number of monochromatic terms employed within a band are adjustable to any desired accuracy. As a first step, a parameterization has been developed that employs 134 monochromatic terms. For clear-sky conditions and a variety of test cases involving different reference profiles and zenith angles, this parameterization yields <1% error in the flux absorbed by the atmosphere and < 10% error in the layer heating rates. For overcast sky cases, the error in the flux absorbed by the cloud is <5%, and in the boundary fluxes, it is <1%. One particularly encouraging outcome of the development is that the errors do not increase when multiple cloud systems are considered, a situation which is not handled well by the single interval broadband concept.

PLANS FY94

The accuracy of the radiative transfer scheme used to compute Rayleigh scattering and ozone absorption in GCMs will be evaluated using the benchmark results. Analyses of the spectral flux dispositions in overcast skies and their dependence on cloud properties, as diagnosed from the benchmark results, will continue.

The accurate parameterization will be used together with the vertical profiles of the radiative constituents in order to compare the modeled and the satellite-derived (ERBE) estimates of the clear sky albedo over different latitudes and seasons.

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.L. Chameides**
*J.N. Galloway******
*P.S. Kasibhatla**
H. Levy II
*J.A. Logan***
J.D. Mahlman
W.J. Moxim
*S. Oltmans ****
L.M. Perliski
*J.L. Richardson*****
J.J. Yienger

* *Georgia Institute of Technology*
** *Harvard University*
*** *Climate Monitoring and Diagnostics Lab*
**** *NASA LaRC*
***** *University of Virginia*

ACTIVITIES FY93

2.1.1 Tropospheric Chemical Model Development

Specific SKYHI tracer model improvements were the development of modules to simulate the physical processes of dry and wet deposition of reactive trace gases and the incorporation of a mass-balance check, which relies on calculated global integrals of tracer mixing-ratios, sources, and sinks, to halt model execution when this criterion is violated.

A set of tracer experiments, which will be integrated on-line in the SKYHI GCM, have been designed and developed. The first is a study of the distribution of reactive nitrogen compounds emitted by surface-based fossil-fuel combustion emissions where NO_x, HNO_3, and PAN (peroxyacylnitrate) are explicitly treated as transported species, chemical interconversion rates among these species are specified in the form of look-up tables, and the fossil-fuel source inventory of NO_x used in the GCTM (Global Chemical Transport Model) is adapted to the SKYHI grid. The second experiment uses ^{222}Rn to study the transport of short-lived trace gases in the GCM. The model-simulated surface temperature is used to specify the surface flux of ^{222}Rn, and the sink is radioactive decay with a loss frequency of 2.1×10^{-6} s^{-1}.

The SKYHI 5° latitude-resolution model was integrated for a period of two months, and history and average-history files were written out for the first two tracer experiments. Development of a graphical analysis package for an arbitrary number of tracers has begun.

Dr. Sillman from the University of Michigan vectorized his fast chemical scheme for GFDL/GCTM and the results from relevant idealized cases are being compared with the Georgia Tech chemical code. A chemical code developed in Julich, Germany at the KFA (Forschungszentrum Julich) has been extended and updated and is now undergoing a detailed intercomparison with the Georgia Tech chemical code.

A detailed source inventory for soil biogenic emissions of NO_x has been developed using a 1° x 1° global vegetation map, observed emission factors for various biomes and cultivated crops, and country by country United Nations' data for cultivation, crop type and nitrogen fertilizer use.

2.1.2 Stratospheric Chemical Model Development

A stratospheric chemistry module has been developed for use in the modular SKYHI code to study in detail three-dimensional transport of trace species and chemical/transport interactions. Although preliminary simulations will not allow computed changes in trace species to affect SKYHI's radiative/dynamical calculations, the eventual goal is a completely interactive simulation of dynamical, radiative and chemical processes in the atmosphere.

The stratospheric chemistry module employs simple Euler differencing to predict the mixing ratios of trace species at time steps of up to 30 minutes. It deals with the stiffness inherent in atmospheric chemical systems by defining chemical families characterized by relatively long lifetimes in comparison to the integration time step, and rapid interchange between member species. Chemical family definitions are allowed to change with time in order to capture the rapid response of stratospheric chemistry to the diurnal variation of solar radiation. Therefore, trace species which are partitioned from a parent species during daylight (when chemical lifetimes tend to be rather short) may be differenced during night (when chemical lifetimes tend to be long). This flexibility allows for relatively accurate simulations of diurnal processes for the chemical families defined in the model: O_x (O, O_3), NO_x (N, NO, NO_2, NO_3, N_2O_5 and HNO_4) and HO_x (H, OH, HO_2). Although the chemical module is capable of treating atmospheric chlorine compounds as well, these will be added to the simulation at a later date.

Since most of the computational cost is paid in calculating gradients of transported species, three trace species categories are defined in SKYHI to maximize computational efficiency: prognostic, semi-prognostic and diagnostic. Transport is not calculated for the latter two categories. Although categorizing all trace species in this manner may well require some experimentation, it is logical to conclude that calculations of O_x, NO_x, H_2O_2, HNO_3 and H_2O will be done prognostically, while the methane oxidation products, $O(^1D)$, and members of chemical families will be calculated diagnostically.

Background distributions of atmospheric CH_4, CO, H_2 and N_2O with latitude and altitude will be specified using either available data or previous SKYHI simulations. Ozone will be initialized from satellite data. All other trace species will be initialized to 2-D chemical model calculations. The kinetic rate coefficients and absorption cross sections used in the chemical scheme are taken from the current JPL (Jet Propulsion Laboratory) recommendations. Photolysis frequencies for the photolytically-active atmospheric species are pre-computed using a matrix inversion radiative transfer model for a specified zonally-averaged seasonal ozone/temperature distribution and are stored as arrays varying with solar zenith angle.

2.1.3 Tropospheric Reactive Nitrogen

The global distribution of reactive nitrogen compounds, NO_y, is the key to understanding both the chemical production and destruction of O_3, which indirectly controls the chemical reactivity of the atmosphere, and the global biogeochemical cycle of nitrogen. Current work focuses on identifying all significant sources of atmospheric NO_x, determining the relative contributions of the various sources to the tropospheric NO_y budget, and then generating a global chemical climatology for NO + NO_2.

Inventories and emission patterns for all known reactive nitrogen sources [surface-based fossil fuel combustion (21 tg N $year^{-1}$), biomass-burning (8.5 tg N $year^{-1}$), biogenic emissions (5.6 tg N $year^{-1}$), lightning (3 tg N $year^{-1}$), stratospheric production (0.65 tg N $year^{-1}$), and sub-sonic aircraft emissions (0.45 tg N $year^{-1}$)] have now been determined. Simulated NO_x fields for July and January at 190 mb, 500 mb and 990 mb are shown in Figs. 2.1 and 2.2, respectively. Preliminary comparisons of observations of NO_x, PAN, HNO3 and NO_y mixing ratios, as well as nitrate deposition, with results from the 11-level GFDL/GCTM with NO_x, HNO_3, and PAN as transported

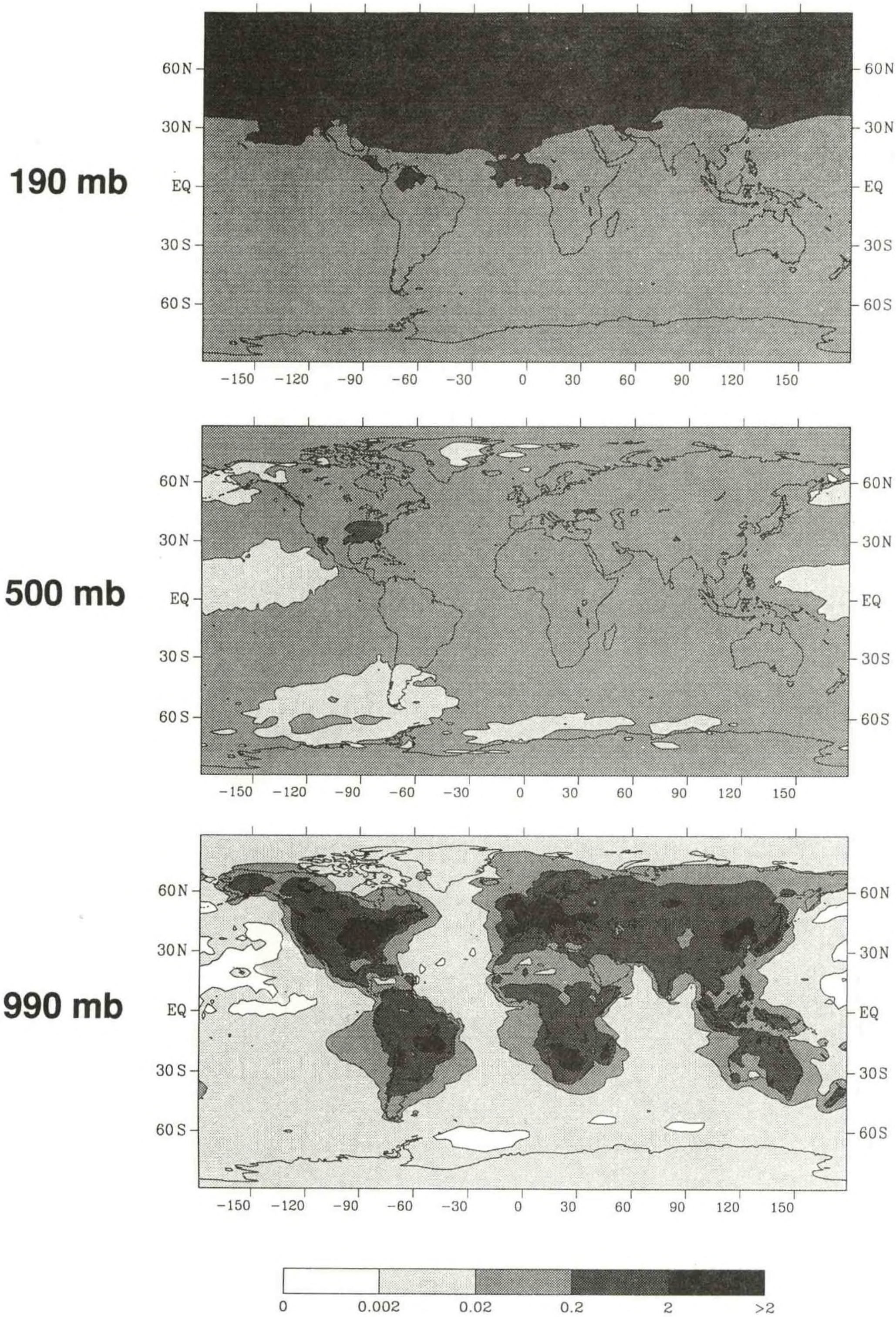


Fig. 2.1 Simulated July-mean NO_x mixing ratios (ppbv) at the 190, 500 and 990 mb model levels.

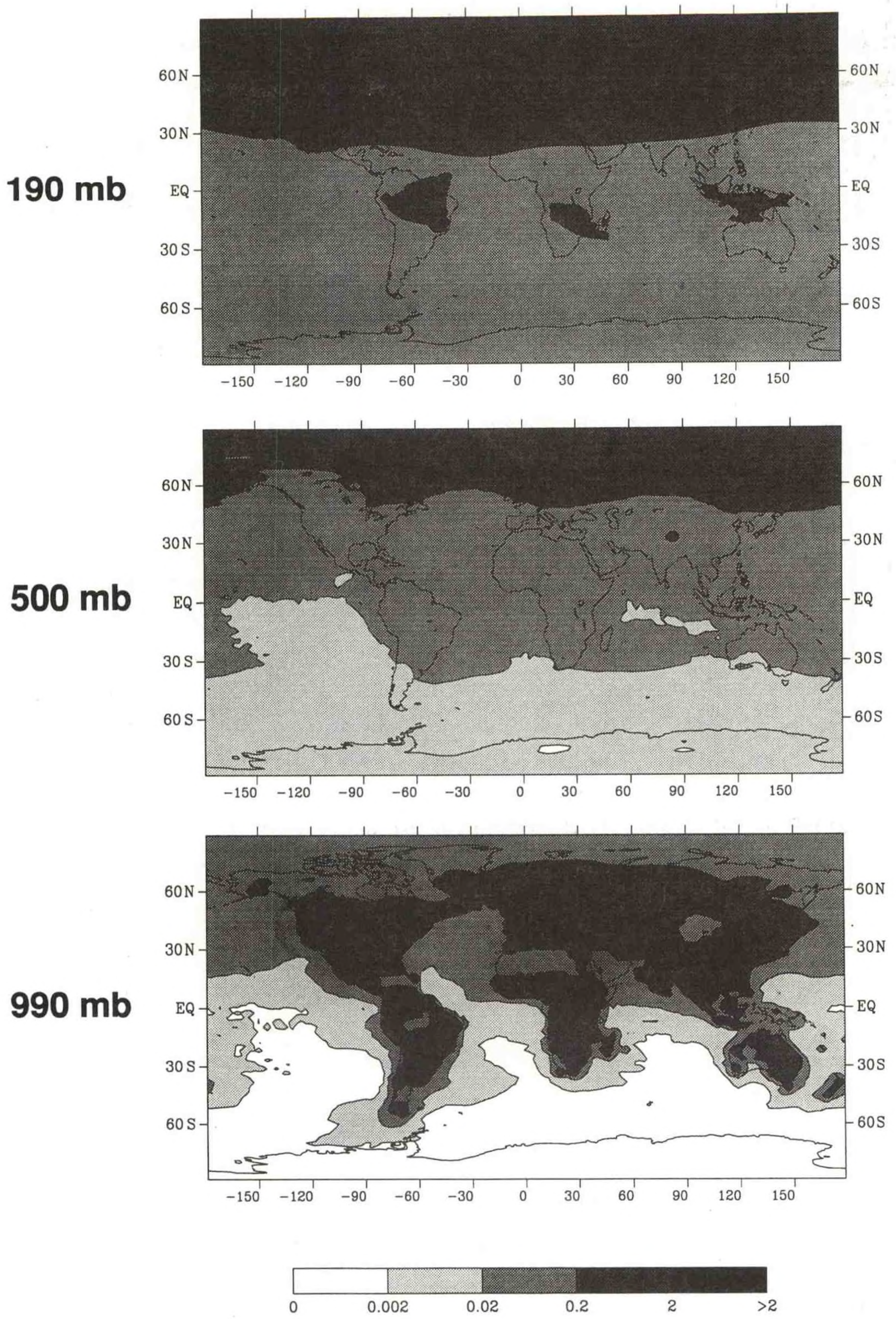


Fig. 2.2 Simulated January-mean NO_x mixing ratios (ppbv) at the 190, 500 and 990 mb model levels.

species were in reasonable agreement with observations near NH mid-latitude continental regions. At more remote sites, the model tended to underestimate NO_y, and to a lesser extent NO_x mixing ratios. Simulated wet deposition of nitrate was in good agreement with observations at sites in the NH continental source regions, at sites in tropical South America, and at NH mid-latitude transport sites such as Nova Scotia, Newfoundland, and Bermuda. At more remote sites, the model underpredicted nitrate wet deposition fluxes. Based on these results, it was concluded that all significant sources have been properly quantified. More detailed comparisons of model results and observations must await the development and implementation of an on-line chemical code in the GCTM.

The same 11-level GFDL/GCTM has been used to assess the impact of subsonic aircraft emissions on the global reactive nitrogen budget (tb). A three-dimensional aircraft source inventory compiled by Boeing and McDonnell Douglas was used, in conjunction with previously compiled surface-based fossil-fuel combustion and stratospheric source inventories. Consistent with previous two-dimensional model calculations, it was found that aircraft emissions have a significant impact on upper tropospheric NO_x and HNO_3 budgets in the mid- and high latitudes of the Northern Hemisphere. Moreover, it was found that the relative impact of the aircraft source on upper tropospheric NO_x levels at mid- and high northern latitudes varies longitudinally, and that in certain regions the aircraft source dominates the total NO_x budget. Aircraft emissions appear to only minimally impact the NO_y budget in the NH lower troposphere, and in much of the SH. In contrast to a previous study with a simplified transport model [Ehhalt et al., 1992[1]], it was found that it is not necessary to invoke fast upward transport of surface emissions to explain available measurements of NO in the upper troposphere of NH mid-latitudes in the GCTM. However, comparisons of model results with NO_y measurements at Mauna Loa, Hawaii, and over western Alaska suggested that sources other than surface-based fossil-fuel combustion, stratospheric NO_x production, and aircraft emissions, are significant in determining the free tropospheric NO_y budget in these regions.

Simulations of nitrate deposition for estimated pre-industrial and year 2020 NO_x emissions have been performed with the GFDL/GCTM. It was found that present levels of fossil fuel emission have greatly increased current nitrate deposition in the NH, particularly at mid- and high latitudes. However, in the future, the biggest increase in nitrate deposition is expected to occur over the North Pacific as a result of large projected increases in Asian emissions.

The impact of PAN chemistry on NO_x distributions was quantified by two GFDL/GCTM simulations that included and excluded PAN chemistry, respectively. The global tropospheric integral of NO_x is barely affected by PAN chemistry with <1%

---

1. Ehhalt, D.H., F. Rohrer, and A. Wahner, 1992: Sources and distribution of NO_x in the upper troposphere at northern mid-latitudes. J. Geophys. Res., 97, 3725-3738.

differences in the summer and no more than 5% differences in the winter. However, PAN, which can be transported long distances in the free troposphere, provides a very effective mechanism for carrying NO_x from continental source regions to the remote oceans. An examination of the resulting NO_x Jan-Apr. 940 mb fields revealed that, with PAN chemistry included, the values of NO_x mixing ratio over the oceans increased significantly. The largest effects were found over the sub-tropical Atlantic and Pacific (factor of 2-5). Over the continents values of NO_x decreased slightly.

2.1.4 Tropospheric Ozone

Tropospheric ozone, which both controls the chemical reactivity of the lower atmosphere and is a significant greenhouse gas, is thought to have increased significantly in a number of regions, possibly throughout much of the globe, over the last 100 years. There are 2 major questions to be answered: 1. The relative importance of ozone transport from the stratosphere, and the net chemical production in the troposphere; 2. The relative contributions of natural and anthropogenic sources of ozone precursors to any chemical production of ozone in the troposphere.

Until the mid-1980s, the limited observations of tropospheric O_3 showed that they were lowest in tropical regions, and lower in the SH than in the NH. However, recent analyses of satellite data, as well as ozonesonde data, find O_3 levels appearing off the west coast of Africa during the SH burning season that are comparable to those over industrialized countries. Emissions of an inert biomass burning tracer were released near the GCTM surface and analyzed to determine areas in the tropics that are affected by either direct emissions from biomass burning or secondary pollutants, such as ozone. A photochemical lifetime of ozone based solely on the water vapor loss via the reaction O(1D)+H2O->2OH was computed using the ECMWF climatological water vapor distribution and was assigned to the emissions tracer. While the magnitudes of emissions between the northern and southern hemispheres are similar in the model, an asymmetry between the resultant tracer distribution was predicted, with higher concentrations found during the southern hemisphere burning season. This is nearer to the observed behavior of tropical ozone.

An objective clustering of the isentropic trajectories finds that the highest levels of ozone observed at Bermuda are associated with transport from North America which is rapidly subsiding, while the lowest values are associated with low-level marine transport around the "Bermuda High". These results confirm earlier qualitative conclusions of Oltmans and Levy (1102) and support a significant lower tropospheric role for transport of ozone from the upper troposphere and lower stratosphere.

2.1.5 Transport Studies

Atmospheric transport is as important as chemical reactions in determining the impact of both natural and anthropogenic emissions on the global chemical climatology of the atmosphere. Moreover, the roles of transport and chemistry are frequently intertwined in a very complex manner. PAN, a major component of tropospheric NO_y, is unique in that its lifetime is a function not only of atmospheric chemistry, but also of meteorology due to its sensitivity to temperature (*i.e.*, 4°C ~ 1 day lifetime: -12°C ~ 20 days). During the NH winter, mid-latitude storms sweep PAN northward and upward, thus storing PAN in the very cold region of 500-600 mb. This pool of PAN is then available to subside to warmer levels behind spring cold fronts, subsequently producing NO_x through thermal decay.

To determine whether the observed seasonal increases in NO_x over the oceans were due to surface advection of NO_x from the polluted continental source regions or subsidence of sequestered PAN from aloft, a unique five tracer study was devised. In addition to carrying HNO and PAN, NO_x was separated into three components: NO_x emitted from any of the six sources; NO_x formed from PAN in the source regions; and NO_x formed from PAN after the PAN is transported away from the source region. Three NH areas were analyzed:

I.) During the winter-spring over the North Atlantic south of Greenland and Iceland (940 mb NO_x ~100-200ppt), a complex region has been identified where chemistry is slow and NO_x consists of roughly equal portions of unconverted NO_x from Europe and Canada and NO_x from transported PAN. Trajectory analysis showed that NO_x transported as PAN is mostly lower level advection from continents to the relatively warm ocean, with a smaller contribution due to subsidence from above.

II.) Over the sub-tropical North Atlantic 20-35°N (NO_x ~20-50ppt), NO_x is almost entirely transported as PAN which sinks anticyclonically southward from the mid-tropospheric pool of PAN far to the north. In the western region near Bermuda, the picture once again becomes a complex mixture of emitted NO_x from the U.S. and NO_x transported as PAN.

III.) Over the sub-tropical eastern South Pacific (940 mb NO_x~20-100ppt), NO_x comes solely from PAN at mid-tropospheric levels which is advected across the Pacific north of 40°N and then sinks anticyclonically southward to lower latitudes, and forming NO_x in the warmer air.

While the SH winter-spring shows similar increases in NO_x over the remote oceans as a result of PAN, the mixing ratios are generally very small (< 5ppt at 940 mb) because the amount of emitted NO_x available for synoptic transport in mid-latitudes is quite small. However, a surprising SH result is an area of high NO_x (~50-100ppt) between South America and Africa from 5 to 35°S which decreases by a factor of 2-5 when PAN chemistry is not included. This region is unique in that it is essentially isolated from mid-latitude transport dynamics, and yet the tropical circulation allows PAN to play a major role in NO_x mixing ratio. In addition, this is an area where a significant maximum of tropospheric ozone is found during July through October. Preliminary analysis indicates that this is a region of significant subsidence which produces a strong surface anticyclone. During this season pollution from the biomass burning areas of South America and Africa may be carried aloft by continental convection and then subside over the South Atlantic.

PLANS FY94

SKYHI transport studies will be performed with a suite of tracers: CFC-11 to characterize the model's interhemispheric transport; reactive nitrogen compounds from fossil-fuel combustion emissions to test mid-latitude transport of tracers that undergo physical and chemical transformations and have surface sources; stratospheric ozone to test downward transport into the troposphere; a biomass burning source of O_3 to test tropospheric transport in the tropics.

The development of an *in situ* interactive chemistry for the GCTM will continue and preliminary simulations of the ozone/nitrogen/hydrocarbon system in a fully interactive chemical transport model will be started.

The analysis of the GCTM simulations with all the nitrogen sources will be completed and both the global fields of NO_y and the chemically important subset, NO_x, will be generated.

Work will continue to unravel the transport processes responsible for the South Atlantic bloom of wintertime NO_x found between South America and Africa. Emphasis will be placed on the possible effect of this NO_x on the observed ozone maximum in this region.

Analysis will begin on determining the transport meteorology which produces seasonal ozone events at Bermuda. Utilizing available observed data and model simulation, sinking of ozone from the upper troposphere and low level advection of chemically produced ozone from the polluted U.S. source region will be examined.

The results from biomass burning tracer simulations will be further analyzed with the aid of ozone photochemical models. The contribution of *in situ* chemical production of ozone, in addition to mass transport from continents, over the remote tropical oceans will be examined.

Tropospheric sulfate aerosols are believed to significantly affect the earth's radiation budget through their direct scattering of solar radiation, as well as indirectly through their effect on CCN (Cloud Condensation Nuclei) distributions. Work will be initiated on box and one-dimensional chemical/microphysical models describing the cycling of biogenic sulfur compounds in the marine boundary layer. The goal of this work is to develop parameterizations for use in SKYHI and the GFDL/GCTM.

The SKYHI stratospheric ozone chemistry model will be extensively tested on a relatively simplified "nitrogen-only" system, including a chemically self-consistent troposphere.

2.2 ATMOSPHERIC DYNAMICS AND CIRCULATION

K. Hamilton	*M.D. Schwarzkopf*
R. Hemler	*S. Strahan*
*C. Kerr**	*R.J. Wilson*
V. Ramaswamy	*L. Yuan*

** Cray Research, Inc.*

ACTIVITIES FY93

2.2.1 SKYHI Model Development

The modular version of the SKYHI model has now been rewritten in a form that is amenable to various scalable architecture computers. The code is in a form that is potentially greater than 99.9% parallel, thus making it a candidate for even highly parallel computational systems. In principle, each horizontal grid point and the atmosphere above it can be assigned to a separate processor. This version of the model has been officially released to the vendor community for review and comment. Responses so far from the vendors indicate that the model is easy to use, and its inherently parallel structure reduces the effort required to implement SKYHI on their own parallel systems.

The modular version of SKYHI now allows easy development of versions with different numbers of vertical levels and different grid spacing. A version with more levels and extending into the lower thermosphere has been developed. As a further step toward including a physics package appropriate for the upper mesosphere/lower thermosphere, an improved parameterization of solar absorption by molecular oxygen has been developed.

2.2.2 SKYHI Control Integrations and Model Climatology

The control integrations with the 1° x 1.2° and 3° x 3.6° latitude-longitude versions of the SKYHI model were continued. The 1° model integration now extends for 24 months, while the control run with the 3° model has proceeded for 31 years. Many aspects of the long term mean climatology from these integrations (and from the nearly 3 year integration with a 2° x 2.4° version completed earlier) have been computed. These results have been compared with observations.

The simulated tropospheric climatology was found to have a significant sensitivity to horizontal resolution. In common with several spectral GCMs that have been examined earlier, the surface zonal-mean westerlies in the SKYHI extratropics become stronger with increasing horizontal resolution. However, this "zonalization" of the flow with resolution is not as prominent in the upper troposphere of SKYHI as it is in some spectral models. It is noteworthy that without parameterized gravity wave drag the SKYHI model at all three resolutions is able to simulate a realistic separation of the subtropical and polar night jet streams, and a rather realistic strength of the lower stratospheric winter polar vortex. It is not clear why SKYHI seems to do so much better in this respect than comparable spectral models when run without gravity wave drag. In order to test one possibility, part of the 3° SKYHI control run was repeated with a topography smoothed to be similar to that which would be used in a low resolution spectral model. This change produces only very modest effects on the zonally-averaged tropospheric and lower stratospheric simulation.

In the winter upper stratosphere, the simulation of the zonal mean wind and temperature fields was shown to display some significant deficiencies. The polar vortex in the NH winter at these heights is unrealistically confined to high latitudes, although the maximum zonal mean zonal wind is close to observed values. This problem is apparent at all three resolutions. The simulation of the upper stratospheric polar vortex in the SH winter is much less satisfactory. Near the stratopause the June-August mean temperatures at the South Pole are colder than observations by ~65°C, 50°C and 30°C in the 3°, 2° and 1° simulations, respectively. The corresponding zonal-mean zonal wind patterns display an unrealistically strong polar vortex.

The extratropical stratospheric stationary wave field in the NH winter was examined in some detail using the multi-year averages available from the 3° SKYHI integration. Comparison with comparable long-term observations suggests that the model captures the amplitude and phase of the stationary waves rather well, particularly in the stratosphere.

The SKYHI model simulates the reversed equator-pole temperature gradient near the summer mesopause. The simulated summer polar mesopause temperatures decrease with increasing horizontal resolution, although even at 1° resolution the predicted temperatures are still warmer than observed. The increasing resolution is accompanied by increased westerly driving of the mean flow in the summer mesosphere by dissipating gravity waves. The residual meridional circulation produced by this eddy mean flow forcing drives the temperature structure far from radiative equilibrium. The present results suggest that the SKYHI model does explicitly resolve a significant fraction of the gravity waves required to produce the observed summer mesopause structure, but that even higher resolution would be needed to achieve quantitative agreement with measured polar mesopause temperatures.

The semiannual oscillation near the tropical stratopause is reasonably well simulated in the 3° version. The main deficiency is in the westerly phase, which is not as strong as observed. There is also a second peak in the amplitude of the semiannual wind oscillation at the top model level (0.0096 mb) corresponding to the observed mesopause semiannual oscillation. This simulated mesopause oscillation is weaker (by a factor of ~3) than that observed. The simulation in the tropical stratopause and mesosphere changes quite significantly with increasing resolution, however. The winds in the westerly phase of the stratopause semiannual oscillation are stronger in the 1° simulation, but the maximum easterly winds are actually weaker. The amplitude of the mesopause semiannual oscillation is somewhat enhanced in the 1° model, but it peaks below the top model level.

Some additional aspects of model behavior of particular relevance for the dynamics of high frequency mesospheric motions have been examined (1120, ts). In particular, a comparison has been made of the turbulent kinetic energy dissipation rates in the model and recently reported measurements in the high latitude mesosphere using new *in situ* techniques. This comparison shows that near the top level of the model SKYHI has no trouble matching (or even exceeding) the observed dissipation rates. The horizontal wavenumber spectrum of gravity waves in the upper stratosphere and mesosphere has also been examined in some detail. These results show that the SKYHI model simulates the rather shallow spectrum that has been inferred by some investigators on the basis of radar observations.

2.2.3 Diurnal Variability in SKYHI

Analysis is continuing on a multi-year 3° SKYHI integration with a diurnal cycle. The focus thus far has been on the atmospheric tides in the mesosphere. The Eliassen-Palm flux divergence associated with the solar diurnal tide in the model has been computed. This represents the most complete calculation of the tidal mean flow forcing, a problem that has been studied extensively with simpler models over the last two decades. The results suggest that the details of the mean flow are crucial to determining even the zeroth order tidal forcing. This sensitivity to the mean flow reveals itself as a strong seasonal dependence of the computed tidal forcing (ts).

A version of SKYHI has been adapted for studies of the much stronger diurnal regime on Mars. Results suggest that global resonance may play a crucial role in determining the Martian tidal fields. This is a very interesting basic geophysical fluid phenomenon, and leads to a prediction of a very strong longitudinal dependence of the amplitude and local time phase of the surface tidal oscillations. This prediction could be evaluated by the observations expected to come from unmanned planetary missions in the foreseeable future.

2.2.4 Response of the NH Winter Circulation in SKYHI to Imposed Tropical Mean Wind Variations

The series of 3° SKYHI model integrations with imposed tropical wind and temperature perturbations discussed in A92/P93 was extended. A total of 20 August-February integrations with westerly zonal mean zonal tropical stratospheric forcing and 20 easterly forced experiments have now been completed. The results fail to show the relatively strong extratropical effects of the quasi-biennial oscillation that have been reported in observational studies. It is striking, however, that the interannual variability in the model is so strong that results composited for ten perturbed experiments (compared with a 25 year control) differ very appreciably from those obtained when all 20 perturbed winters are included. This emphasizes the possible difficulty in obtaining reliable observational statistics (tn).

2.2.5 Sea Surface Temperature Perturbations in SKYHI

Analysis continued on the 20 August-February integrations of the 3° SKYHI model described in A92/P93. Ten of these runs had positive sea-surface temperature anomalies imposed in the equatorial Pacific and ten had negative anomalies imposed. The tropospheric response of the model is quite similar to that seen in observations (or in earlier models). The direct penetration of the circulation anomalies into the tropical stratosphere is remarkably weak. By contrast, the effect of the imposed sea surface temperature anomalies is clearly detectable in the extratropical Northern Hemisphere stratosphere. Fig. 2.3a displays the December-February 50 mb height anomaly in the ten warm phase perturbed experiments minus that in 25 control winters. This model result is shown with a comparable observational composite in Fig. 2.3b (see 2.2.8). The agreement is really quite impressive and this result represents a rather significant achievement for a comprehensive general circulation model (sp, un).

2.2.6 Sudden Warmings and Interannual Variability in SKYHI

As noted in A92/P93 the 3° SKYHI model appears to have a rather realistic climatology of sudden warming occurrences. The interannual variability of the Northern Hemisphere winter circulation in this model has now been extensively

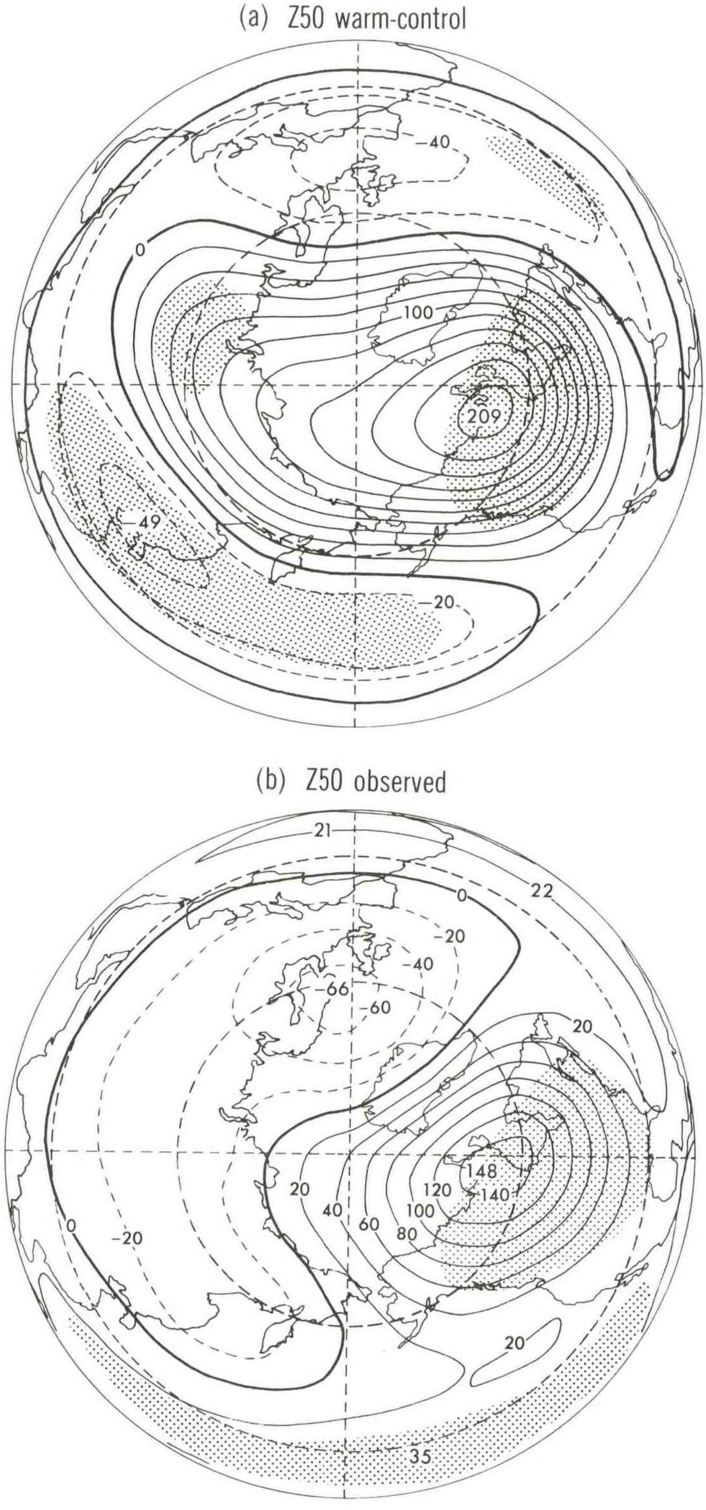


Fig. 2.3 (a) The SKYHI model simulated December-February 50 mb height averaged over ten experiments with warm tropical Pacific SST (positive anomalies) minus that in a 25 year control run. (b) The difference between the observed December-February 50 mb geopotential height averaged over 9 mature phase El Nino winters minus the average over 18 "normal" winters (*i.e.*, winters in which the Southern Oscillation was in neither its warm nor cold extreme). In each case the contour interval is 20 m and negative values are represented by dashed contours. The shading is for areas where the results are judged significantly different from zero using a 95% criterion in a two-tailed t-test.

compared with observations. The results demonstrate an impressive agreement between model and observations in many measures of the interannual variability. It is striking that this agreement occurs in a simulation with fixed sea surface temperatures and virtually no tropical quasi-biennial oscillation. One bias that does show up clearly is a tendency for the December vortex in the model to be more susceptible to major warmings than is apparent in the real world.

An intriguing aspect of the model performance is a long period (*i.e.*, multi-year) persistence which is apparent in the stratospheric polar vortex. This is a phenomenon similar to that which has been found recently by other investigators in simulations by idealized tropospheric general circulation models. This persistence may be related to the reports of a quasi-ten year cycle in the real Northern Hemisphere stratosphere.

The experiments to examine the predictability of the warmings in the model described in A92/P93 have been extended to include more cases. Analysis is continuing on these results.

2.2.7 Experiments on Tropical Wind Variations in a Spectral Model

This project described in A92/P93 has been completed. The results have clarified the nature of the problems that general circulation models have had in simulating the tropical stratospheric circulation (1115).

2.2.8 Observational Study of Southern Oscillation Effects in the Stratosphere

The effects of the Southern Oscillation in the stratosphere were examined using 34 years of lower stratospheric analyses from the Free University of Berlin. No evidence for a significant relation between the Southern Oscillation and the zonally averaged flow was found for any region poleward of 20°N. Some more suggestive results are evident when hemispheric maps of anomalies in the 50 mb or 30 mb heights are composited for the warm extremes of the Southern Oscillation. Fig. 2.3b shows the December-February 50 mb height anomaly composited for the mature phases of the nine significant El Nino events in the record. The present findings are broadly consistent with earlier suggestions that, on average, the Aleutian High is intensified during the warm phase of the Southern Oscillation (sp).

2.2.9 Simulation of the Mesoscale Velocity Variance Regime

The study of the statistical equilibrium in the forced-dissipative shallow water f-plane model described in A92/P93 was continued. A fundamental problem in geophysical fluid dynamics is the separation of the flow into a balanced component (in which the flow and pressure field are connected by a purely diagnostic relation) and a free component (which should resemble linear inertia-gravity waves). As part of this project a new scheme was proposed to perform this separation. This approach turns out to be very effective for the shallow water system, at least in the range of Rossby numbers considered in this study (up to about unity). The numerical experiments were designed to look at the response of the shallow water model to large-scale forcing restricted to only the balanced component of the flow. The resulting spectrum of balanced motions is very similar to the familiar k^{-3} regime seen in purely two-dimensional models and was shown to result from a forward enstrophy cascade. An important new finding was a direct demonstration of the local nature of the enstrophy cascade in wavenumber space. In addition to the balanced motions, a significant gravity wave component is generated in these experiments. When the Rossby number exceeds about 0.2, the slope of the gravity wave spectrum is significantly shallower than that of the balanced motions; thus at high wavenumbers the total energy is dominated by the gravity wave component. This behavior has obvious parallels with the mesoscale spectral regime observed in the atmosphere. It is striking that when parameters roughly appropriate for midlatitude atmospheric flow are employed, the break between the k^{-3} and shallower regimes in the model tends to occur at wavelengths of a few hundred km, *i.e.*, near the beginning of the mesoscale regime in typical observations.

This research represents an impressive contribution to the theory of homogeneous geophysical turbulence. It is summarized in a Princeton University Ph.D. thesis (1150).

2.2.10 Diagnosis of Polar Stratosphere and Tracer Structure

Analysis has been completed on the comparison of SKYHI structure with that obtained from the recent Antarctic and Arctic aircraft expeditions (si, sj).

In addition to the results reported in A92/P93, new insights have been obtained on the mesoscale variance spectra observed in the lower stratosphere and simulated in SKYHI. Both model and observations show spectral variance slopes of N_2O (a highly conservative tracer) in the range "-5/3" to "-2" (Fig. 2.4). The analysis shows that both observations and model mesoscale variations in the isentropic plane are dominated by "debris" from planetary-scale wave breaking events.

Current theory predicts, however, that such a quasi-horizontal variance cascade should have a spectral slope closer to "-1". This result suggests that the dissipative processes acting to destroy tracer variance measured on isentropic surfaces must have an important contribution in the third dimension. That is, diabatic processes must play an important role in determining the shape of the variance structure, even at these relatively short (~10-1000 km) spatial scales.

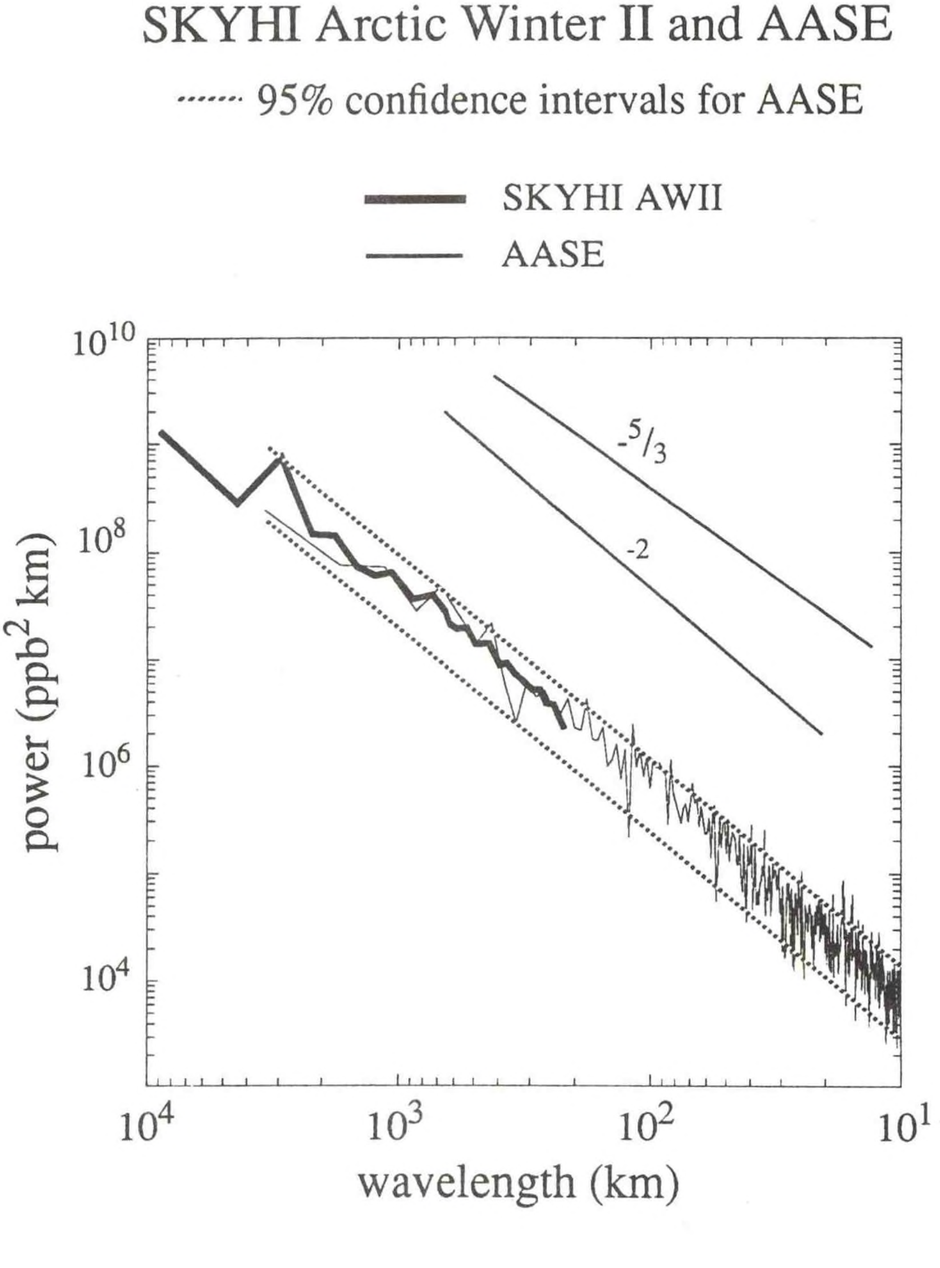


Fig. 2.4 Comparison of variance spectrum for N_2O from the Arctic Airborne Stratospheric Experiment (AASE) (thin line) with that of SKYHI (thick line). Both are taken from "flight" logs taken through the atmosphere and through SKYHI on isentropic surfaces ranging from 420-480°K. The dotted lines show the 99% confidence limits and the least squares slope for the AASE data.

PLANS FY94

Further development of models with representation of the lower thermosphere will continue.

The small-scale wind and temperature variations in the middle atmosphere from the GCM integrations will be compared with observations from rockets, lidars and radars.

Analysis of the detailed dynamics of the simulated sudden warmings will continue.

Analysis of the role of the diurnal cycle will continue.

Exploration of a new version of SKYHI more amenable to troposphere and lower stratosphere chemical problems will be underway.

The modular, parallel version of SKYHI will be adapted for trial high-resolution calculations on the CM-5 computer at Los Alamos National Laboratories.

2.3 EFFECTS OF CHANGES IN ATMOSPHERIC COMPOSITION

M. M. Bowen *V. Ramaswamy*
J. D. Mahlman *M.D. Schwarzkopf*
R. Orris

ACTIVITIES FY93

2.3.1 Ozone Climatology

Efforts are underway to update and improve the ozone field used in the SKYHI GCM. For this purpose, a zonal mean, monthly climatology has been constructed corresponding approximately to 1980 atmospheric conditions. The vertical coverage is from the surface to 80km, while the horizontal coverage extends from 90°S to 90°N. The stratospheric and the mesospheric profile is based on the information from the SBUV (Solar Backscatter Ultraviolet), LIMS (Limb Infrared Monitor of the Stratosphere), SME (Solar Mesosphere Explorer), and SAGE (Stratospheric Aerosol and Gases Experiment) satellites, as well as the CIRA (COSPAR International Reference Atmosphere) dataset. The tropospheric ozone profile consists of data from available investigations (courtesy: J. Logan and W. Komhyr et al.).

Narrow-band (10 cm^{-1}) radiative calculations have been performed to compute the change in the solar and the longwave heating rates due to the change in the ozone climatology. A comparison has been made between observed temperatures (Fleming et al., 1988[2]) and the temperature profile obtained using the new ozone climatology and the assumption of Fixed Dynamical Heating (FDH). The results for latitudes between 25°N and 25°S suggest that, between pressures of 2 and 10 mb, the FDH model yields temperatures that are too low. It remains to be determined whether this discrepancy is an artifact of the FDH experiment or whether the ozone amounts inferred from observations and the temperature measurements are fundamentally inconsistent with each other.

2.3.2 Stratospheric Aerosols and their Climatic Effects

The clear-sky sensitivity of the top-of-the-atmosphere solar and longwave radiative perturbations induced by stratospheric aerosols, and their dependence on season and latitude, has been examined. The solar forcing is negative (*i.e.*, tends to cool the surface-atmosphere system) while the longwave effect is positive. The maximum change in the net radiative flux due to an increase in stratospheric aerosol optical depth occurs in the mid-to-high latitudes during summer by virtue of the large insolation occurring there, and is a net negative forcing. The wintertime polar latitudes exhibit a positive (owing to the presence of the longwave component only) but weaker radiative forcing. The sharp contrast in the magnitude of the forcing between winter and summer is less equatorward of the polar latitudes, for any size distribution. For small particle size distributions, the radiative forcing in the tropics all through the year is negative and only slightly less in magnitude than that at the summertime midlatitudes. However, the tropical forcing can become positive if large particles are present when the longwave radiative effects dominate the solar. Hence, the global distribution of the stratospheric aerosol radiative forcing varies with space and time, even if the aerosol optical depth perturbations are uniform, thus distinguishing them from the radiative forcing due to the increase in the greenhouse gases.

2.3.3 Radiative Effects Due to Trace Species

A series of one-dimensional radiative-convective modeling experiments were conducted to investigate the effects due to competing surface-troposphere forcings upon the lower stratospheric temperatures (uj). Two examples of competing surface-troposphere forcings are a) increases in the greenhouse gas concentrations over the past century versus the increases in tropospheric aerosols (*e.g.*, sulfate, biomass), and b) the loss of stratospheric ozone over the past decade versus the increase in tropospheric ozone over the same period.

---

2. Fleming, E.L., S. Chandra, M.R. Schoeberl, and J.J. Barnett, 1988: Monthly mean global climatology of temperature, wind, geopotential height, and pressure for 0-120 km. NASA Technical Memorandum 100697.

As is well-known, the increase of greenhouse gases tends to warm the surface and the troposphere while cooling the lower stratosphere. The increase of sulfate aerosols leads to a cooling of the surface-troposphere system. Because of the radiative coupling between the surface-troposphere and the lower stratosphere, essentially through the longwave radiative exchange, there is a cooling of the lower stratosphere in this instance as well. Increases in the tropospheric aerosol optical depth diminish the positive surface-troposphere forcing due to the greenhouse gas increases over the past century, leading to a surface temperature change that is less than that caused by the greenhouse gas increases only (Fig. 2.5a). In contrast, since both types of species yield a cooling in the lower stratosphere, the lower stratospheric temperature decrease due to simultaneous increases in greenhouse gases and aerosols exceeds that due to the gases alone. Estimates of the tropospheric aerosol optical depth changes over the past century due to sulfate and biomass aerosols suggest that their contribution to the lower stratospheric cooling is comparable to that due to the greenhouse gases.

The loss of stratospheric ozone leads to a cooling of the lower stratosphere due to the reduction in solar absorption and due to the reduction in the absorption of the upwelling longwave radiation from the troposphere. In addition, if there are increases in tropospheric ozone, there is a further cooling of the lower stratosphere. This effect is due to the 'trapping' of the upwelling longwave radiation by tropospheric ozone, making less radiation available in the lower stratosphere. Fig. 2.5b illustrates the effect on the surface and lower stratospheric temperatures due to vertically uniform percentage increases in tropospheric ozone superposed on the stratospheric loss. While tropospheric ozone increases reduce the surface cooling induced by the stratospheric loss, they augment the lower stratospheric cooling.

In collaboration with Drs. Burkholder and Ravishankara at the Aeronomy Laboratory, high resolution absorption spectra of a number of halocarbons have been obtained. Included among these are a new class of halocarbon species - the perfluorocarbons (or PFCs) which have extremely long lifetimes in the atmosphere. They have absorption bands in the infrared spectrum, and therefore their presence in the atmosphere contributes to the "greenhouse" effect. High spectral resolution calculations have been performed to determine the net radiative flux change at the tropopause due to a 1 ppbv increase in each compound. The results are listed in Table 2.1 (negative value implies a trapping of the infrared flux). Also listed for purposes of comparison is the forcing due to a 1 ppbv increase in CFC11. While most of the PFCs exert an effect comparable to or exceeding the effect due to CFC11, CF_4 has much less of an effect owing to its absorption band lying outside the infrared 'window' region, where the terrestrial infrared energy is less.

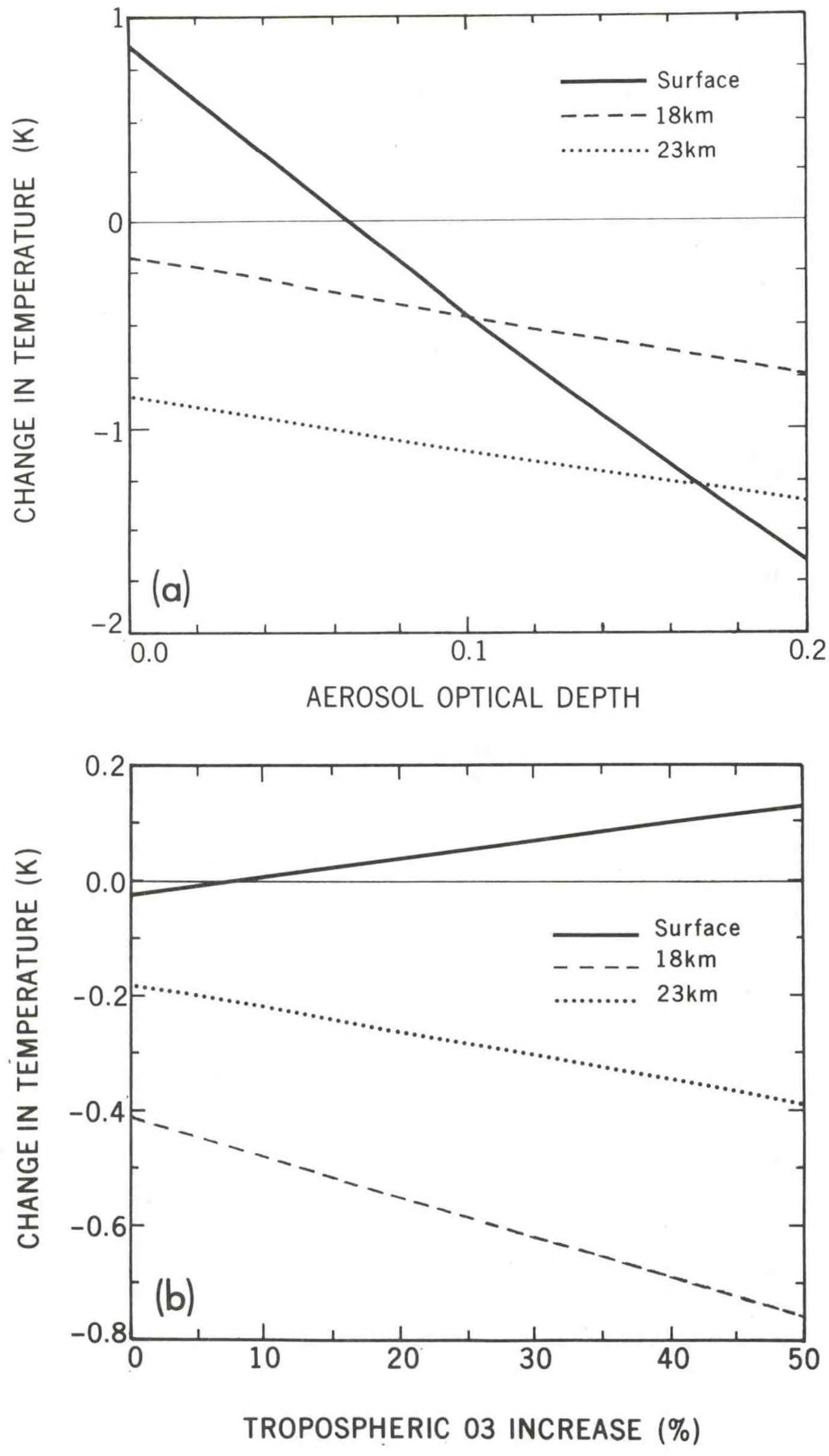


Fig. 2.5 (a) Change in the temperature at the surface, and at 18 and 23 km. in the lower stratosphere, as obtained from a one-dimensional radiative-convective model that considers increases in tropospheric aerosol optical depth of various amounts, superposed on the greenhouse gas increases of the past century. (b) Change in the temperature at the surface, and at 18 and 23 km. in the lower stratosphere, as obtained from a one-dimensional radiative-convective model that considers vertically uniform percentage increases in tropospheric ozone of various amounts, superposed on the stratospheric ozone loss over the past decade.

Table 2.1. Change in the net radiative flux at the tropopause due to a 1 ppbv increase in CFC11 and in various perfluorocarbons.

Molecule	Change in the net radiative flux at the tropopause (W/m^2)
$CFCl_3$ (CFC11)	-0.345
CF_4	-0.097
C_4F_8	-0.394
C_2F_6	-0.323
C_5F_{12}	-0.536
C_6F_{12}	-0.505
C_6F_{14}	-0.546
CHF_3	-0.256

2.3.4 Stratospheric Effects Due to Increased Carbon Dioxide

The multi-year run of the doubled CO_2 experiment in the N30 SKYHI GCM has now run for eight years. Analyses of the simulations thus far indicate that the latitudinal distribution of the annual mean temperature changes in the stratosphere bear a qualitative resemblance to earlier SKYHI results at much lower resolution.

2.3.5 Climatic Effects of the Observed 1979-1990 Ozone Changes

A project dealing with the sensitivity of the radiative forcing to simultaneous stratospheric ozone loss and tropospheric ozone increase, as observed by satellite and ground-based systems, has been completed (1122).

The 3° latitude SKYHI GCM experiment, with an imposed annually-averaged stratospheric ozone loss at each latitude similar to the 1979-1990 observations (Fig. 2.6a), has now been run for 7 years. A FDH experiment corresponding to the same ozone loss has also been performed. The GCM results, averaged over the last 6 years (Fig. 2.6c) indicate that the annually-averaged zonal mean cooling extends to the tropical lower stratosphere as well even though there is no ozone loss and, thus, no initial radiative perturbation there. Since the corresponding FDH experiment (Fig. 2.6b) exhibits no such response, the GCM result is indicative of a dynamically-induced effect. The GCM result suggests a smaller cooling than the FDH experiment in the lower stratosphere of the high latitudes. The difference between the GCM and the FDH results is more striking in the southern hemisphere. Also, the GCM result indicates a warming in the middle stratosphere that is a result of changes in the circulation pattern. The solar and the longwave fluxes at the tropopause in the GCM experiment undergo more complex changes than in the FDH case. Thus, even though the lesser temperature decrease in the GCM's lower stratosphere would suggest a

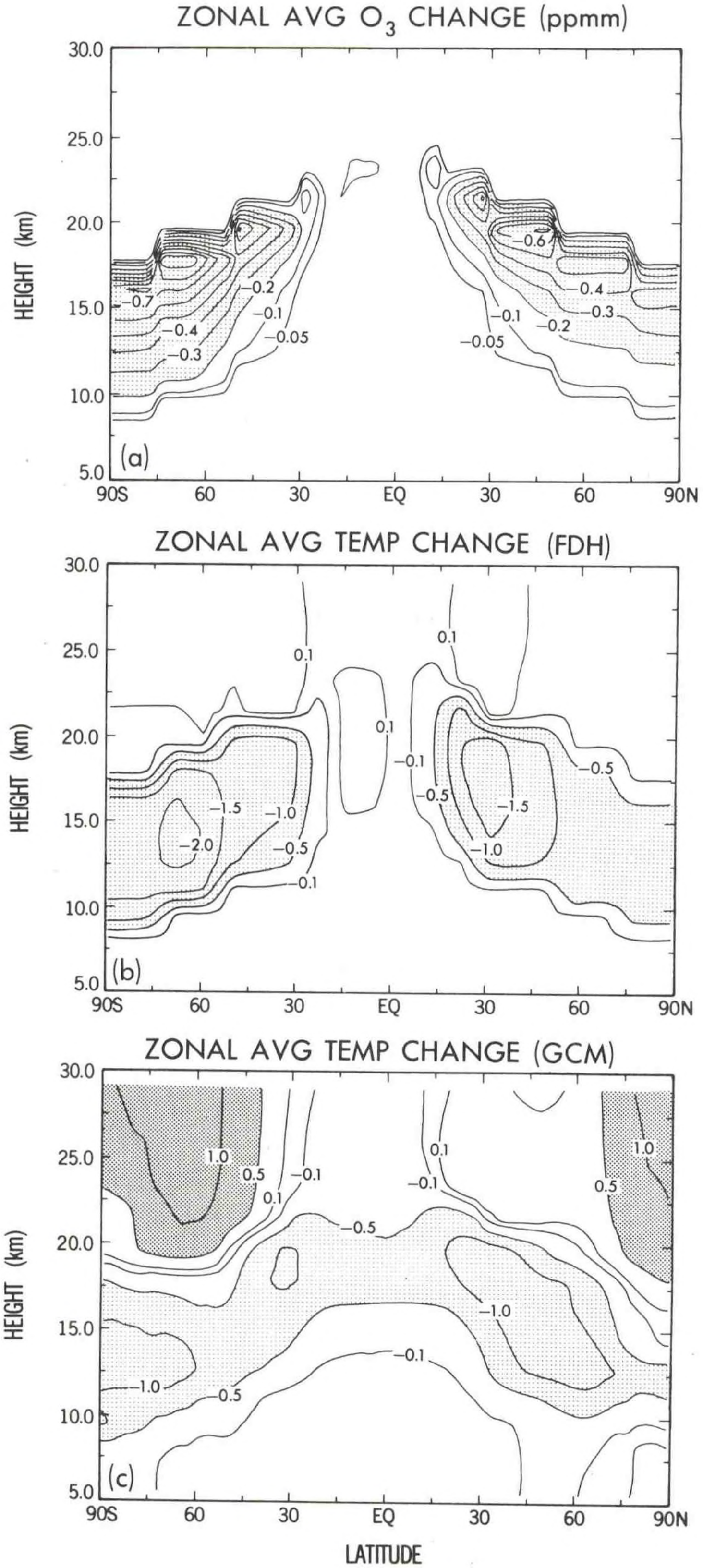


Fig. 2.6 (a) Vertical profile of the prescribed annual mean stratospheric ozone loss (in parts per million by mass) at each latitude; (b) the Fixed Dynamical Heating model temperature response (°K); and (c) the temperature response in the 3 degree latitude SKYHI GCM.

lesser (in magnitude) net longwave radiative flux change at the tropopause compared to the FDH result, this is not so. Instead, because of the changes in the upper tropospheric temperatures and the moisture field, the net longwave radiative flux change at the tropopause in the GCM is actually more negative than in the FDH case.

Another set of GCM and FDH experiments have been performed in which the ozone perturbation is allowed to vary with month, again according to the satellite observations. This experiment has run for 6 years. The annually-averaged, zonal mean result in the GCM exhibits a spatial pattern very similar to Fig. 2.6c. The results from both experiments are consistent with the observed decadal trend in the lower stratospheric temperature, including the sharp decrease suggested by the radiosonde records during the mid-1980s (1124).

PLANS FY94

Future work will attempt to identify the source of the inconsistency between the ozone and the temperature fields in the middle stratosphere, as diagnosed using the FDH concept. Comparison of the modeled and the observed temperatures will be extended to the upper and the lower stratospheric regions.

Development and testing of a 1D aerosol radiative transfer model suitable for incorporation into the SKYHI GCM, and satisfying the constraints of accuracy and computational timing, will continue. An effort will be made to compare the computed radiative sensitivities due to stratospheric aerosol perturbations with estimates inferred from satellite observations following the 1991 Pinatubo eruption.

A comparison of the radiative forcing due to several halocarbon species, as obtained using high-resolution spectral measurements of absorption by three different groups (including the Aeronomy Laboratory), will be conducted.

The doubled CO_2 runs with the SKYHI GCM will continue in order to analyze the variability of the response, especially in the polar winter stratospheres.

Analyses of the SKYHI GCM experiments involving stratospheric ozone decrease will continue. The stratospheric temperature changes will be compared with that due to the increases in the well-mixed greenhouse gases.

3. EXPERIMENTAL PREDICTION

GOALS

To develop improved monthly and seasonal forecast techniques, including more accurate and efficient GCMs, ensemble predictions, and model bias reduction.

To develop a coupled ocean-atmosphere GCM suitable for seasonal forecasts.

To investigate the effect of upper-ocean-atmosphere and land-surface-atmosphere, and cloud-radiation interactions on forecasts with ranges of several seasons.

To develop appropriate means of specifying the initial states of the atmosphere, oceans, soil moisture, and snow/ice cover.

3.1 MODEL IMPROVEMENT

J. Anderson
K. Dixon
C.T. Gordon
K. Miyakoda
A. Navarra
R. Pacanowski
N. Pinardi
A. Rosati
J. Sirutis
W. Stern
B. Wyman

ACTIVITIES FY93

3.1.1 Spectral Model

As part of an international collaboration, the Experimental Prediction spectral model, at a resolution of T42L18 (T42SM), is one of about 30 GCMs participating in the Atmospheric Model Intercomparison Project (AMIP). The goal of the project is a better understanding of systematic errors in climate models by inter-comparing and evaluating the performance of atmospheric GCMs on seasonal and interannual time scales, under realistic conditions (Gates 1992)[1]. Some degree of standardization was

1. Gates, W.L., 1992: The atmospheric model intercomparison project. Bull. Amer. Meteor. Soc., 73, 1962-1970.

achieved by requiring all GCMs to prescribe SSTs based on the same data set and specifying the same values for the solar constant and CO_2 mixing ratio. GCM integrations have been carried out for the period 1 January 1979 to 31 December 1988. The T42SM model output has been processed to meet the AMIP daily and monthly averaged standard output formats. These data have been made available to the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for further in-depth diagnostic analysis.

3.1.2 Upper Ocean Model

An effort has been made to adapt the surface pressure ocean model, as opposed to the conventional stream function model. This model has two advantages: a) to include as many islands as possible without any particular difficulty and expense; and b) to handle steep gradients in bottom topography. This version of MOM (Modular Ocean Model) has been completed after eliminating several bugs. The solution in a long run is now in good agreement with that of the stream function model.

3.1.3 Ensemble Forecasting with Simple Models

A forced barotropic model characterized by two distinct regimes (zonal vs. blocked flow) was developed to explore techniques for ensemble forecasting. Traditional linear techniques for selecting ensemble members were shown to be inadequate. Several non-linear mechanisms for ensemble selection have been evaluated and found to produce better results. The widely held view that regime transitions are inherently difficult to predict has also been called into question.

3.1.4 Global Eta-Model

Four-year model integrations have been completed using the E45L18 and E60L18 resolutions. Parallel runs were made for both the eta (step-mountain) and sigma (terrain-following) vertical coordinate using the same computer code via a simple switch. Seasonally averaged fields for the two vertical coordinates were compared using only the last three years of the four-year runs as a sample of the model's climate.

Preliminary results do not reveal any significant differences in the large-scale tropospheric circulation of the eta coordinate versus that of the sigma coordinate. However, in the stratosphere, there exists large unexplained differences in the strength of the Northern Hemisphere winter stationary eddies.

Precipitation distribution for the E45L18 eta coordinate model is not clearly better than the sigma coordinate. However, at the higher E60L18 resolution, the eta coordinate precipitation distribution appears to be superior to the sigma coordinate, especially in the region of the Indian monsoon.

3.1.5 Global Cloud Prediction Studies

The monthly mean cloud-radiation climatology of the T42L18 atmospheric spectral model has been verified against ERBE and ISCCP C2 data. In response to observed SST forcing, the model simulates the observed interannual variability of tropical OLR and high clouds quite well. However, the simulation of marine stratocumulus is adversely affected by a local negative bias in lower tropospheric relative humidity. Boundary layer physics appears to play a greater role here than either an excessive, remotely forced subsidence or the cloud scheme.

Cloud data derived from ISCCP C2 cloud fields have been assimilated into the GCM to constrain the model's surface cloud-radiation forcing to agree more closely with ERBE observations. The radiation budgets at the surface and at the top of the atmosphere improve significantly over marine stratocumulus regions, although moderately large discrepancies remain in some other regions.

3.1.6 Study of Subgrid-Scale Parameterizations

Implementation of improved parameterization is being pursued via two approaches. One is the comparison of two packages of physics parameterizations. Another is an effort to reduce systematic biases, which are fatal to the air-sea coupling.

Regarding the first approach, two versions of the atmospheric parameterization packages have been incorporated into the spectral model, and the impact of the physics on the GCM is tested by making three year runs for each version. One version is the E-physics, which is based on the "moist convective adjustment" for the cumulus parameterization, and the other is the F-physics, which is based on the Arakawa-Schubert scheme.

In both versions, other parameterizations are exactly the same, but they have been considerably updated compared with those of the previous study (987). The updated or the newly added parameterizations are: the surface exchange coefficients over the ocean, the mixing length scale in the turbulence closure scheme, the mountain gravity wave drag, the shallow convection, and the interactive clouds (1097). In addition, the F-physics includes an arrangement to enhance the Madden-Julian Oscillation in the equatorial zone. All simulations have been performed using the orography processed by the Lanczos filtering technique to reduce the Gibbs Oscillation, which is associated with the spectral representation (uk). These runs include diurnal variation.

The three year simulations from 1985 to 1987 were compared with each other and with the observations. In particular, the ECMWF (European Centre for Medium-Range Weather Forecasts) analyses made available by Schubert et al., (1990)[2] enable the validation of the models.

Regarding the second approach, issues related to the air-sea coupling are discussed in (3.2.2).

PLANS FY94

An investigation will be conducted to determine why large differences are occurring in the strength of stratospheric stationary eddies, between the eta and sigma vertical coordinates. Ensemble techniques developed with simple models will be evaluated in GCM ensemble forecasts. The vertical resolution of the ocean model will be increased to reduce the systematic error in the thermocline structure. A bucket versus an SiB (Simple Biosphere) surface hydrology test will be pursued.

3.2 SIMULATION AND DIAGNOSTIC STUDIES

J. Anderson	*A. Rosati*
C.T. Gordon	*J. Sirutis*
R. Gudgel	*R. Smith*
K. Miyakoda	*W. Stern*

ACTIVITIES FY93

3.2.1 Ten-Year Simulations of Atmospheric GCMs

Two sets of nine ensemble simulations have been completed for a 10 year time period (1979-88) using both the T30L18 and the T42L18 spectral models. The two models include the same physics, except very slight differences in carbon-dioxide and solar constant. A rather large difference is included in the specification of the lower boundary conditions, *i.e.*, the SST and ice-boundary. This is due to the fact that the T30L18 experiments used an SST data set of Reynolds (1988)[3], while the T42L18 experiments were designed to be consistent with the requirements of AMIP (see 3.1.1). One of the objectives is to assess the model's climatology using ECMWF statistics (Schubert et al. 1990)[2] and also to evaluate time series of model simulated fields (for example, the temperature and winds at 850 and 200 hPa and the rate of precipitation) in the extratropics by comparing them with observational counterparts.

---

2. Schubert, S.D. et al., 1990: An atlas of ECMWF analysis (1980-87). Part 1-- First moment quantities. NASA, Tech. Memorandum 100747.
3. Reynolds, R., 1988: Real-time global sea surface temperature analysis. J. Climate, 1, 75-86.

The three droughts, *i.e.*, 1980, 1981 and 1988, and the heavy rainfall in 1983 are well captured for the U.S. region.

3.2.2 Sensitivity Study with the Air-Sea Model

In contrast to the first approach of physics parameterizations described in (3.1.6), the focus has now been turned to the air-sea interface. The results of a 33 vertical level coupled model were shown in A92/P93. Investigation of a key deficiency suggests some reasons why the SST in the equatorial Pacific, *i.e.*, NINO 3 region, lacks an annual cycle. Two major possibilities are considered. One is the erroneous surface wind field over the eastern Pacific, *i.e.*, along the coast of Peru and Chile, which may be suppressing cold water upwelling. Another is the erroneous cold water along the equator, which is both excessive and extends too far westward.

With these ideas in mind, a number of sensitivity tests are being carried out by varying the specification of physics and orography. The results are being compared with ECMWF observations. The first objective is to prepare realistic thermodynamical fields over the tropical Pacific and over the Indian Ocean. Second, the general circulation fields over the global domain are to be examined for validity. For the first objective, various physics parameterizations are being critically tested and improved, if necessary, particularly related to specification of the interfacial conditions between the air and sea/land. For the latter objective, various orographic arrangements are being varied, related to the Gibbs treatment of mountains and coast-line adjustments.

3.2.3 Systematic Biases in the Air-Sea Coupled Model

As will be discussed in (3.4.3) and as related to (3.3.1), there is a clear systematic bias in the L15 oceanic model. When forecasts or simulations start from realistic initial conditions, the equatorial thermocline in the model begin to drift away from the assimilated configuration. Eventually the thermal gradient becomes considerably weaker and too diffuse, and the thermocline level becomes shallower. The time for the transition is about three months. It is hypothesized that this occurs because of the lack of sufficient vertical resolution.

Another bias is the presence of a cold tongue along the equator. It is speculated that the non-isotropic and inhomogeneous grid structure of the equatorial zone in the ocean model produces unrealistically strong upwelling. The zonality of the simulated SST pattern is also considered to be the consequence of the model's grid structure. In observations, the SPCZ (South Pacific Convergence Zone) is not parallel to the equator but is oriented from the western equatorial Pacific to the eastern South Pacific. In order to confirm this speculation, the homogeneous $1° \times 1°$ ocean model without the equatorial refinement was coupled with the T30 atmospheric model. However, the results are inconclusive at this time.

3.2.4 Evaluating Ensemble Forecasts

A method for evaluating the skill of sets of ensemble forecasts was developed. Forecasts are verified against the corresponding observations and also against observations from the correct season, but from a different year. These false verifications provide an unskillful control against which skill can be measured. Results demonstrated that extreme care must be exercised when evaluating large sets of forecasts that are expected to have little skill.

PLANS FY94

Experiments will be conducted with simple models and GCMs to examine methods for reducing "climate drift" in extended integrations. A 40 year simulation similar to the 10 year integration (3.2.1) will be started. This is joint work with C.K. Folland of the U.K. Meteorological Office. The sensitivity study in (3.2.2) will be continued. After the best of physics parameterizations for the uncoupled atmospheric GCM is determined, additional modification for the coupled system will begin. Two points are of particular concern. First is the prediction of the marine stratiform clouds over the eastern Pacific. Second is the surface insolation adjustment, so that the resulting SST becomes adequate. Related to the systematic bias in the air-sea coupled model of (3.2.3), the vertical resolution of the ocean model will be increased to about 30 levels and the experiment continued with the 1° x 1° homogeneous ocean model.

3.3 DATA ASSIMILATION

R. Gudgel	*N. Pinardi*
J. Ploshay	*A. Rosati*
K. Miyakoda	*W. Stern*

ACTIVITIES FY93

3.3.1 Initialization for Atmospheric Seasonal Forecasts

Soil moisture or snow coverage are important elements in the initial conditions for seasonal forecasts. However, there are complications: a) the soil moisture, for example, is not entirely an objective quantity; it is determined within the context of the particular scheme of ground hydrology; and b) these variables cannot be specified arbitrarily, because they are determined by various effects, such as the SST etc. and their histories. In the study of the decadal simulation ensemble (3.2.1, 3.4.2), it was shown that three variables, *i.e.*, the precipitation, the surface temperature, and the soil moisture, vary coherently in time for all but the first year. The reason this spin-up occurred is that the soil moisture at the initial time was not balanced with other variables. It is somewhat surprising to learn that the adjustment is such a slow process; about one year is required for the soil moisture to reach its equilibrium. This implies that the initialization of these elements needs special care with a broader view.

3.3.2 Ten-Year Series of Ocean Data Assimilation

Decadal series of ocean data assimilation have been completed, using newly provided TOGA data with already existing data. Three kinds of assimilation systems are used. One version is based on the variational method (950) (this data set is referred to as RGM93); the second is a simple assimilation, in which the ocean temperature in the uppermost oceanic layer of a coupled model is nudged to the observed SST; and the third is also a nudging, in which not only the ocean temperature but also the surface wind are nudged to the observed SST and the wind of the NMC analysis, respectively.

Various aspects of assimilated analyses were compared with independent data or independently analyzed maps. In particular, the XBT (Expendable Bathythermograph) plots obtained by a special cruise across the western equatorial Pacific were used for the evaluation. The analyses of (528) and Gulf Stream monthly reports were also used for the comparison. Conclusions so far are that the full assimilation appears to be of the best quality, except that the meander of the Gulf Stream is somewhat distorted, and the current intensities in the tropics are weaker than those of the direct measurements.

The simpler data assimilations, based on the nudging methods, are not comparable in quality with the full assimilation, *i.e.,* RGM93. In particular, the temperature nudging analysis is quite deficient, probably because the coupled model does not produce accurate surface wind stress.

3.3.3 Data Assimilation of Altimeter Measurements

The altimeter data of GEOSAT (Geodetic Satellite) from January 1987 to December 1988 were processed and compared with the sea surface height obtained from the decadal assimilation data set, *i.e.*, RGM93 (3.3.2). Clear correspondence was noticed between the two anomaly components, but excellent agreement has not been obtained, the reason being obscure.

Meanwhile, in order to explore a method to assimilate the altimeter measurements into the ocean analysis system, an *identical twin test* was designed based on the RGM93 data set. First, this data set provides statistical relations between the surface pressure and the subsurface temperature distribution for different geographical locations. Secondly, utilizing these statistics, the pseudo-altimeter data are injected into the data assimilation for a one year period. This test gives a somewhat optimistic view of the utility of the altimeter data, but further investigation is definitely required. A more elaborate assimilation algorithm may be needed.

PLANS FY94

The initialization for seasonal forecasts should be pursued; this is a challenging issue. A more refined algorithm to assimilate the altimeter data will be developed. The ocean data assimilation will be repeated, using the higher resolution ocean model.

3.4 LONG-RANGE FORECAST EXPERIMENTS

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

ACTIVITIES FY93

3.4.1 Ensemble Forecast

The preliminary investigation reported in A92/P93 is still underway. This study is to utilize the *identical twin* approach, in which the true solution and the analysis error are perfectly known. Questions of interest are whether bifurcation exists in the ensemble forecasts and whether the density of the distribution yields a measure of predictability.

One of the difficult problems that must be solved before facing the main question is the initialization of the Monté Carlo perturbation. First, is the initialization necessary? Investigation shows that it is indeed necessary, otherwise the forecast ensemble does not cluster around the truth (*i.e.*, the truth is outside the ensemble clouds). Second, how can the initialization be achieved? This is the research which has been continued from FY92/93. The GFDL data assimilation technique is being investigated as the method of initialization. The forward continuous injection of full components of perturbation is a quite successful technique, as opposed to the nudging technique, or the non-linear normal mode initialization. But a difficulty is that the injection period is too short. In order to overcome this shortcoming, the forward-backward process should be adopted.

3.4.2 Feasibility of Seasonal Forecasts

The nine member ensemble simulations (3.2.1) were used to explore the feasibility of seasonal forecasts. The feasibility is assessed by the degree of consistency among the nine members which is measured by the ensemble spread.

Figure 3.1 is the global distribution of the normalized spread, *i.e.*, σ_n/σ_s (the ratio of standard deviations of nine members and of climatology), for the season of June-July-August, which is produced by the T30L18 model (*upper*) and by the higher resolution T42L18 model (*lower*). The basic features are very similar to each other, implying the high degree of credibility of the results.The low values for σ_n/σ_s in the equatorial Pacific indicate that the model's solution is highly reproducible among the nine simulations. The higher values in the extratropics are indicative of more chaotic behavior, *i.e.*, considerably more scatter within the ensemble. Although the results of the two model resolutions shown in Fig. 3.1 are qualitatively similar, closer examination shows that the T42 system has more regions of lower σ_n/σ_s extending into the extratropics than in the T30 system; the reason is unclear at this time.

One may look at the feasibility of seasonal prediction as a function of time in the extratropics. In this regard, the U.S. is chosen as an extratropical region of focus. A time series analysis of σ_n/σ_s for the U.S. region appears somewhat chaotic, however, occasionally the ensemble spread becomes noticeably small. Some of the motivation for investigating the time-dependent reproducibility over the U.S. comes from the areas of lower σ_n/σ_s values seen in Fig. 3.1. Another reason to expect some seasonal predictability over the U.S. is its close proximity to the El Niño region in the east equatorial Pacific (see Fig. 3.2). Also, with the U.S. being located just downstream of the Pacific, it is reasonable to expect periods when quasi-stationary PNA (Pacific-North American) patterns may dominate the atmospheric circulation features over much of the U.S. In fact, Lau and Nath (up) pointed out that notable spatial correspondence can be identified between the SST anomalies in the tropical Pacific and a PNA-type atmospheric mode. For these foregoing reasons, it should also be noted that the episodes of low reproducibility seen over the U.S. may provide an overly optimistic view of reproducibility throughout the extratropics in general.

3.4.3 ENSO Forecasts

Using the coupled model, an experiment consisting of 13 month forecasts was carried out for seven different years. The model's spatial resolutions are: T30L18 for the atmosphere and 1° x 1° L15 for the ocean. All cases start at 1 January of the respective years. The experiments indicate the initial conditions for the upper ocean are of primary importance for forecasts, particularly the ENSO prediction.

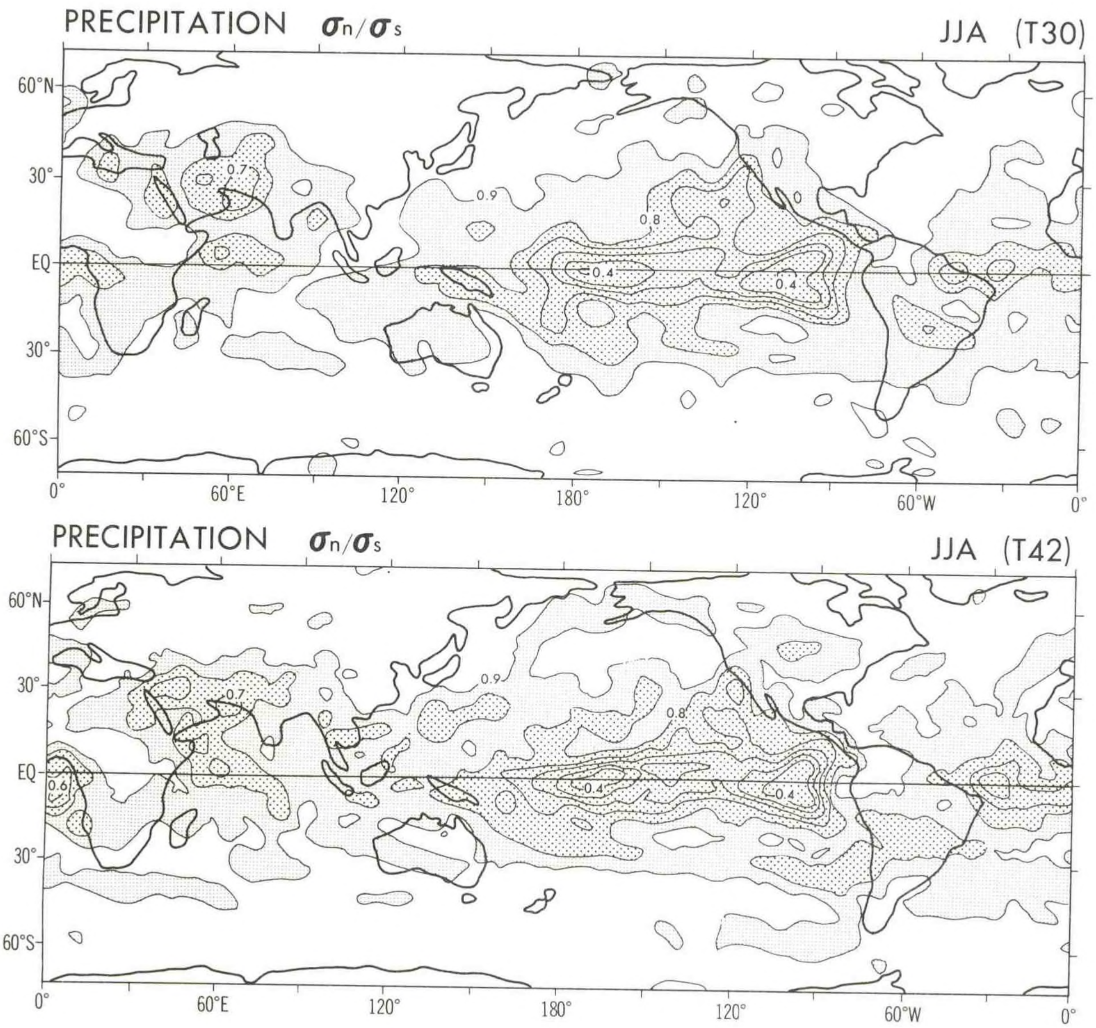


Fig. 3.1 Normalized spread (*i.e.*, reproducibility) of the rate of precipitation for June-July-August (JJA) obtained by T30 (*upper*) and by T42 (*lower*) spectral models.

In order to demonstrate the importance of the oceanic heat content distribution in the initial condition, two types of ocean data assimilation were used (3.3.2). One is a full-fledged data assimilation (F-DA), and the other is a simple data assimilation (S-DA), which uses temperature nudging. On the other hand, the atmospheric conditions are the same for both the F-DA and S-DA, which are taken from the NMC analyses.

The performance of predictions was assessed by the SST anomalies in the eastern equatorial Pacific (NINO 3) and also by the so-called ENSO index which is represented by the east-west gradient of 20°C isotherms along the equator.

The most remarkable results are that the forecasts of the F-DA perform well, producing the realistic ENSO index and SST anomalies, while the forecasts of the S-DA are not good; they fail in the forecasts of the ENSO index for three times out of seven cases.

Figure 3.2 shows an example of the two forecasts for the case of 1982/83 El Niño. The results are for a 13 month prognosis over the Pacific, starting from January 1982. The upper panels are the SST anomaly maps and the lower panels are the longitude-depth sections of ocean isotherms. The observation is at the left, the forecast for the F-DA is at the middle, and the forecast for the S-DA is at the right.

One of the striking aspects is that both the F-DA and S-DA forecasts do not produce a good annual cycle in the NINO 3 region. Yet the anomaly component of the SST forecast agrees well with observations. This point is consistent with the assertions of Cane and Zebiak (1985)[4], who have achieved success in forecasts with their anomaly model, and also agrees with Philander et al. (1077), who produced a realistic El Niño signature in their coupled model simulation without inclusion of the seasonal cycle.

PLANS FY94

Associated with the ensemble forecast, an adequate initialization technique will be developed. This technique, if successful, can be used also for the initialization of soil moisture and snow cover. Ensemble forecasts will be performed using about 300 members of perturbed initial conditions. As a reasonable way of stratifying the ensemble, two states of atmospheric circulation, *zonal flow* and *blocked* patterns, will be investigated.

---

4. Cane, M.A. and S. E. Zebiak, 1985: A theory for El Niño and the Southern Oscillation. Science, 228, 1084-1087.

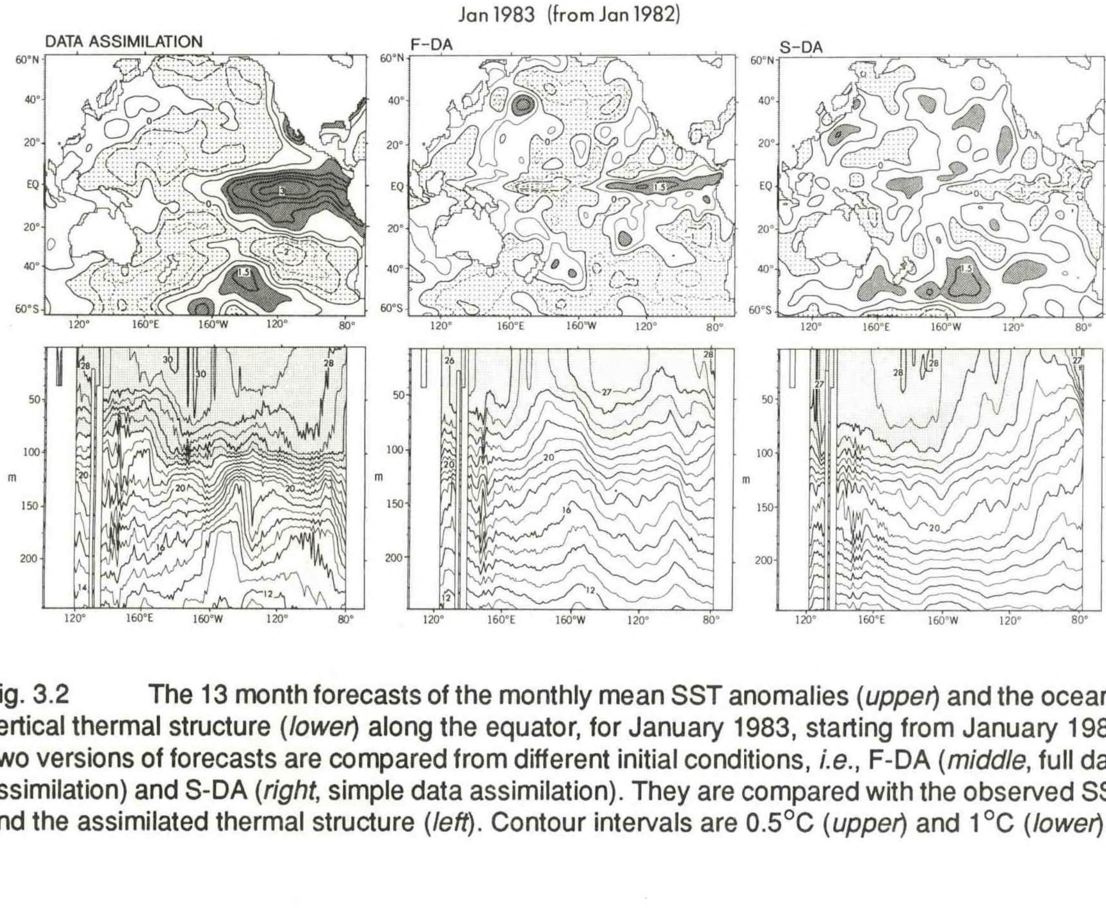


Fig. 3.2 The 13 month forecasts of the monthly mean SST anomalies (*upper*) and the oceanic vertical thermal structure (*lower*) along the equator, for January 1983, starting from January 1982. Two versions of forecasts are compared from different initial conditions, *i.e.*, F-DA (*middle*, full data assimilation) and S-DA (*right*, simple data assimilation). They are compared with the observed SST and the assimilated thermal structure (*left*). Contour intervals are 0.5°C (*upper*) and 1°C (*lower*).

The nine decadal runs with the T42L18 model will be analyzed, and reproducibility will be studied. Comparison of the model's drought index with the observations over the U.S. will be carried out further. The revised 40 year SST data set is expected to be supplied by the U.K. Meteorological Office (Mr. C.K. Folland). Using this data, a 40 year simulation will be started.

Seasonal forecasts using the coupled model will be made, exploring the effects of vertical resolution as well as the isotropy and homogeneity of the grid of the ocean model (see 3.2.3).

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

K. Dixon
L. Goddard
D. Gu
D.-M. Hu
N.-C. Lau
T. Li
Z. Liu
R.C. Pacanowski
S.G.H. Philander
A. Rosati
S. Xie

ACTIVITIES FY93

Interactions between the ocean and atmosphere influence various interrelated aspects of the Earth's climate: its time-mean state, its interannual variability, and its response to seasonal variations in solar radiation. Because of the interrelations it is not possible for a model to simulate (or predict) the interannual climate fluctuations such as the Southern Oscillation unless it reproduces the mean state and the seasonal cycle realistically. For an understanding of these various phenomena, it is invaluable to have information about the structure of the modes of oscillation that are possible because of interactions between the ocean and atmosphere. The phenomenon that has received the most attention thus far, the Southern Oscillation, corresponds to particularly unstable coupled modes. They appear spontaneously, and the Southern Oscillation is simulated realistically in a coupled model developed at GFDL when the forcing is the steady, annual mean solar radiation. Simulations of the response to seasonally varying solar radiation are proving more difficult. The following studies have been initiated to overcome this problem.

4.1.1 Climatic Asymmetries Relative to the Equator

Ocean-atmosphere modes that are antisymmetrical about the equator are likely to play a prominent role in the seasonal cycle and in climatic asymmetries relative to the equator. These asymmetries include the appearance of the ITCZ (Intertropical Convergence Zone), and the occurrence of the warmest surface waters north of the equator in the eastern tropical Pacific and Atlantic Oceans even though the annual mean solar radiation is nearly symmetrical about the equator. Relatively simple coupled ocean-atmosphere models are being used to explore antisymmetrical modes. (Studies related to El Niño have thus far focused strictly on symmetrical modes.) The crucial feedbacks are between the winds and the SST. Southerly winds that converge onto an ITCZ in the northern hemisphere create a sea surface temperature pattern - warm north of and cold south of the equator - that keeps the ITCZ north of the equator, thus ensuring southerly winds. One of the processes that makes this possible is wind-stirring in the surface layers of the ocean. The winds that converge onto the ITCZ are weak at the ITCZ but are intense elsewhere, so that the absence of wind stirring under the ITCZ keeps temperatures there high. Upwelling because of divergent surface currents south of the equator also contributes to low SST at and south of the equator. These oceanic processes create an SST pattern that keeps the ITCZ in its off-equatorial position, if it is there initially. The antisymmetrical ocean-atmosphere modes that exist because of the feedbacks between wind and SST are most unstable at zero (real) frequency. In other words, they amplify but do not oscillate and thus influence the mean state and the seasonal cycle.

The results described thus far imply that a very modest perturbation to perfectly symmetrical conditions can result in stable asymmetrical conditions which favor either hemisphere. In reality the Northern Hemisphere is favored as the warm one with the ITCZ. Why not the Southern Hemisphere? The answer must involve the distribution of land masses and the details of coastal geometry. In order to answer this question, atmospheric and oceanic GCMs are being coupled for use in experiments in which the shapes of the continents are modified. In all of these calculations, the forcing is a time-mean solar radiation which is symmetrical about the equator. The very first calculations are with an R30 atmospheric GCM with specified sea surface temperatures that are a function of latitude only. The temperatures are symmetrical about the equator and correspond to the temperatures observed along the date line. For realistic continents, the time-mean atmospheric response (surface winds, ITCZ location, etc.) is realistic. Next, when the Pacific is bounded by coasts that run north-south, the winds are symmetrical about the equator. However, when the eastern boundary (the western coast of the Americas) is inclined to a meridian (in approximation of reality), the southeast Trades parallel to this coast penetrate into the Northern Hemisphere, the northeast Trades veer offshore well to the north of the equator, and there is a definite asymmetry about the equator. The key to these results is the atmospheric response to the temperature difference between the land and ocean. Far from the equator it generates alongshore geostrophic winds. When the coast is north-south, these winds veer off-shore near the equator and become the Trades. When the coast is inclined, the southeast Trades do not veer off-shore until they have practically crossed the equator.

Preliminary results with coupled GCMs show that ocean-atmosphere interactions intensify the equatorial asymmetries just described, because of the processes mentioned earlier. The presence of interannual variability means that these integrations have to be continued for a considerable time to obtain a stable time-mean.

4.1.2 Simulation of the Seasonal Cycle with Coupled GCMs

The coupled GCMs that simulate a realistic Southern Oscillation when forced with annual mean solar radiation have been modified by expanding the oceanic component from a high resolution *tropical Pacific* model to a high resolution model of the *global tropics* with a realistic western Pacific geometry that permits flow into the Indian Ocean. The resolution of the atmospheric component has been increased from R15 to R30 (A92/P93). When forced with seasonally varying solar radiation, the coupled model runs into considerable difficulties, but matters are improving steadily.

The first problem with the coupled model simulations was enormous climate drift. (Surprisingly, the model behaves well when forced with time-mean radiation, however, the addition of seasonal variations that do not change the time-mean creates problems.) This problem has been remedied by changing the cloud parameterization (in collaboration with S. Manabe) and by allowing short wave radiation to penetrate into the ocean to a depth of approximately 50 m. The simulations are now reasonably realistic, except in the eastern tropical Pacific where SSTs are too high, especially off the coast of Peru towards the end of the southern summer. They are sufficiently high for the ITCZ to cross the equator seasonally, the way it does in the western Pacific.

Part of the problem in simulating SST is the treatment of the Andes mountains. The atmospheric model is spectral and a Gibbs' phenomenon causes tall, narrow mountains to ripple onto the adjacent ocean, so that winds near the coast are weak where they ought to be strong. Improved filters and other tricks are being devised to reduce this effect. Another problem is the poor treatment of low stratus clouds in the model which can significantly reduce radiation into the ocean, lowering SSTs, a condition that favors more stratus. These results have been compared with those from modeling groups at UCLA (Arakawa, Mechoso) and NASA (Schopf and Suarez). The UCLA and NASA models, which are quite different from those used here, have been improved by making very different changes (in the radiation scheme for example) and have brought them to a stage where they have problems similar to ours: SST that is too high off Peru and California. These comparisons, which thus far have led to the conclusion that the treatment of stratus clouds is a problem in all these models, will be continued. Although there are numerous studies of cumulus clouds and their relation to SST, little attention has been paid to stratus clouds, a topic of considerable interest to EPOCS (Equatorial Pacific Ocean Climate Studies).

4.1.3 Secular Changes of Seasonal and Interannual Variability during the Past Century

Wavelet transform methods have been used to analyze the COADS (Comprehensive Ocean Atmosphere Data Set) for the period 1870 to 1988. Energy at periods of 3 to 5 years (associated with El Niño) was high early in this century and during the past few decades, but was small between approximately 1915 and 1950. The intensity of the Trade winds over the equatorial Pacific show a similar variation and was low when the amplitudes of El Niño episodes were small. Surprisingly, the amplitude of the annual cycle in the eastern equatorial Pacific did not vary significantly during this period. On short time scales of three to five years, however, the amplitude of the annual cycle is significantly smaller during El Niño than during La Niña. The latter variation is due to variations in the depth of the thermocline in the eastern tropical Pacific.

4.1.4 Tropical-Subtropical Exchanges

The mean depth of the tropical thermocline profoundly influences the amplitude of seasonal and interannual variability in the tropics, but which factors determine that depth? Models of the tropical oceans simply specify the depth of the thermocline and calculate how its topography changes because of a redistribution of warm surface waters in response to changes in the wind. Since the depth of the thermocline depends on more than just conditions in the tropics, a model to investigate this matter needs to extend at least into the subtropics. Such an oceanic GCM has been used to determine how the tropical and subtropical circulations are linked and how subtropical winds affect the tropical thermocline. One of the principal results is that the northeastern side of an ocean basin has the strongest links to the tropics. Water that subducts there flows southwestward until it joins the Equatorial Undercurrent, either directly or via a deep western boundary current. Equatorial upwelling brings the water to the surface and poleward Ekman drift returns it to the subtropics. The subtropical winds, although they do not significantly influence the transport of the Undercurrent, affect the structure of the lower thermocline and indirectly the magnitude of seasonal and interannual variability in the tropics.

4.1.5 GFDL Modular Ocean Model Development

In collaboration with Rick Smith at Los Alamos (CHAMMP (Computer Hardware, Advanced Mathematics and Model Physics project) program), a rigid lid surface pressure option and an implicit free surface option have been added to MOM (Modular Ocean Model). The free surface option adds an important ability to model the hydrological cycle more accurately, and can include an unlimited number of islands without decreasing the efficiency of the model.

In a separate development, a global isopycnal model has been worked out for the B-grid with a free surface.

PLANS FY94

The goal of research during the coming year is to explore further aspects of seasonal and interannual climate variability with a variety of coupled models including coupled GCMs. The structure of the annual and semi-annual harmonics of the seasonal cycle will be studied by means of a variety of coupled ocean-atmosphere models. Efforts to reproduce a realistic simulation of the seasonal and interannual variability with coupled GCMs will focus on the problems being encountered in the eastern tropical Pacific where simulations produce SST which is too high. The role of stratus clouds in particular will receive attention.

Testing of new options for MOM will continue along with further exploration into methods which will lead to an optimal modular structure for the code, including modification for massively parallel processor (MPP) computers.

The performance of the isopycnal model will be compared with a global version of MOM.

4.2 WORLD OCEAN STUDIES

4.2.1 Nutrient Dynamics in the Tropical Ocean

S. Carson *J.R. Toggweiler*

ACTIVITIES FY93

A simple ecosystem model (1155, rx) has been coupled with a high-resolution model of the tropical oceans (758) to study the dynamics of nutrient cycling. The goal is to use the ecosystem model to simulate both the uptake of nitrate by organisms in the upper euphotic layers of the tropical ocean and the remineralization of sinking detrital particles below the euphotic zone. The physical model can then be used to study the ways in which inorganic nitrate is introduced to the upper euphotic layers and the ways in which remineralized nitrate returns to the upper ocean again. This project was initiated as part of the JGOFS (Joint Global Ocean Flux Study) Equatorial Pacific Process Study, the field phase of which was just completed in 1992. It has been carried out in collaboration with NOAA scientists at AOML (Atlantic Oceanographic Meteorological Laboratory) and PMEL (Pacific Marine Environmental Laboratory).

The model is initialized with a three-dimensional field of nitrate mapped from seasonally averaged observations (984). Nitrate is taken up by model "phytoplankton" and is distributed among five other compartments: zooplankton, bacteria, sinking detritus, ammonia, and dissolved organic nitrogen. When forced with a climatological seasonal cycle in wind stress and surface heating, the ecosystem variables settle into a repeatable seasonal cycle after only two years. When forced with observed monthly mean winds from the 1980s, the model simulates the rise and fall of nitrate levels during the course of two ENSO (El Niño Southern Oscillation) cycles.

Figure 4.1 shows current vectors in the meridional, vertical plane along 140°W longitude (top) along with the predicted nitrate distribution for a climatological July (bottom). The equator is a zone of intense upwelling which brings subsurface nitrate to the surface. The model successfully predicts surface levels of nitrate at this longitude (6-8 micromoles per liter). Analysis of the three-dimensional nitrate flow field shows that virtually all the upwelled nitrate comes from the Equatorial Undercurrent, which flows across the section toward the east between 100 and 150 m. There is virtually no input of nitrate from below the Undercurrent. Subsurface equatorward flows between 50 and 100 m contribute strongly to the total mass of upwelled water, but contribute very little nitrate. The equatorward subsurface flow south of the equator converges on the equator from beyond 5°S and actually dilutes higher nitrate water upwelling from the Undercurrent.

PLANS FY94

A simulation is planned for the fall and spring JGOFS field seasons when forcing fields (wind stress and surface heating) are available for 1992. This will allow for a comparison of model results against a complete suite of field measurements characterizing biological standing stocks, primary production, grazing rates, bacterial production, and sinking particle fluxes. A second goal is to introduce a set of model compartments for carbon. With combined nitrogen and carbon compartments, the model will be able to predict the surface distribution of pCO_2 and the equatorial outgassing of CO_2. These results can be validated against a large set of CO_2 measurements made during the JGOFS field study.

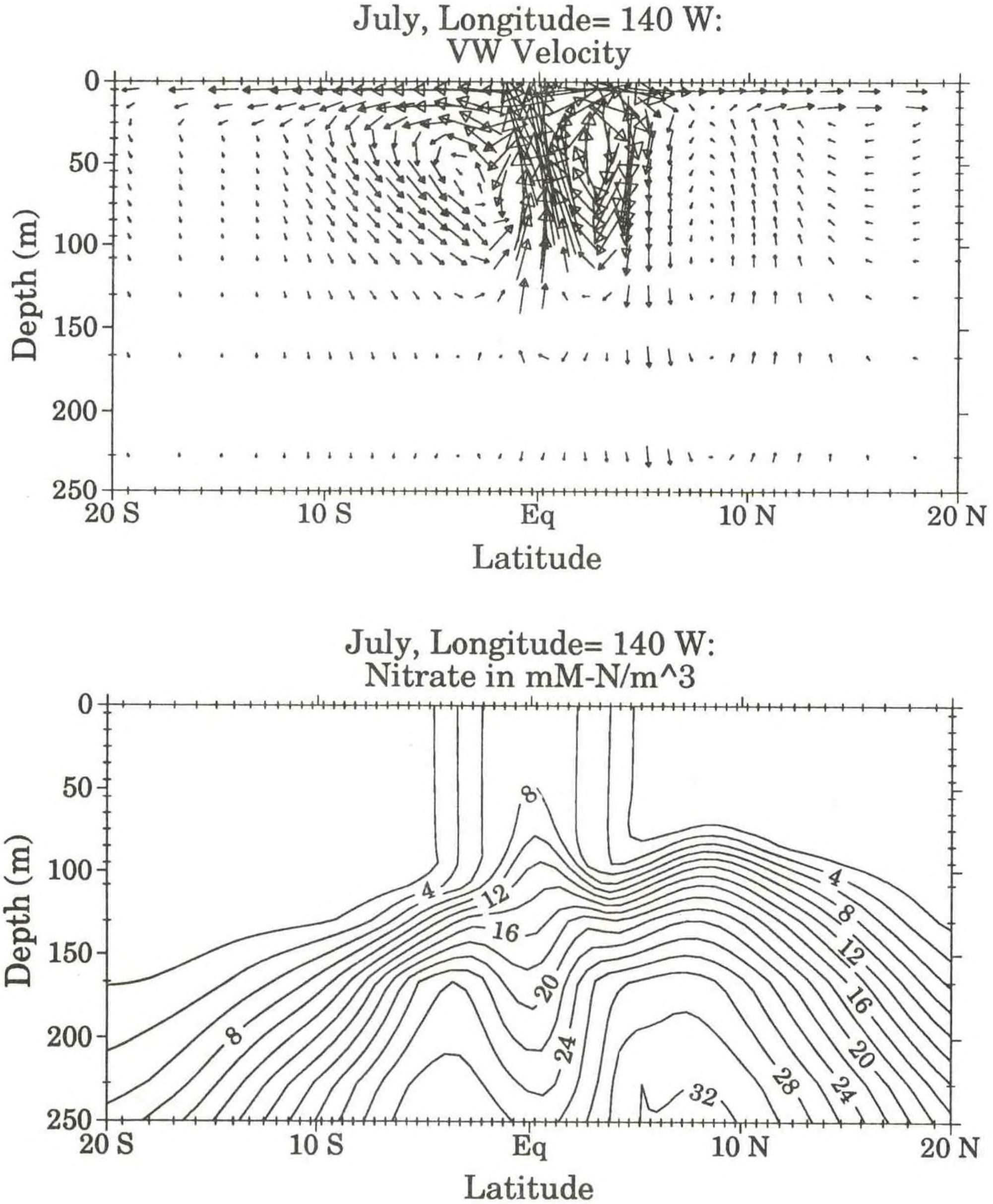


Fig. 4.1 V,W flow field (*top*) and predicted nitrate concentrations (*bottom*) along 140°W for climatological July conditions from a circulation model of the tropical Pacific with an embedded ecosystem model. The main source of upwelled nitrate is the Equatorial Undercurrent flowing eastward, out of the page, between 100 and 150 m.

4.2.2 Water Masses and Thermohaline Circulation

K. Bryan *B. Samuels*
A. Rosati *J.R. Toggweiler*

The ocean general circulation models currently coupled to atmospheric GCMs typically have a resolution of 4° latitude by 4° longitude with 10-15 vertical levels. Ocean circulation fields produced at this resolution are limited by topography fields which lack important features (mid-ocean ridges, narrow passages, sills and islands). These models also tend to be very diffusive. During the past year, the ocean group has set up a world ocean model with a horizontal resolution of 1° by 1° with 60 vertical levels. It is expected that this 1° model, or some derivative, should be the workhorse of coupled ocean-atmosphere climate studies 5 or 10 years from now. The 1° model requires about 18 hours of a single Cray processor per year of simulation.

Thus far the 1° model has been run out for several short 14-year experiments. These model runs have been compared with thousand-year integrations of the existing 4° models and a 2.5°, 30 level model set up several years ago. Each of the 1° experiments was initialized with the observed temperature and salinity distributions and was run out with only its surface temperature salinities restored to observations.

During the early spin-up phase (years 1 and 2), the model maintains a vigorous thermohaline overturning in all three ocean basins. However, the vigorous overturning soon begins to run down as the integration proceeds. The decline is especially sharp in the Atlantic basin. The main cause of the decline appears to be the lack of a dense overflow across the sills isolating the Norwegian and Greenland Seas from the North Atlantic. The model, as presently configured, does not generate the flow of cold dense water through the narrow passage between Greenland and Iceland (Denmark Strait) which maintains the density of North Atlantic Deep Water. It has been found that making the Norwegian/Greenland Sea water denser by modifying the local temperature and salinity boundary conditions does not seem to make much difference. The main resistance seems to involve the dynamics of the overflow itself.

In examining older low-resolution models, it was found that the thermohaline overturning in the North Atlantic returns if a model is run for 100 years or more. However, the main source of deep water in these longer integrations is an overflow originating in the easternmost part of the Norwegian Sea, *i.e.*, off the coast of Norway. The water in this sector of the Norwegian Sea is much warmer and less dense than the Denmark Straits overflow. It seems that a vigorous thermohaline overturning can be re-initiated with this type of overflow only after the North Atlantic has warmed by several degrees.

PLANS FY94

Previous attempts to generate realistic global-scale thermohaline circulations in high-resolution models have avoided the North Atlantic overflow issue by terminating the North Atlantic at the latitude of Iceland. Restoring temperatures and salinities adjacent to the northern wall toward subsurface observations is used to generate the dense water which fills the deep Atlantic. If the goal is to use a model as part of an interactive ocean/atmosphere system, restoring at depths below the surface is no solution for model deficiencies.

Careful analysis is planned of the results from the whole suite of models in order to understand why one system of overflows works (*i.e.*, the overflows off Norway) and one system does not (*i.e.*, the overflows over Denmark Strait). Having narrowed the problem to dynamical issues, it should be possible to find a physically correct solution to the overflow problem. Reproducing the kind of Denmark Strait overflow which actually occurs in nature may require that one resolve an explicit boundary layer which is simply not possible at 1° resolution.

4.2.3 High Resolution North Atlantic/Arctic Ocean Studies

K. Bryan *W. Hurlin*

ACTIVITIES FY93

A North Atlantic/Arctic ocean configuration of MOM has been constructed to conduct studies of the North Atlantic Western Boundary Currents from the Gulf Stream separation off of North America in the south to the Greenland Currents in the north. To avoid possible distortions in model solutions, due to filtering at high latitudes necessitated by the convergence of meridians at the pole, the model grid is a rotated Mercator projection. A 1° version of the model is designed to contrast sector model solutions of the North Atlantic to the 1° global solutions (4.2.2). These dual experiments will provide insight into the effects of the sector model southern boundary on the model solution, in particular the thermohaline circulation. Another goal is to glean information as to how the strength of the modeled thermohaline circulation affects the interaction of the different western boundary currents. Further, does numerical filtering of model fields significantly distort the Arctic solution and, if so, does this distortion affect the Denmark Strait overflow and the thermohaline circulation?

A variable high resolution version (up to 10 km x 10 km) of this same model has been constructed to study in detail the dynamics of the western boundary currents with physics more suitable to an eddy resolving model. The nature of the coordinate rotation allows the western boundary region to be covered by a much narrower region of high resolution than would be obtainable with a traditional grid projection. The premise here is that strong topographical gradients are important for steering the western boundary currents, and high resolution is necessary to capture them. Current experiments involve parameter tests to gain understanding of the implications of the wide range in grid spacings used in this model.

PLANS FY94

Implementation of open boundary conditions is planned for the 1° model so that control can be exerted over the intensity of the thermohaline circulation. The time and spatial influences of the southern boundary on the North Atlantic solution will be investigated. In addition, various surface boundary condition experiments involving the use of stochastic forcing are anticipated. Knowledge gained from these experiments will be applied to the high resolution model. After final adjustments are made in the model setup, a detailed look into the dynamics of the western boundary currents in the Grand Banks region will be made.

4.3 GLOBAL SEA LEVEL STUDIES

4.3.1 Water Masses and Carbon Cycle

K. Bryan *S. Griffies*
K. Dixon

ACTIVITIES FY93

Two studies of sea level rise have been completed (tm, vg). The first study analyzes the sea level rise associated with enhanced greenhouse warming. The results of a coupled ocean-atmosphere model (1042) developed by GFDL for global change studies were used to determine the sea level rise due to thermal expansion of the ocean in response to an enhanced greenhouse warming equivalent to an increase of atmospheric carbon dioxide of 1% per year. The model indicates a rise of about 10 cm at the time of carbon dioxide doubling. When corrected for a downward drift in sea level of the control run, this amounts to 15 cm. This study shows how large scale internal waves in the ocean redistribute heat within the ocean, causing a nearly uniform sea level rise in response to an anomalous heat input which is largely at high latitudes.

Retrospective studies of the global ocean for the period 1888-1988 predict the sea level rise over the past century due to the observed increase of sea surface temperature. In this preliminary study, the ocean circulation is assumed to remain stationary and temperature anomalies generated at the surface are allowed to penetrate into the deep ocean as passive tracers. The observed globally averaged temperature anomaly and the sea level rise predicted in this study are shown in Fig. 4.2. Also shown are two estimates of total sea level rise derived from tide gauge data. Since the total rise is due to combined effects of thermal expansion and the melting of glaciers, the thermal expansion effect should be less than that indicated by tide gauges.

PLANS FY94

Coupled atmosphere-ocean runs with the low resolution GFDL climate model will be used to assess the predictability of high latitude, ultra low frequency air-sea interaction. The aim is to estimate the accuracy of ocean data needed to predict long term fluctuations of the Atlantic thermohaline circulation, believed to be closely linked with sea surface temperature anomalies in the Northwest Atlantic.

4.4 COASTAL OCEAN MODELING AND DATA ASSIMILATION

4.4.1 Model Development

T. Ezer *G.L. Mellor*

ACTIVITIES FY93

The Princeton Ocean Model (POM) is a free-surface, three-dimensional, primitive equation model with a bottom following, sigma coordinate system in the vertical and a coastal following curvilinear coordinate system in the horizontal. A user's group, established in FY91, now includes about 100 users who are connected for information and code exchange through the GFDL server. Some of the efforts during FY93 involved improvements in the POM code, and the conversion of the code to a massive parallel architecture; the model has been run successfully on the connection machines CM2 and CM5. Due to a recent concern in the ocean modeling community of the possible errors in the pressure gradient term of sigma coordinate models over steep topography, a study aimed at the evaluation of this problem has been completed (uz). This study shows that most of the errors are removed by the subtraction of the area mean density field, and that the circulation in a coarse resolution North Atlantic sigma model is almost identical to the results obtained when pressure gradient terms are evaluated on z-level coordinates.

Studies that have been started in previous years and are now being completed include modeling of instabilities of the western boundary current along the South Atlantic Bight (uz), modeling the Mediterranean Sea (uy), and modeling the Arctic Ocean (1161).

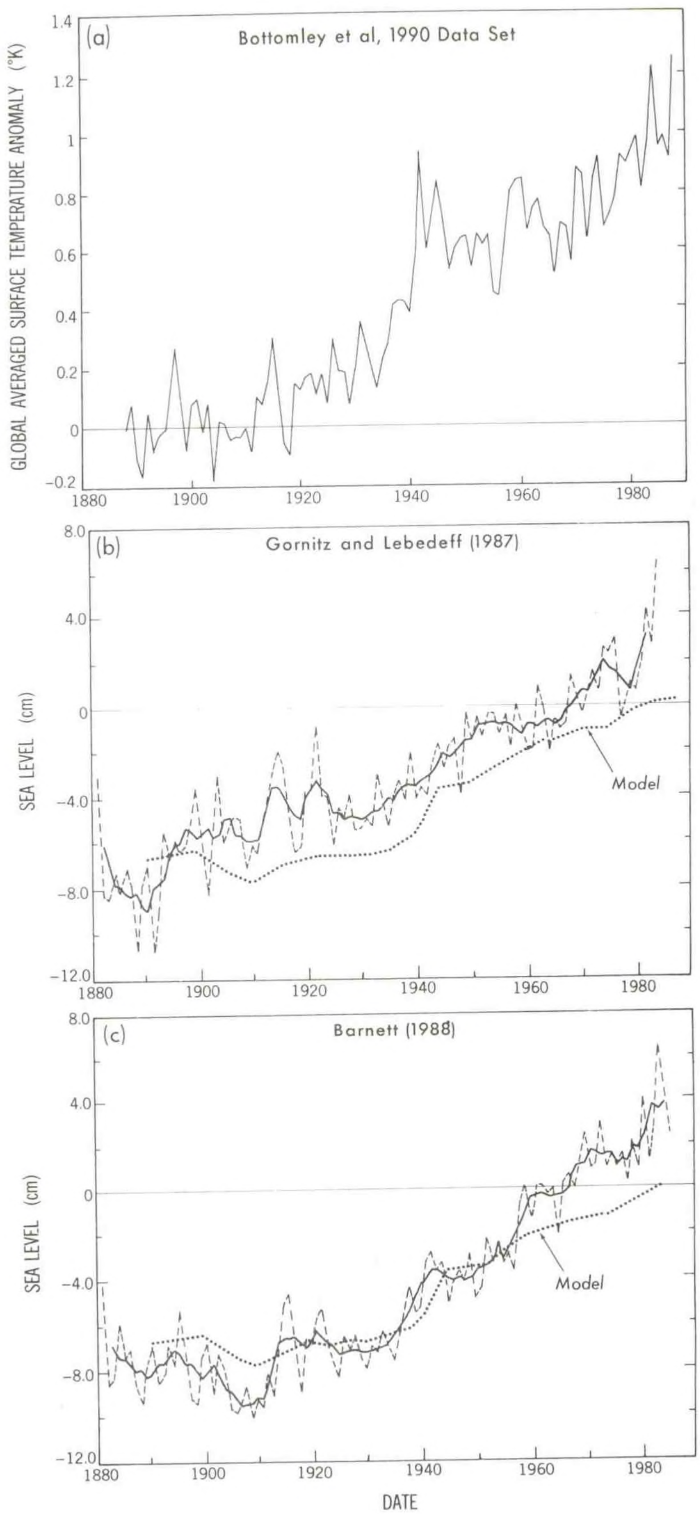


Fig. 4.2 (a) Globally averaged sea surface temperature rise from the British Meteorological Office/Mass. Inst. Tech. sea surface data set. (b) Estimated sea level rise from tide gauges by Gornitz and Lebedeff (1987) dashed and solid. Sea level rise predicted by the GFDL model (dotted line).(c) same as (b) but for the estimate of Barnett (1988). See "Climate Change: The IPCC Scientific Assessment", edited by J.T. Houghton, G.J.Jenkins and J.J. Ephraums, Cambridge Univ. Press,1990, for references.

Most of the effort during FY93 focuses on modeling and data assimilation studies in the Gulf Stream region. This work, begun in FY91 (1044), and FY92 (1092, 1104, sc), has continued with experiments which test the data assimilation scheme, previously used only with simulated data (1044), with real altimetry and SST data (uw, va). These studies demonstrate that a realistic high resolution regional ocean model and an efficient data assimilation scheme can provide useful nowcast and forecast information.

PLANS FY94

Work will continue on the Gulf Stream model and data assimilation with additional emphasis on evaluating the capability of the model to serve as a base for an operational forecast system for the U.S. east coast. Also, the feasibility of extending the data assimilation scheme to the entire North Atlantic Ocean and to model coastal sea level variability associated with ocean circulation and climatic changes will be evaluated.

4.4.2 Development of a Coastal Forecast System for the East Coast

T. Ezer *G.L. Mellor*

ACTIVITIES FY93

This project, started in FY93, is a cooperative effort between Princeton University, GFDL, the National Meteorological Center (NOAA/NMC), and the National Ocean Service (NOAA/NOS). At its initial stage, the feasibility of developing a real-time Coastal Forecast System (CFS) will be evaluated for the first time. The Princeton Ocean Model will be coupled (at first only in a one-way interaction) to NMC's ETA atmospheric model, in order to provide nowcast and forecast information (*e.g.*, storm surge) of the coastal ocean. Tide gauge measurements along the U.S. east coast will be used to test the skill of the forecast system. The experimental system has been implemented in an operational environment at NMC with a similar system operated at Princeton/GFDL for scientific and developmental purposes.

PLANS FY94

In addition to the heat and momentum surface fluxes now included in the forecast system, buoyant fluxes (including river runoffs) and tidal forcing will be added. In the future, regional estuarine and bay models will be connected to the system.

4.4.3 North Atlantic and Arctic Ocean Modeling

T. Ezer *G.L. Mellor*

ACTIVITIES FY93

This project is done in cooperation with S. Hakkinen (Goddard/NASA), under the support of the climate change program. Previous use of the POM model has been mostly for coastal and estuarine applications. However, recently it has been used for basin-scale problems. In particular, models of the Arctic Ocean, including the sea-ice interaction (1161), and a model of the North Atlantic Ocean (va) are being tested. The Atlantic model has been used for diagnostic and prognostic calculations aimed at the calculation of the ocean circulation and coastal sea level obtained from observed hydrography and surface wind stress. Model results show that the general circulation obtained from the 3-D model (running in a diagnostic mode) are in fair agreement with those obtained by a simpler diagnostic model (Fig. 4.3). However, model dynamics is used to filter the observed data so density fields are dynamically adjusted to wind stress and bottom topography. Moreover, areas of complicated topography and coastal regions that could not be resolved in previous studies are now included in the calculations.

PLANS FY94

The Arctic and the Atlantic models will be connected in order to study climate problems such as the long-term fluctuations of the North Atlantic Ocean.

4.5 OCEAN CIRCULATION AND CHEMISTRY

4.5.1 Carbon System

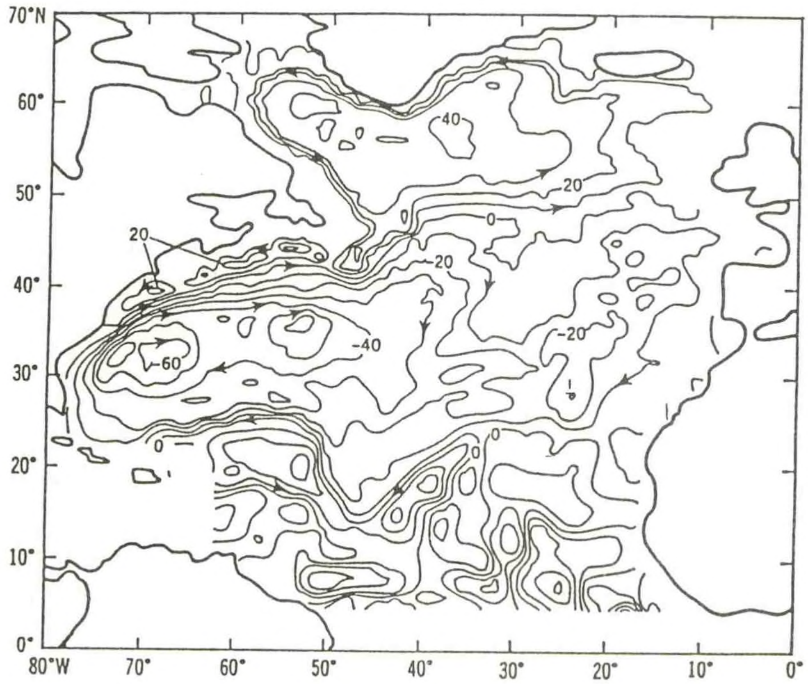
4.5.1.1 Anthropogenic CO_2 Budget

C. LeQuere *P. Rayner*
J. Olszewski *J. Sarmiento*
S. Pacala *U. Siegenthaler **

** University of Bern, Bern, Switzerland*

ACTIVITIES FY93

The uptake of anthropogenic carbon by the ocean for the industrial period was simulated using an ocean general circulation model coupled with different versions of a perturbation model of the carbon cycle (1084), and with models which include the



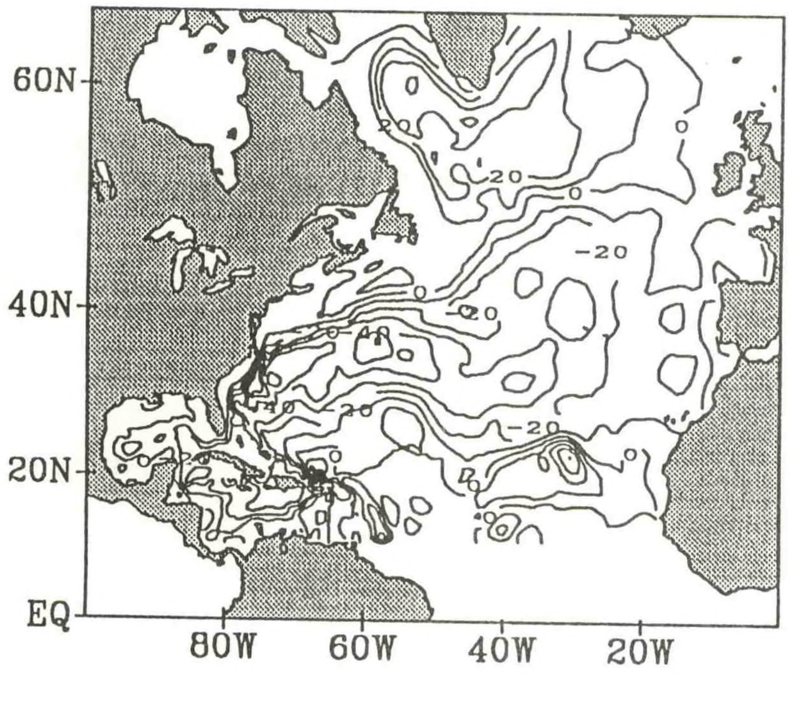


Fig. 4.3 Diagnostic calculation of the vertically integrated horizontal transport of the North Atlantic, derived from the Levitus climatology and annual wind stress. Top: from the simple diagnostic model of Mellor et al. (1982); bottom: from the 3-D sigma coordinate ocean model. Units are Sverdrups (1 Sv = 10^6 m^3 s^{-1}).

natural cycle of carbon resulting from the solubility pump only, and biology plus solubility pumps (4.5.2). The robustness of the models to gas exchange, carbonate equilibrium constants, differencing schemes, and model physics was evaluated. Except for the differencing scheme, the uptake of carbon by the models was little affected by the choice of parameters. Using an upstream differencing scheme, however, led to an 18% increase uptake of carbon by the ocean over the usual centered differencing scheme. A 10% uptake difference between the perturbation model and the solubility model remains. It is thought that this difference will disappear when a $CaCO_3$ pump is included, because the surface alkalinity will then be reached. There is no significant change in uptake of carbon between the solubility model and the biology plus solubility model. Progress in understanding the ocean carbon cycle contributed by these and previous studies has been reviewed (1165, ug).

Simulations of the oceanic contribution to various scenarios for the future carbon cycle are being carried out in support of the preparation of the 1995 Intergovernmental Panel on Climate Change assessment.

An atmospheric CO_2 transport inversion study has been performed using a three-dimensional tracer transport model developed by the Middle Atmosphere Dynamics and Chemistry group. The results of this model and of our ocean models have been used to estimate the spatial distribution of terrestrial anthropogenic CO_2 sources minus sinks (4.5.3).

A study of the carbon-13 cycle in the ocean was initiated. Atmospheric $\delta^{13}C$ decreased constantly since the beginning of the industrial era, but its decrease has accelerated in the last 30 years. Quay et al. (1992)[1] developed the idea of using this tracer as a constraint to the uptake of carbon by the ocean. They analyzed new Pacific $\delta^{13}C$ data from 1990 and compared them with data of the same stations from 1970. Quay et al. estimated the total change of $\delta^{13}C$ to be 208 ‰ m for these twenty years, linking this value to an uptake of 2.1 Pg of carbon per year. The total change of $\delta^{13}C$ computed using our biology plus solubility carbon model is just over 60% of this, while the carbon uptake for the same model is greater than their resulting value. Similar calculations done by F. Joos (personal communication) and J.C. Orr (personal communication) gave results far less than Quay et al.'s estimate as well. More analysis is being done to explain this discrepancy.

PLANS FY94

The sensitivity studies of uptake of carbon by the ocean for the industrial period will be continued. A complete model of the carbon cycle including the solubility,

---

1. Quay, P.D., B. Tilbrook, C.S. Wong, 1992: Oceanic uptake of Fossil Fuel CO_2: Carbon-13 Evidence. Science, 256, 74-79.

biological and $CaCO_3$ pumps will be used in an effort to bring together different results so far obtained using a perturbation model of carbon and a biology plus solubility pump model.

A project is being initiated in collaboration with the Climate Dynamics group to calculate oceanic uptake of anthropogenic CO_2 in a coupled air-sea model of the climate response to increased atmospheric CO_2. This model shows a very large response of the ocean circulation to climate warming. It is expected that this might have a large impact on oceanic uptake of anthropogenic CO_2.

4.5.2 Ocean Carbon Cycle

L. Anderson	*G. Hurtt*
R. Armstrong	*R. Murnane*
M. Bacon	*S. Pacala*
R.F. Bryan *	*J.L. Sarmiento*
M. Fasham **	*R. Slater*

* *National Center for Atmospheric Research*
** *Institute of Ocean Sciences, Wormely, UK*

ACTIVITIES FY93

Photosynthetic uptake plays a major role in determining the distribution of carbon in the ocean. Work is continuing on using a nitrogen-based ecosystem model to generate predictions of biological productivity and the effects of this biological activity on the carbon cycle. Analysis of the ecosystem model of nitrogen cycling in the North Atlantic has been completed (1155, 1166). Work has been initiated on coupling a carbon-nitrogen ecosystem model into a global circulation ocean model.

Three new research avenues are being pursued: (1) improving the basic structure of the ecosystem model; (2) improving parameter estimates for use in this model; and (3) testing model predictions against satellite chlorophyll estimates. A new nitrogen-based ecosystem model with multiple size classes of phytoplankton and zooplankton has been developed (tc) and implemented in the GCM. Preliminary results show marked differences between the behavior of the new model and that of the standard model with single phytoplankton and zooplankton species. The new model, for example, removes all nitrate from the mixed layer during the summer at high latitudes in the North Atlantic, while the old model shows only slowly decreasing nitrate during this period.

Second, we have been using a simulated annealing technique to estimate ecosystem model parameters from Joint Global Ocean Flux Study Bermuda Atlantic

Time Series (BATS) data. These studies will be continued using other time series data from Ocean Weathership Station India and the subarctic Pacific in search of a unified set of parameters that can be used at all locations.

Finally, work has continued on assimilating satellite ocean color data into the GCM, and have begun to investigate alternative ways to compare satellite data to model output. In particular, ways are being sought to "line up" the model output geographically with the satellite imagery. This alignment is needed because, while the physical GCM gets most large-scale structures (the existence of a gyre and a Gulf Stream) right, these are often not in the right place geographically. The alignment will ensure that ocean color data are assimilated into an appropriate place in the GCM.

Most of the carbon removed by photosynthesis in the surface ocean is remineralized in the deep ocean or sediments. Three models of the carbon cycle are being used to assess the effects on the distribution of dissolved carbon in the deep ocean of: (a) the temperature and salinity dependence of the equilibrium constants affecting carbon chemistry (the solubility pump); (b) the cycling of organic carbon (the biological pump); and (c) the cycling of calcium carbonate. Most of the surface to deep ocean increase in dissolved inorganic carbon (DIC) is a result of the cycling of organic carbon. These models, which include $\delta^{13}C$ as well, are being used in simulations of oceanic uptake of anthropogenic CO_2 (4.5.1) as well as estimating its missing sink (4.5.3).

An important part of the strategy for modeling the cycling of organic matter is the potential to key the cycling of carbon by organisms to the cycling of major nutrients, nitrate and phosphate, through the use of Redfield ratios. A major data analysis and modeling study of the actual magnitude of the Redfield ratio of remineralization in the deep ocean has recently been completed (1117, vk).

Inverse techniques were used to determine the rates of particle aggregation and disaggregation during the North Atlantic Bloom using data from JGOFS (rv, vl). The results indicate that particle cycling rates increase dramatically through the course of the bloom. The cause of the increase is not known.

PLANS FY94

The multiple chain ecosystem model development will be continued using the parameter estimation approach. The model will be placed in the ocean GCM.

Work on assimilating satellite color data will be continued.

Work on placing the carbon-nitrogen model into global circulation model will continue.

Simulations of the oceanic cycling of carbon will continue. The contributions of river dissolved carbon will be included. The prescribed Redfield C/P ratio for remineralization will be assessed through an examination of the consistency between observed and predicted tracer concentrations and fluxes.

4.5.3 Terrestrial Carbon Cycle

R. Armstrong *S. Pacala*
S. Levin *J.L. Sarmiento*

ACTIVITIES FY93

A new project to develop a model of the terrestrial carbon cycle was initiated during the last year. A major emphasis of research on the anthropogenic CO_2 budget during the last year has been to investigate the nature of the so-called "missing sink", generally assumed to result from terrestrial processes. An estimate of the temporal history of the missing sink has been obtained by combining all components of the anthropogenic CO_2 budget for which quantitative constraints are available: the observed atmospheric increase, estimates of anthropogenic CO_2 release from fossil carbon and land use changes, and simulations of oceanic uptake by 3-D ocean general circulation models (4.5.1). The nature of the missing sink is being investigated with a series of modeling studies which treat it as resulting from processes such as enhanced photosynthesis due to CO_2 fertilization.

An estimate of the spatial distribution of the missing sink has been obtained by combining observations of the distribution of CO_2 release from fossil carbon and land use changes with 3-D ocean model estimates of air-sea fluxes (4.5.1) and an atmospheric model of CO_2 transport (4.5.1). The atmospheric CO_2 transport has been obtained by an inversion using a three-dimensional tracer transport model developed by the Middle Atmosphere Dynamics and Chemistry group constrained by zonal mean estimates based on atmospheric CO_2 tracer observations. While all reasonable distributions of tracer show the northern hemisphere as a large sink for locally produced CO_2, results for the tropics are more sensitive. Depending on the curvature of the zonal mean profile at low latitudes, the land surface in the tropics can be a considerable sink. The southern hemisphere is also very sensitive to the values at the limited number of stations, with the magnitude of the sink changing by a factor of two. All of these results are subject to large interannual variability forced by variations in the tracer field alone.

PLANS FY94

Studies of the spatial and temporal distribution of the missing sink will be completed.

Development of a terrestrial ecosystem model will continue.

The carbon 13 inventory will be used to constrain the global carbon 13 budget and the timing and location of the "missing sink".

4.5.4 Measurements

R.M. Key *J.L. Sarmiento*
C. Sabine

ACTIVITIES FY93

A new carbon system measurement program has now been operational for its first full year in support of the World Ocean Circulation Experiment/Hydrographic Program (WOCE/HP). These measurements will help evaluate the marine carbon cycle and will be used to constrain ocean carbon models. Construction of an underway pCO_2 system was completed to measure surface water and atmospheric boundary layer pCO_2's with infrared detection. The system was used for measurements in the Southeast Pacific for two months. Sabine also participated in the same cruise, assisting another group with their TCO_2 and discrete pCO_2 measurements in addition to collecting alkalinity samples to be returned to Princeton for analysis. Since this cruise, two alkalinity systems have been constructed, and analysis of the alkalinity samples has begun. A SOMMA system TCO_2 analyzer for the measurement of TCO_2 by coulometry has been obtained. The next cruise, WOCE/HP P-10, will be departing from Fiji in October. This will be the first cruise that the Princeton OTL-CO_2 group had full responsibility for since its formation.

PLANS FY94

Three members of the group will go to Fiji in October for WOCE LEG P-10 to make measurements of underway pCO_2 in the surface water and atmosphere, as well as discrete measurements of TCO_2 and alkalinity from the surface to the ocean bottom between Fiji and Japan. Back at the lab, alkalinity samples from the last cruise will be analyzed and improvements to the four carbon system instruments now in operation will continue. As tentatively scheduled, CO_2 measurements on WOCE LEG P-21W from Tahiti to Australia in March, and LEG I-10 from Java to Australia in November of 1994 will be made. Between cruises attention will focus on evaluating the measurements and attempting to understand the carbon system of the far western Pacific.

Algorithms that relate observed ocean properties to delta pCO_2 (the difference between the ocean and atmosphere partial pressure of CO_2) will be developed using existing data bases and statistical techniques.

4.6 NITROUS OXIDE

J.L. Sarmiento *P. Suntharalingham*

ACTIVITIES FY93

The ocean is a significant source of atmospheric nitrous oxide. However, large uncertainties attend its estimated magnitude, spatial and temporal distribution, and the processes involved in marine N_2O formation. These issues are being investigated by the development of a model of the oceanic nitrous oxide cycle. N_2O is treated as a non-conserved tracer in an ocean GCM, and is subject to biological sources and sinks, and gas-exchange processes at the ocean surface. The source function of N_2O exploits the observed correlation between AOU (Apparent Oxygen Utilization) and excess N_2O, and models N_2O production by a process of aerobic nitrification during the remineralization of organic matter.

Experiments have been run to determine the oceanic flux, and to investigate the relative contributions of solubility and biology to the oceanic N_2O distribution. Results indicate that the simple biological parameterization employed is able to reproduce the large-scale features of the observed N_2O distribution. Analysis of the biology vs. solubility experiments and examination of the model values of AOU and excess N_2O suggest that biological processes are mainly responsible for the observed distributions and correlations in the ocean.

PLANS FY94

The parameterization implemented is a simple one and ignores many of the complexities associated with the marine N_2O cycle. Longer-term research will focus on improving the parameterization by incorporating analysis of the available observational data sets for N_2O.

4.7 OCEAN CIRCULATION TRACERS

H. Figueroa *J.L. Sarmiento*
R. Key *J.R. Toggweiler*
G. MacDonald *V. Webb*
R. Rotter

ACTIVITIES FY93

The exchange of properties between the mixed layer and the permanent thermocline have been investigated with the aid of a numerical model of the North Atlantic Basin and in connection with modeling the distribution of tritium (vj). The results clearly point to the horizontal transport of mass across sloping mixed layers as one of the main mechanisms for the ventilation of the thermocline, particularly in the Subpolar Gyre.

Measurements of previously obtained radium-228 samples and collection of samples for radiocarbon analysis on the WOCE/HP cruises are proceeding apace.

PLANS FY94

Tracer modeling studies are being extended to the world ocean, in combination with analysis of the double diffusive processes and salt fingers instabilities as another possible mechanism for the ventilation of thermocline and Central Waters.

The Ocean Tracers Laboratory will continue to participate in the WOCE Pacific Ocean measurement program. If current plans hold up, responsibility for ^{14}C and ^{228}Ra in the Indian Ocean program will be assumed. Modeling work using both tracers will continue.

5. 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.

5.1 ATMOSPHERIC DATA PROCESSING

J.R. Lanzante *A. Raval*
A.H. Oort *M. Rosenstein*

ACTIVITIES FY93

5.1.1 Processing of Daily Upper-Air Data

Substantial progress was made in the processing of the TD54 radiosonde data set. This data set, which consists of early rawinsonde observations (~ mid-1940's-early 1960's card deck data), is being examined in a collaborative effort with Roy Jenne from NCAR for possible use in the NMC/NCAR reanalysis project. As a first step, the 32 magnetic tapes provided by NCAR were read, treating data words as character fields. The fields were checked to assure that they are both reasonable and internally consistent; obvious errors were corrected and indecipherable reports were set to a missing value. A special procedure was developed to convert "overpunched characters" (a common means of data compression in the era of card decks) into numeric values.

Considerable time and effort was required, since any fields flagged as suspicious had to be examined through diagnostics and often visually to determine the appropriate course of action. Although about 120,000 data records were initially flagged, the vast majority were able to be salvaged. The data were also sorted by deck of origin, station number, and chronologically. Following the removal of duplicate records, more than five million individual observations remain. The contents of this data set (which exceeds 4 GB) were summarized by an inventory. After "clean-up", the data from stations in Finland were returned to NCAR for use in a pilot project involving cross checking of data sources.

5.1.2 Processing of Monthly Mean Rawinsonde Data

The radiosonde covariance data set, which has been generated at GFDL during the last 25 years, has been reorganized into a more accessible form. The data were rewritten using one standardized format for the entire period of record. In addition, specialized subsets were created, as well as a routine which streamlines the export of these data.

As part of a continuing effort aimed at revision of the scheme for processing radiosonde data, the routine used for spatial analysis (transforming irregularly observed data onto a regular grid) has been rewritten. In addition to creating more modular code using standard FORTRAN, extensive comments have been inserted. Also, a new smoothing algorithm was developed. The new package was tested and evaluated using a sample of monthly mean historical data; the analysis product was compared for consistency with a similar product which was produced using the old analysis package.

5.1.3 Data Requests

The interest in using the observational data sets produced at GFDL has continued at a steady rate of one to two requests a month. Examples are the analyzed energy flux fields for a study of the Arctic heat budget at PMEL, all the high resolution (1.5° latitude x 2° longitude) analyses for May 1973-December 1989 as a standard for the international GCM intercomparison project (Atmospheric Model Intercomparison Project or AMIP) at Lawrence Livermore Laboratory, and all monthly station covariance statistics (about 4 GB of data) to Goddard Institute for Space Studies in New York for use in the ISCCP.

PLANS FY94

Processing of the TD54 radiosonde data will continue. Assessment of the quality of the observed data will begin. Initially, this will include hydrostatic checking applied to individual soundings.

The reformatting and restructuring of the basic analyses produced at GFDL will continue.

5.2 CLIMATE OF THE ATMOSPHERE

M.W. Crane
J.R. Lanzante
*A.-K. Lau **
N.-C. Lau
C.R. Lindberg
H. Nakamura
M.J. Nath
A.H. Oort
*J.P. Peixoto ***
M. Rosenstein
*J.M. Wallace **

* *University of Washington*
** *University of Lisbon, Portugal*

ACTIVITIES FY93

5.2.1 Atmospheric Temperature and Humidity Variations

Extensive work has begun to construct a "clean" humidity data set using those upper air stations that do not show clear instrumental jumps in their time series. The intercomparisons of the available 00 GMT and 12 GMT station data for temperature, specific humidity, and relative humidity for the May 1973-December 1989 period have proven to be very useful. They provide not only valuable cross checks on the validity of the data, but also new information on the magnitude of diurnal variations in these quantities. The first results based on the clean data tend to show much weaker trends in relative humidity, especially in the upper troposphere, than the trends previously found based on the "raw" station data. Instrument-related jumps in some station time series appear to be responsible for the unrealistic large downward trends in upper tropospheric relative humidity in the "raw" data.

5.2.2 Seasonal Dependence of Regional Circulation Features

As part of the NOAA/Universities collaborative effort on model diagnosis, a joint study with A.-K. Lau on the basis of a 40-year integration with a rhomboidal 30-wavenumber, 9-layer GCM reveals that the current GFDL climate model offers a good simulation of the seasonal reversal of the atmospheric circulation in the principal monsoon regions of the world (sl). These regions include south and east Asia, northern Australia, southwestern U.S./Central America, and Gulf of Guinea. The seasonal variations of the ambient flow field are accompanied by distinct shifts in the preferred trajectories of synoptic-scale disturbances in the tropics. Linear model calculations (778, 863, 904, 985, 1018) performed by M.-F. Ting using the GCM-derived forcings as input indicate that the latent heat release associated with tropical convection constitutes the major driving mechanism for the monsoonal circulations.

In collaboration with J.M. Wallace, the spring-versus-autumn differences in both the extratropical stationary waves and the near-equatorial circulation over the eastern Pacific and eastern Atlantic have been documented using the output from the model described in the preceding paragraph. Similar results have been obtained from another 15-year integration of a GCM with improved vertical resolution (14 layers). Several experiments with the latter model have been designed, so as to differentiate the roles of land and ocean forcings in the seasonal asymmetries of the circulation in various regions.

5.2.3 Structure of Interannual Ozone Variations

Interannual fluctuations of total column ozone were studied at a number of sites and were found to be organized in an interesting fashion. Spectral energy of the ozone signal is concentrated in a suite of broadband peaks, centered on the harmonics and subharmonics of the annual cycle. The signals represented by these peaks are coherent with each other, and with the energy in corresponding peaks at other recording stations.

An estimate of the coherence between total column ozone and Kp, the global planetary magnetic index summarizing solar particle radiation, shows a strong coherence (magnitude squared coherence > 0.7) between Kp and total column ozone at 2 cycles/year. The probability of two random independent Gaussian-distributed series producing this level of coherence is significantly less than 5%. Other bands also show strong coherence, but at less spectacular levels.

5.2.4 Volcanic Effects in Temperature Records

The question of volcanic influence on temperatures was revisited. A new method to compensate for the confounding effects of the El Niño oscillation and other low frequency components was developed.

5.2.5 Book "Physics of Climate"

Reviews of the book "Physics of Climate" published in 1992 (1065) have appeared in, *e.g.*, Nature, Bulletin of the American Meteorological Society, Physics World, Physics Today, Climatic Change, Taylor and Francis Magazine, Choice, and Geotimes. A translation into Chinese is in preparation.

PLANS FY94

Thorough comparisons will be made between the new, "clean" analyses and the earlier analyses of specific and relative humidity. A reliable climatology of the 3-dimensional global structure of relative humidity in the atmosphere will be prepared, since it is much needed for model evaluation and is not available in the present literature.

Sensitivity experiments will be conducted using a high-resolution GCM to delineate the relative contributions of the seasonal marches of sea surface temperature and land surface temperature to the marked spring-versus-autumn differences in the circulation regimes over the tropical oceans of the Western Hemisphere, and to evaluate the impacts of such seasonal asymmetries on the tropical flow on the extratropical atmosphere.

5.3 ATMOSPHERIC DYNAMICS

M.W. Crane *M.J. Nath*
J.R. Lanzante *A.H. Oort*
N.-C. Lau *D.-Z. Sun*
H. Nakamura

ACTIVITIES FY93

5.3.1 Large-Amplitude Circulation Anomalies

Anticyclonic circulation anomalies with extremely large amplitudes observed in the Northern Hemisphere winter were investigated. At almost all locations north of 50°N, they represent the blocking flow configuration with locally-closed streamlines and constant potential vorticity lines. A strong blocking high observed over a continent or an eastern ocean tends to be accompanied with a quasi-stationary wave train during its growing stage. The wave energy associated with the wave train seems to contribute to the amplification of the block. The blocking decays as it emits energy downstream. Besides the feedback from the migratory transient eddies, low-frequency dynamics are important in the development of the blocking over the continents and eastern oceans.

Cyclonic circulation anomalies with extremely large amplitudes were investigated in a similar manner. Again, upstream quasi-stationary wave trains are important for the amplification of the strong cyclonic anomalies over the eastern oceans and continents, and their decay is accompanied by the downstream wave trains.

5.3.2 Vertical Structure of Temperature and Humidity Variations

Using monthly global radiosonde data for the past 26 years, the vertical structure of the low frequency fluctuations of temperature and humidity was examined. In the regions of the Hadley circulation, the first EOF for the vertical structure of the temperature fluctuations was found to be consistent with that in a moist adiabatic troposphere. In the case of the normalized specific humidity, the first EOF is almost constant with height, which suggests effective mixing by moist convection throughout the troposphere. The time series corresponding to the first EOFs for temperature and humidity are dominated by ENSO-scale variations.

Regarding the correlation of the fluctuations in the free troposphere with those in the planetary boundary layer, the strongest correlations tend to occur in the ascending branch of the Hadley circulation and in midlatitudes, whereas the correlations in the descending branch of the Hadley circulation are weak. Thus, the latitudinal variation of the correlations agrees remarkably well with the meridional structure of the meridional circulation and of precipitation.

5.3.3 Circulation Response to Increased CO_2

Further statistical analyses were performed in the on-going project involving examination of the circulation response to increased CO_2. This involves GCM experiments performed by the Climate Dynamics Group as well as observed data produced by the Observational Studies Group. The focus is the response of the atmospheric circulation. Earlier work involving the stationary wave response (as evidenced by the eddy component of geopotential height) has been extended to the zonally averaged zonal component of the wind. The results for the wind indicate a highly significant response, particularly in the lower stratosphere. The observed data show evidence of some of the changes suggested by the GCM experiments. However, these findings must be viewed with caution due to the crudeness with which this model simulates the stratospheric circulation; in addition, the effects of the observed stratospheric ozone depletion which could be responsible for some of the changes in the real atmosphere have not been incorporated into these model simulations.

PLANS FY94

Research delineating the observed vertical structure of atmospheric temperature and humidity variations will continue.

The examination of the increased CO_2 GCM experiments and comparison with observed data will continue. Eigenvector analysis will be used to assess response in the model and changes in the observed data. The nature of the changes in atmospheric modes will be studied in this regard.

5.4 AIR-SEA INTERACTIONS

*L.A. Anderson ** *M.J. Nath*
I.M. Held *A.H. Oort*
N.-C. Lau *M. Rosenstein*

** Harvard University*

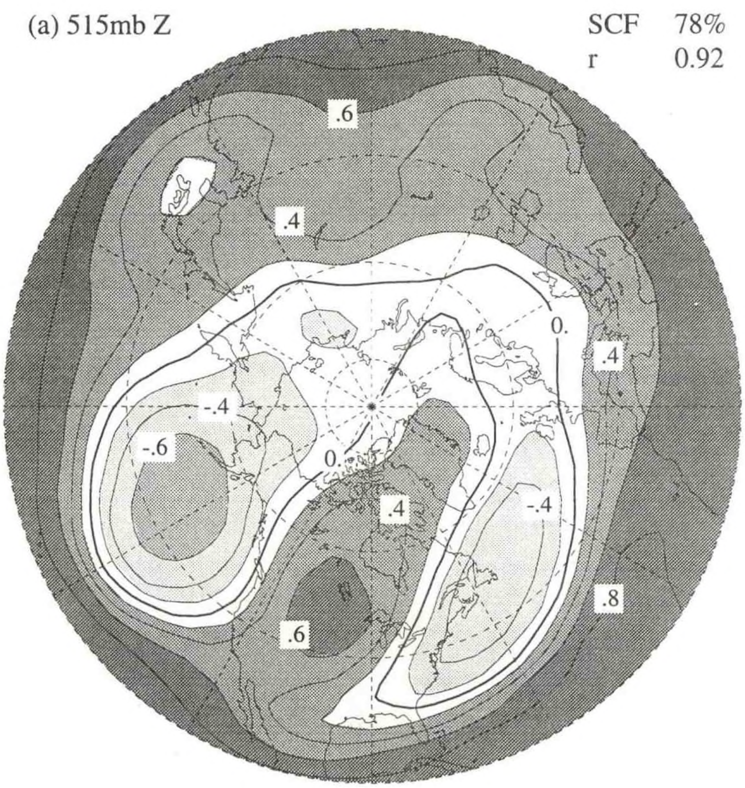
ACTIVITIES FY93

5.4.1 Relative Roles of Tropical and Extratropical SST Anomalies in Atmosphere-Ocean Variability

In association with the NOAA/Universities collaborative effort to diagnose regional climate changes using model data, three parallel sets of GCM experiments have been conducted. In these integrations, an atmospheric GCM has been subjected to observed, monthly varying sea surface temperature (SST) conditions in each of the following domains: near-global ocean ("GOGA" run), tropical Pacific ("TOGA" run) and midlatitude North Pacific ("MOGA" run). Four independent realizations were obtained for the model response to the sequence of SST anomalies during the 1946-88 period in each of the above regions. A detailed documentation of the output from this suite of model runs has been completed (up).

The principal modes of coupling between the imposed SST forcing and the simulated Northern Hemisphere wintertime 515 mb height field in various experiments have been identified using a singular value decomposition (SVD) procedure. The leading SVD mode for the GOGA experiment is qualitatively similar to that based on observational data, although the amplitudes of the simulated height anomalies are notably lower than the observed values. The SST pattern of this mode (Fig. 5.1b) resembles that associated with El Niño events. The accompanying 515 mb height anomaly (Fig. 5.1a) is dominated by a wave-like pattern in the North Pacific/ North American sector. The TOGA experiment reproduces many of the atmosphere-ocean relationships discerned from the GOGA output. Conversely, the MOGA run yields a much weaker and less reproducible response. The contrast between the TOGA and MOGA runs is indicative of the primacy of tropical Pacific SST anomalies in forcing the midlatitude atmospheric circulation.

In the TOGA experiment, the remote atmospheric responses to tropical Pacific SST anomalies influence the energy exchange across the local air-sea interface, and could thereby perturb the SST field outside of the tropical Pacific. Through this "atmospheric bridge", the tropical Pacific could set the pace for variability of the global ocean. Analysis of the TOGA output indicates that, over the North Pacific, changes in the surface energy fluxes are mainly determined by the surface wind speed, and by



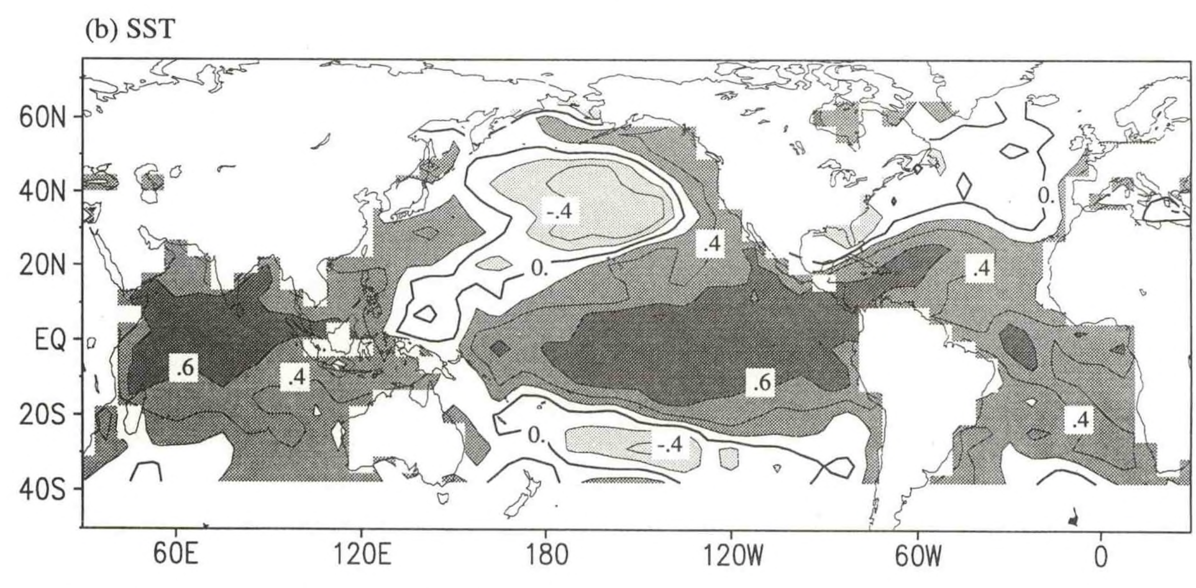


Fig. 5.1 Spatial patterns for the leading singular value decomposition (SVD) mode of the (a) 515 mb height response in the GOGA experiment, and (b) SST forcing prescribed in the near-global ocean, for the northern winter. These patterns of correlation coefficients (contour interval: 0.2) highlight those features in one field that exhibit strong temporal relationships with the companion field.

the strength of temperature and moisture advection. Over the Indian Ocean, variations in the incident solar radiation due to changes in cloud cover also affect the surface fluxes. The worldwide SST tendencies inferred from the variations in surface fluxes simulated in the TOGA experiment are in good agreement with the local observed SST anomalies.

5.4.2 Energy Cycle in the Ocean

An improved formulation of the global cycles of available gravitational potential energy (P) and kinetic energy (K) in the oceans has been derived (te). Using a variety of ocean surface observations, the time rates of change and the generation rates of P and K have been estimated for the four seasons and the year. The strongest energy generation rates of about 8 mW m^{-2} were found in the winter hemisphere.

PLANS FY94

The effects of the extratropical atmospheric response to tropical SST anomalies on the local air-sea exchange will be critically examined by coupling the atmospheric GCM to a hierarchy of oceanic mixed-layer models. The seasonal dependence of the ocean-atmosphere interactions related to ENSO will be investigated. The variability of the climate system on decadal time scales as simulated in the GOGA/TOGA/MOGA experiments will be explored.

Work on the energy cycle in the world ocean will continue.

5.5 SATELLITE DATA

M.W. Crane
L.P. Dritt
N.-C. Lau
A.H. Oort
V. Ramaswamy
A. Raval
B. Soden

ACTIVITIES FY93

5.5.1 ERBE Longwave Analysis

The ERBE data set was extended to include the period February 1985 through December 1988 (ta). The main focus of research has been the observed dependence of outgoing longwave radiation (OLR) on sea surface temperature and humidity. In midlatitudes, the surface temperature explains over 80% of the variability in the clear sky and almost half of the variability in total OLR. However, it fails badly in the tropics and subtropics, where the OLR variations depend mainly on the humidity variations.

The observed dependence of OLR on sea surface temperature and humidity have also been compared with GCM results.

5.5.2 Relationships between Satellite-Derived Cloud Fields and Various Atmospheric Circulation Systems

This project is mainly concerned with the diagnosis of the three-hourly multi-level cloud fields produced by the International Satellite Cloud Climatology Project (ISCCP) for the 1983-1990 period. The trimmed time series for cloud optical depth as well as cloud amount at various altitudes have been subjected to a diversity of statistical analysis procedures. Such procedures include spectral analysis, temporal filtering, Fourier fitting, cross-correlation among fluctuations of different fields or at different locations, regression techniques with and without temporal lags, and construction of composite patterns. For a direct comparison between the ISCCP results and findings based on more conventional meteorological data fields, analogous diagnostic tools have also been applied to twice-daily analyses of temperature, wind, geopotential height, and humidity by the European Centre for Medium-Range Weather Forecasts (ECMWF).

These analyses have yielded fresh insights on the geographical dependence of the diurnal and seasonal cycles of various cloud types, the sites of enhanced variability in cloud parameters on different time scales, the prevalent modes of propagation of the cloud fields in various regions, as well as the preferred locations of formation and dissipation of cloudiness. By combining the cloud information with the ECMWF data, it has been demonstrated that fluctuations of cloudiness on synoptic time scales (3-12 days) in the middle latitudes are accompanied by well organized perturbations in the motion, thermal and mass fields of the atmosphere. The characteristics of these synoptic disturbances are reminiscent of those associated with extratropical baroclinic cyclones (Fig. 5.2). Analogously, the near-equatorial cloud variations on intraseasonal time scales (25-80 days) and their relationships with the atmospheric flow pattern are consistent with the known behavior of Madden-Julian Oscillations (749, 903). The notable degree of consistency between findings based on the independent ISCCP and ECMWF data sets lends credibility to the cloud information derived from satellite platforms, and offers promise for enhancing knowledge of different atmospheric circulation systems by exploiting satellite data sets.

PLANS FY94

The detailed three-dimensional structure of the cloud field associated with different types of atmospheric circulation systems will be documented in detail, with emphasis on seasonal dependence and land-ocean contrasts. The role of cloud-related radiative forcing in the dynamics of such circulation systems will be assessed.

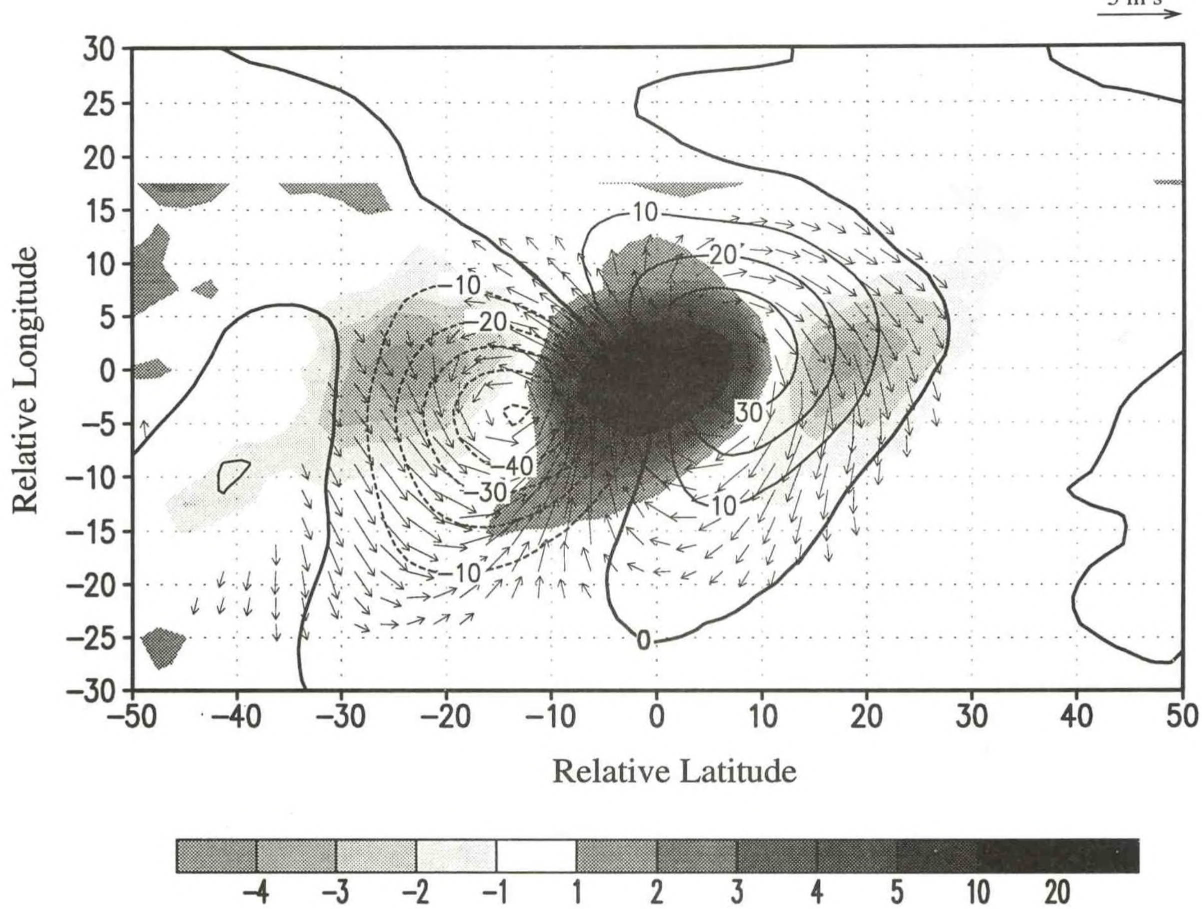


Fig. 5.2 Composite charts of the fluctuations in 1000 mb height (contour interval: 5 m; solid - positive anomalies, dashed - negative anomalies), 1000 mb vector wind (arrows, see scale at the upper right corner; arrows too short to show up clearly have been omitted), and cloud optical depth (stippling, see scale bar at the bottom) associated with 630 outstanding cloudy episodes over the extratropical western North Atlantic during the winters in the 1983-1990 period. Heavy (light) stippling indicates regions with relatively large (small) cloud amounts. The center of this chart corresponds to the origin of the common reference frame upon which data fields from different geographical sites are superposed. The selected sites correspond to regions of maximum day-to-day variability in cloud optical depth over the North Atlantic between 45° and 55°N, and 35° and 50°W. The ordinate (abscissa) of this diagram represents latitudinal (longitudinal) displacements from this common origin. The height and wind data are extracted from the ECMWF analyses. The cloud optical depth data are obtained from the ISSCP archives.

Observations from a broad spectrum of satellite instruments will be used to evaluate the simulation of various components of the hydrologic cycle (*e.g.*, water vapor, clouds) by the GFDL GCMs. Studies of upper tropospheric water vapor will also be conducted. This will involve the development and testing of an algorithm to infer humidity from geostationary satellite imagery. Also, intercomparison of data from radiosondes and from the GOES (Geostationary Operational Environmental Satellite), TOVS (TIROS Operational Vertical Sounder), and SAGE (Stratospheric Aerosol and Gases Experiment) satellites will begin.

6. 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.

6.1 EXPERIMENTAL HURRICANE PREDICTION

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

ACTIVITIES FY93

An automated GFDL hurricane prediction system (A92/P93) was used in a semi-operational mode throughout the 1992 hurricane season. In total, 20 cases were treated (nine forecasts for Hurricane Andrew, three for Hurricane Iniki, three for Hurricane Bonnie, three for Tropical Storm Danielle, one for Tropical Storm Earl, and one for Hurricane Frances). The forecast results of the storm position, the minimum sea level pressure and maximum surface wind were sent to the National Hurricane Center. In addition, the distribution of the maximum wind during the passage of the storm was made available immediately after the model integration for some cases. Accuracy of the hurricane forecasts using the 1992 version of the prediction system was satisfactory in cases of strong storms. For example, the system accurately predicted the landfall of Hurricane Andrew onto the Louisiana coast and the recurvature of Hurricane Iniki. However, difficult situations were encountered in cases of weak storms.

Subsequent to the 1992 hurricane season, an intensive effort was made to evaluate and improve the capability of the prediction system. It was found from the inspection of model products for many difficult cases that the original initialization technique tended to remove mesoscale features within the storm area which otherwise could have played a significant role in the storm movement. Also, the introduction of more complete automation procedures was desirable. Therefore, a revision of the vortex specification method and establishment of an advanced automated system, including a quality control of input data, were carried out (6.5.1 and 6.5.2). All changes in the methods used, as well as in the system structure, were carefully tested and proven to yield significant reduction in forecast error while eliminating human intervention. The 1993 version of the GFDL hurricane prediction system was established in time for the current hurricane season. The new system is successfully functioning and its forecast performance is promising so far.

A joint project with the National Meteorological Center (NMC) was continued. Fourteen cases of data which had been reanalyzed at NMC with and without dropsonde observations were all transferred to GFDL. The prediction experiments continued with these data to evaluate the impact of dropsonde observations on hurricane prediction. The experiments also provided valuable results for improving the GFDL hurricane prediction model.

PLANS FY94

The 1993 version of the hurricane prediction system will be applied in a semi-operational mode to the Atlantic and Eastern Pacific hurricanes in the 1993 season. Post season analysis of the system performance will follow.

A study to fully utilize the available observational data within the storm region may be made.

6.2 GENESIS OF TROPICAL CYCLONES

Y. Kurihara *R.E. Tuleya*

ACTIVITIES FY93

A study was continued to investigate the mechanism which prohibits or strongly retards tropical cyclogenesis over the land and also leads to the decay of storms after landfall. Numerical results from a series of idealized experiments using the GFDL Multiply-nested Movable Mesh (MMM) hurricane model (A92/P93) were analyzed (ud). In the model, the land surface temperature was predicted from the heat budget of a land subsurface layer. At issue in this study, and in the problem of tropical cyclogenesis in general, is how the time change in the vortex intensity is related to the surface temperature and the intensity of an existing vortex or, more specifically, the surface wind speed.

The present work, when combined with the study of tropical cyclone-ocean interaction (6.4), considerably advanced understanding of tropical cyclogenesis. In a vortex system, two feedbacks compete with each other at the surface boundary. Given the surface wind, a positive feedback attempts to produce more heat flux into the system and stronger surface wind. On the other hand, a negative feedback is set up if surface cooling occurs, leading to the reduction of heat flux and weakening of the wind. It is now clear that the storm formation is very sensitive to the variation in the surface temperature which is controlled in large part by the thermal capacity of the layer beneath the vortex. Over the warm ocean, the positive feedback between the wind and evaporation is predominant and the negative effect appears only after the wind becomes strong. In contrast, the negative process is so quick and effective over the land, perhaps except over very hot land, that the positive feedback is overwhelmed.

The energy exchange at the land surface depends not only on the surface temperature, but also on the surface roughness and surface wetness. However, the sensitivity of storm development on the latter two parameters was found to be rather small. The diurnal change of radiation and the cloud-radiation interaction cause interesting changes in the storm behavior, but do not change the overall evolution tendency of the storm. In simple arguments concerning storm formation, it is often assumed that the heat flux is directly linked to the surface wind with little time lag. In the real atmosphere, this link may not be strong, especially at the incipient stage of the storm genesis. Moreover, the link can be modulated by many other factors, making the genesis prediction more complex.

PLANS FY94

Studies will be made on the diurnal variability of tropical cyclones over the ocean. Also, an investigation may be made on the diurnal variation of tropical convection in general.

6.3 SCALE INTERACTION

Y. Kurihara *C.-C. Wu*
R.J. Ross

ACTIVITIES FY93

A study was conducted to understand how tropical cyclones affect the surrounding environmental conditions. The approach taken in this study was to make comparative analysis between two model integrations, one from an initial condition which included a hurricane and the other which did not include it. Numerical results from the model integrations for three cases of Hurricane Gloria, in particular that from 25 September 1985, were analyzed.

It was found that the influence of the hurricane spreads with time to a large region and propagates with a moving storm. Fig. 6.1 shows the sea level pressure difference at 60h between the two integrations, *i.e.*, the integration with the hurricane minus the integration without the hurricane. The difference existed only in the storm domain at the initial time. The rate of spreading of the hurricane influence correlated fairly well with the strength of the upper level outflow of the storm.

The modification of the wind and moisture fields in a large area due to the hurricane caused significant changes in the behavior of a cold front which was approaching the storm from the west. The movement of the front was retarded to the northwest of the storm and accelerated to the southwest. This contributed to the increase (decrease) of precipitation associated with the front northwest (southwest) of the storm.

The change of local meteorological conditions during the passage of the storm was also analyzed. It seems the storm caused no significant after-effect to the area swept by the outer region of the storm. It was determined that the evolution of an anticyclonic system over the Atlantic was not strongly governed by the hurricane. Although the modification of the large scale system by the storm appears to be small, it can significantly influence the storm motion. The implication of this study is that accurate prediction of tropical cyclones, both movement and intensity, will improve the accuracy of the numerical weather prediction in the surrounding region. In turn it can improve the hurricane prediction.

PLANS FY94

The first phase of this work will be completed.

A study may be initiated to understand the interaction between the low level disturbance and the upper level synoptic features.

6.4 HURRICANE-OCEAN INTERACTION

M.A. Bender *Y. Kurihara*
I. Ginis

ACTIVITIES FY93

An extensive analysis of the numerical results from the tropical cyclone-ocean coupled model (A92/P93) was conducted. In this model, the GFDL triply nested

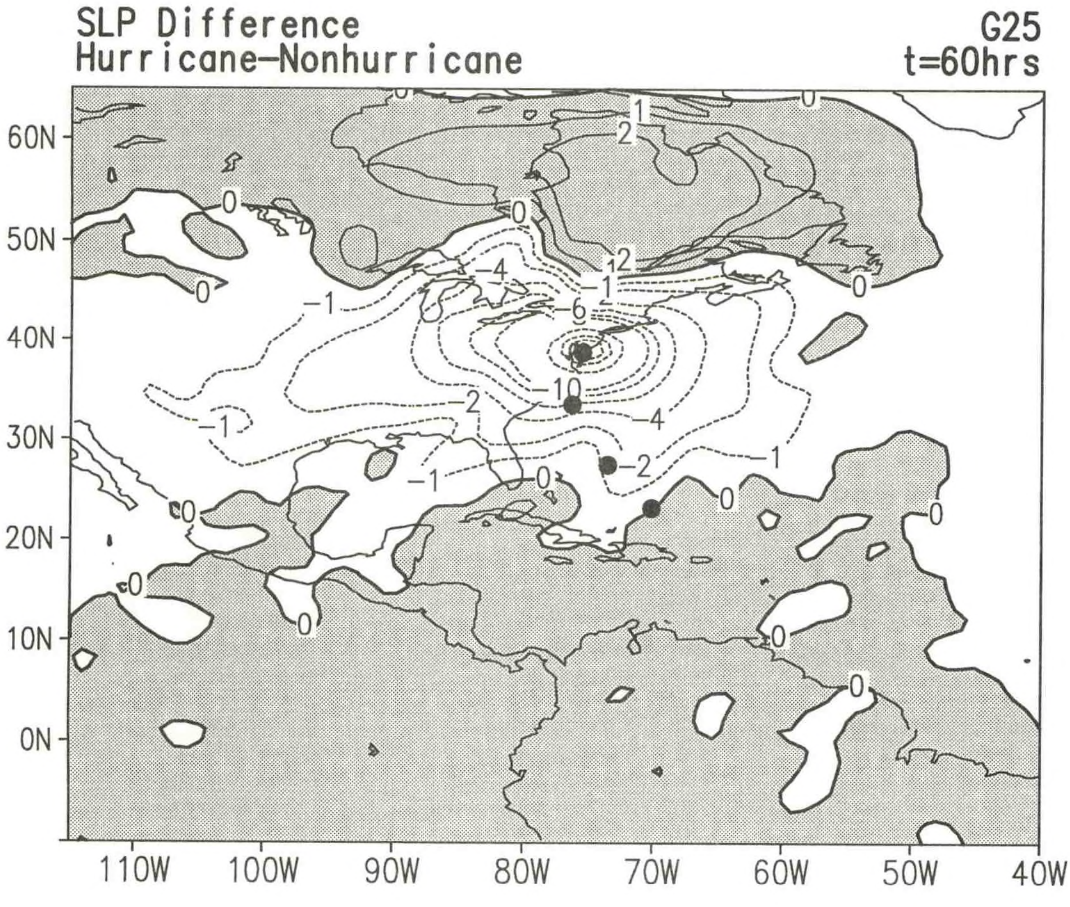


Fig. 6.1 Difference in the sea level pressure distribution (in hPa) after 60hrs between two integrations, *i.e.*, the one starting from the initial condition including Hurricane Gloria minus the other which excludes it. At the initial time, 0000 UTC September 25, 1985, the difference was present only within the storm domain. This figure indicates that the influence of Hurricane Gloria spread to a very large region. Black circles show the predicted locations of the Hurricane at 0 (southernmost circle), 24, 48 and 60h, respectively.

movable mesh hurricane model and an ocean multi-layer model were coupled through the exchange of momentum and heat energy at the sea surface in the course of a time integration. A hurricane vortex generated by the GFDL initialization scheme was embedded onto uniform basic flows of different strengths. The analysis revealed that a response of the ocean mixed layer to the storm produced a narrow cold wake, the location of which was biased to the right of the storm track. The above reduction of the SST reduced the heat flux primarily in the region above the cold wake. The resulting change in the equivalent potential temperature in the lower part of the planetary boundary layer spread to a much larger domain. The equivalent potential temperature at the storm center did not attain the value obtained in the corresponding non-coupled experiment in which the SST was kept unchanged. The weakening of the storm was dependent on the storm's translational speed.

The simulated effects of the ocean coupling on the storm intensity are summarized in Table 6.1, together with observational statistics. The model simulations indicate that the larger sea surface cooling is caused by the slower moving storms, which agrees well with observations. Another effect of ocean coupling is a significant reduction of the precipitation accumulated with respect to the moving storm. The tracks of only the slow moving storms were affected, apparently because of the change in the beta-gyre structure resulting from the weakening of the wind in the outer region of the storm (ua). In the real atmosphere, the sensitivity of the storm intensity to the sea surface cooling can be modulated by many other environmental factors. Yet, it is now clear that the SST decrease caused by the tropical cyclone-ocean coupling is an additional mechanism that can make the storm weaker than its potential intensity.

PLANS FY94

A further analysis of the numerical results obtained from the tropical cyclone-ocean coupled model will be conducted, with emphasis on the development of asymmetric structure in the tropical cyclone.

Table 6.1 Sea surface temperature (SST) decrease due to tropical cyclone-ocean coupling and its effects on storm intensity.

• TROPICAL CYCLONE - OCEAN COUPLED MODEL

Basic flow (m/s)	translational speed (m/s)	max. change in SST (°C)	increase of min. sfc pressure (hPa)	decrease of max. sfc wind (m/s)
no basic flow				
	1.7	-5.6	16.4	7.0
westerly				
2.5	2.2	-4.6	15.6	6.7
5.0	4.2	-3.7	12.0	4.8
7.5	6.6	-3.0	7.0	2.6
easterly				
2.5	3.8	-4.1	11.8	5.0
5.0	6.1	-3.2	9.7	3.2
7.5	8.3	-2.6	7.7	2.8

• OBSERVATION

storm movement	translational speed (m/s)		max. change in SST (°C)		number of cases
	mean	(range)	mean	(range)	
slow	2.4	(1.5 – 3.0)	-5.3	(-4.5 – -6.0)	4
medium	5.7	(4.0 – 6.8)	-3.5	(-2.0 – -5.0)	7
fast	12.0	(9.0 – 15.0)	-1.8	(-1.0 – -2.5)	5

6.5 MODEL IMPROVEMENT

M.A. Bender *R.J. Ross*
Y. Kurihara *R.E. Tuleya*
P.J. Rears

ACTIVITIES FY93

6.5.1 Initialization Scheme

Various undesirable problems in the dynamical prediction of hurricanes in the past, such as the initial adjustment and false spin-up of the model vortex, were fairly well corrected by the initialization package (1147) used in the GFDL hurricane prediction system during the 1992 hurricane season. However, the result of post-season evaluation of the model performance suggested that the initial environmental flow field in the storm area was not always represented at a satisfactory level of accuracy. A technique has been developed which can retain important mesoscale features after the analyzed vortex is filtered from the NMC global analysis. The design of the new technique is original in that the filter domain is not necessarily circular and also an optimum interpolation method is used in constructing the environmental flow field within the filter domain. The forecast error in the prediction tests for many difficult cases in the past was significantly reduced with the use of the new methods. In addition to the new filtering method, the revised scheme includes a refined vortex generation process.

6.5.2 Automated Hurricane Prediction System

In the 1992 version of the GFDL hurricane prediction system, the hurricane message transferred from NMC and processed data in the initialization step were subjectively inspected. These processes were now upgraded by the introduction of an automated quality control of the input message and data. The 1993 version of the hurricane prediction system runs with no human intervention at all once the name of the target storm is designated. In the revised version, routine transmission of the model output to the National Hurricane Center, including maps showing the storm track and distribution of the maximum winds at low levels, is a part of the automated processes.

To give an off-line support to the automated system, a program was developed to compare the track prediction by the GFDL model against the official NHC forecast, the predictions by the NMC global (AVN) and hurricane (QLM) models, as well as that by the CLIPER (combination of climatology and persistence). The intensity predication is compared against the official NHC forecast and the two statistical forecasts.

6.5.3 Model Physics

Some observational reports, as well as the NMC global analysis, indicate that the temperature difference between the air and the underlying sea surface can be as large as 5° Celsius. Assuming that the non-local convective mixing is strong in such cases, the background diffusion was appropriately increased during the process of vortex generation in the initialization scheme. This change resulted in improvement of the wind profile in the planetary boundary layer. Implementation of the above effect in the model integration phase requires further study.

PLANS FY94

Performance of the 1993 version of the automated GFDL hurricane prediction system will be carefully monitored and evaluated. An effort will be made to improve the tropical cyclone tracking algorithm.

Study will continue to seek improvement in the treatment of cloud, precipitation, and land surface processes in the model.

7. 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 using numerical simulations of mesoscale phenomena.

7.1 THE LIFE CYCLE OF MID-LATITUDE CYCLONES

E. Chang *L. Polinsky*
I. Orlanski *J. Sheldon*

ACTIVITIES FY93

7.1.1 Theoretical Studies of Downstream Baroclinic Development

The recent discovery that the development of atmospheric baroclinic waves is as much a product of energy dispersed from decaying waves upstream as it is of the classical baroclinic conversion has opened fertile new ground for reinterpreting analyses and simulations of idealized and observed systems. A three-dimensional primitive equation model has been used to demonstrate that the convergence/ divergence of ageostrophic geopotential fluxes can constitute a major source/sink of kinetic energy for both downstream and upstream development of baroclinic waves, and can play a dominant role during all stages of wave development. This study laid the groundwork crucial to revising previous concepts regarding the energy budget of individual eddies as well as an ensemble of eddies in storm tracks (1116).

In a follow-up study which extended the earlier findings with respect to storm tracks, an idealized model was used to show that the existence of a localized source of enhanced baroclinicity, while leading to localized maxima in baroclinic conversion at, or immediately downstream of the baroclinic region, does not necessarily lead to the localization of eddy activity. Energy radiated downstream by eddies which develop in this highly baroclinic region will trigger and sustain eddies in the downstream region, despite the lower baroclinicity there, thus extending the storm track. These results confirm the importance of the ageostrophic geopotential fluxes previously discussed (1116), and provides a new framework for interpreting the mechanisms that shape the areas of strong eddy activity (1125).

7.1.2 Observational Studies of Downstream Baroclinic Development

In a concurrent study, the structure and evolution of transient disturbances in the Northern Hemisphere winter season were examined using one-point regression maps and longitude-height sections derived from the ECMWF operational analysis for seven winters. The regression analysis, which focused on the middle latitudes of the Pacific Ocean, revealed many of the already known characteristics of baroclinic waves, such as westward tilt with height in the velocity and height fields and eastward tilt in the temperature field, with typical wavelengths of 4000 km and periods of around 4 days. An important result, which fully supports the new findings regarding downstream development (1116,1125) and differs drastically from previous diagnostic studies, was the fact that downstream baroclinic development was a primary mechanism in the Pacific storm track. It is suggested that the time filter used for those early studies precluded the detection of such a mechanism (1154).

As in the case of analysis using time filters, other methods currently employed for analyzing wave activity are not well-suited to the detection of downstream development in high frequency, synoptic scale waves. However, the knowledge that downstream development is operating in localized regions of a storm track is of paramount importance given the fact that the convergence of energy fluxes can be a good indicator for later development of an energy center (*i.e.*, a new eddy). It has been pointed out in the literature that the use of energy budgets/cycles may not be the best diagnostic tool with which to examine the dynamics of waves because the conversion terms are not uniquely defined. A more promising approach has been identified in a study which has just been completed in which it is shown that the eddy energy flux, when normalized by the total eddy energy and modified to take the effects of a variable Coriolis parameter into account, gives a very good approximation to the group velocity of a system. This new formulation needs to be tested in different regions around the globe, particularly in the Pacific storm track where considerable downstream energy flux has been found (uc).

In a related study in progress, an attempt is being made to develop an index that measures the relative strength of downstream energy fluxes and surface baroclinic development in areas of strong wave activity around the globe. As pointed out in other studies (1117, 1125, 1154 and tk), the characteristics of the synoptic waves strongly depend on the mechanism responsible for its development. In particular, waves that develop mainly due to surface baroclinicity are shallower than those produced by downstream development. An index which consists of the ratio of monthly averaged upper level (300 mb) ageostrophic flux convergence to the low level (700 mb) baroclinic conversion has been proposed and tested on 8 years of ECMWF daily data. The upper panel of Fig. 7.1 shows the 8 year January average of the eddy kinetic energy over the Pacific region, while the middle panel displays the new index based on the eddy activity for the same period. The results are very encouraging and support earlier findings that surface baroclinicity is very important at the entrance of the Pacific storm track, with downstream development becoming more important in the eastern part of the storm track. A similar index (bottom panel of Fig. 7.1) based only on monthly mean flow conditions has also been suggested; it depends on the vertical shear of the entire atmospheric column as well as the low-level stratification and wind shear (parameterized as the Eady growth rate, σ_i, and corresponding wavenumber, k_{max}). This "bulk" index shows a high correlation with the index derived from the wave activity itself (middle panel of Fig. 7.1) and may prove valuable in identifying regions of eddy activity using only time-mean parameters.

7.1.3 Downstream Baroclinic Development over Western North America

The analysis of a rapidly amplifying wave over the eastern Pacific/western U.S. in December 1990 has been completed. Application of an energy budget which distinguishes between energy generation via baroclinic processes and geopotential flux convergence revealed that energy generation during the early stages of storm development was due almost entirely to the convergence of geopotential fluxes from a decaying system upstream. Baroclinic conversion, mostly in the form of cold advection, became the primary energy source only after the development was well underway. This sequence of energy growth via flux convergence followed by additional contributions by lower level baroclinic conversion constituted an excellent case of downstream baroclinic development. These findings suggest considerable potential for using these fluxes as a diagnostic in the identification of growing and decaying systems and the analysis of model deficiencies (tk).

PLANS FY94

Additional case studies will be initiated to better understand the role of geopotential fluxes and baroclinic conversion in the development of cyclones. Explosively developing storms will be analyzed to identify the roles played by localized baroclinicity and the decay of upstream systems. The new suggested index measuring the intensity of downstream vs. baroclinic development will be tested for different months of the year to evaluate its qualities.

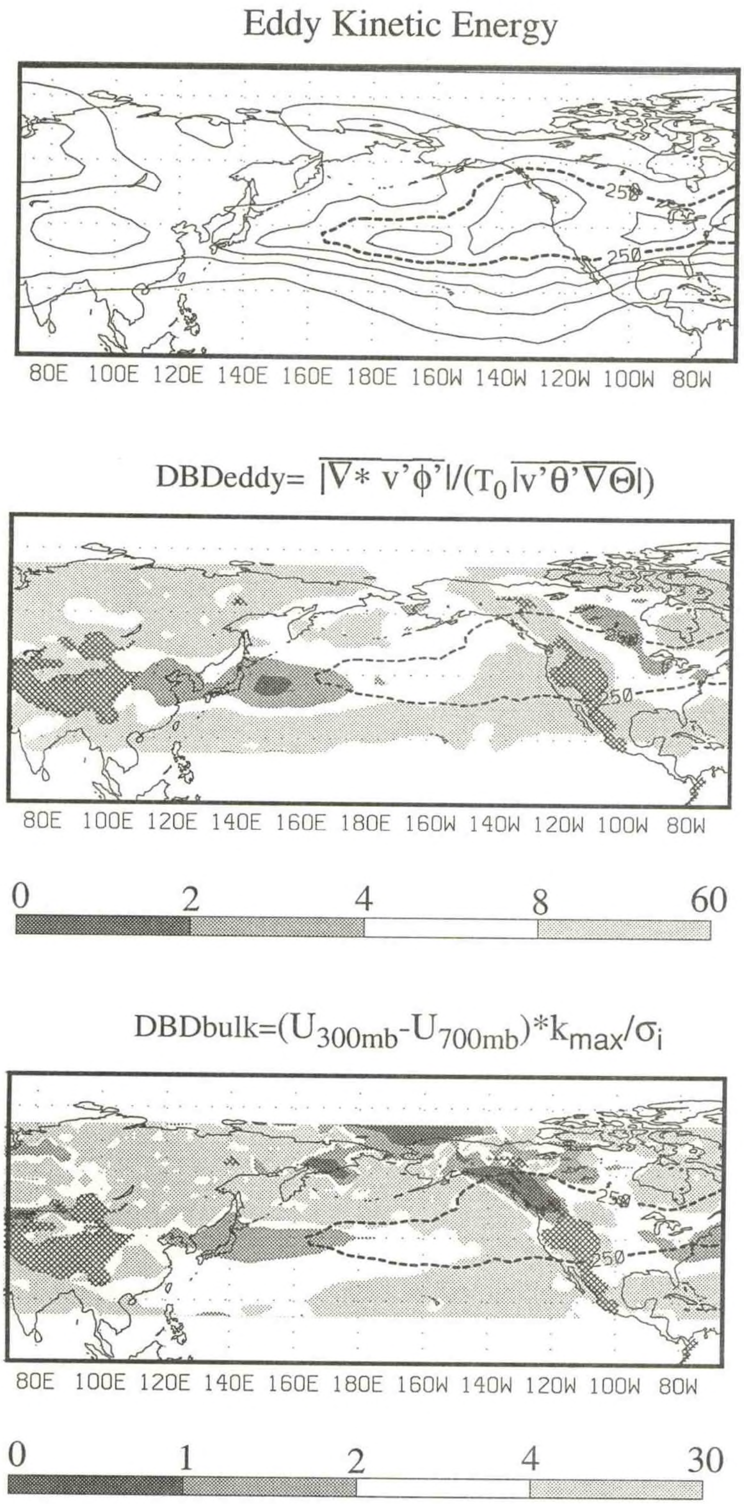


Fig. 7.1 Eddy kinetic energy at 300mb calculated using daily departures from the monthly mean wind and averaged over the period 1980-1987 (upper panel). The Downstream Baroclinic Development index (DBD_{eddy}), calculated as a ratio of the ageostrophic geopotential flux convergence at 300 mb to the baroclinic conversion evaluated at 700 mb (middle panel), and a "bulk" index which parameterizes DBD, calculated from monthly mean flow conditions (lower panel). A reference contour (dashed) from the top panel is reproduced on the other panels.

7.2 SENSITIVITY STUDIES OF MID-LATITUDE CYCLONES

I. Orlanski *J. Sheldon*

ACTIVITIES FY93

7.2.1 Cold Outbreak in the Western U.S.

Although the energy budget of the late December 1990 cold outbreak has been completed (see 7.1.3), the sensitivity of the storm to the lower boundary conditions continues to be of interest. A number of trial modifications were made to the GFDL Limited Area HIBU Model (LAHM) in terms of sea surface temperatures and surface drag, but little change in the general characteristics of the storm was noted, which is not surprising given that the growth of the system in question was driven primarily by geopotential flux convergence at upper levels. The only significant change in the storm's characteristics resulted when the surface drag coefficient was made a function of topographic height, increasing C_D in high terrain. While this change had minimal impact on the overall system, the simulation of the lower level circulation and surface pressure was substantially improved. This was consistent with many earlier observations that the E2 physics package tended to exhibit inadequate coupling between the boundary layer and the rest of the troposphere. An initial test which replaced the mixing length approach to vertical mixing of momentum with a scheme based on the local Richardson number (see 7.2.2) improved both the boundary layer wind intensity and the sea level pressure distribution. Further development of this scheme, and its application to this case, is currently being conducted in conjunction with its application to other cases (tk).

7.2.2 The Blizzard of '93

A detailed analysis was initiated of the development of the so-called "Blizzard of '93", which roared up the east coast of the U.S. on 13-14 March 1993, setting new records in terms of snowfall, temperatures, and sea-level pressures. The energy budget of this storm revealed that its initial development was triggered by massive convergence of geopotential fluxes over the lower Mississippi valley, primarily from a system moving south along the eastern slopes of the Rocky mountains. Once a nominal circulation was induced, equally impressive baroclinic conversion took place, with energy generation in sinking cold air behind the system being nearly as large a contributor as that in the rising warm air ahead of the system.

The model (LAHM) has been used to simulate this storm with great success, particularly when a new, experimental scheme for vertical turbulent mixing was incorporated. This new scheme makes vertical turbulent mixing of heat, moisture, and momentum dependent on the local Richardson number, replacing the GFDL

E2-physics mixing length approach and obviating the need for dry convective adjustment. It also results in a greater coupling between the boundary layer and the rest of the troposphere and its use has improved the accuracy of the boundary layer winds. Fig. 7.2a shows the sea-level pressure distribution at 00Z 14 March (36h) for the simulation which incorporated this new scheme, along with storm tracks derived from the analysis (A) and the simulation (S). Both the speed and track of the simulated storm were extremely good. Fig. 7.2b shows the evolution of the minimum sea-level pressure for the analysis, a control simulation and the "Ri-mixing" simulation, and indicates a considerable skill in simulating the pressure minimum, particularly when the new mixing scheme is used.

PLANS FY94

The Ri-based vertical mixing parameterization will be investigated in greater detail, especially with respect to drag over mountainous terrain, its potential similarity to empirically derived drag coefficients over water, and the reasons for its superior performance in the (explosive) blizzard case. Additional insight may be gained by examining cases in which development is less dominated by upper-level geopotential flux convergence.

7.3 THEORETICAL STUDIES OF FRONTAL DYNAMICS

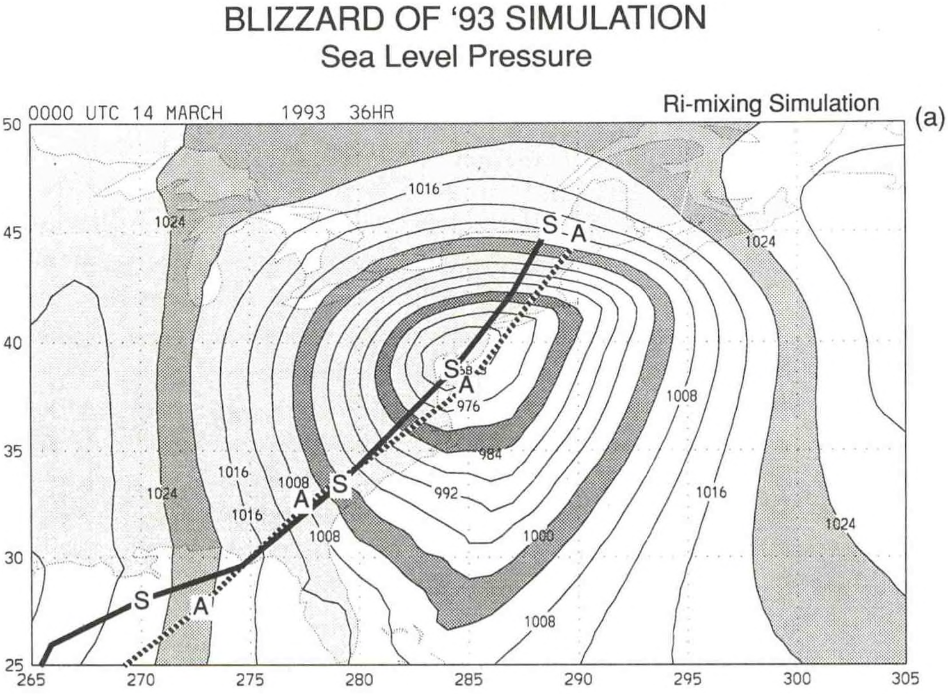
S. Garner *I. Orlanski*
B. Gross

ACTIVITIES FY93

7.3.1 A New Look at Lee Cyclogenesis

An investigation into the orographic modification of cyclone development has been completed. The primitive equation zeta model was used to show that when a mature baroclinic wave impinges on an east-west oriented mountain ridge, a relatively intense cyclone forms on the south side of the mountain ridge. This cyclone extends throughout the depth of the troposphere and possesses relatively small vertical tilts, large velocities, and strong temperature perturbations compared to classical baroclinic eddies. The vorticity growth in the orographic cyclone center is larger than that of baroclinic eddies that grow over flat terrain. However, there is no absolute instability associated with this orographic enhancement. A longer ridge produces a more intense eddy.

A novel mechanism responsible for the generation of the orographic cyclone was found to be the interaction between the frontal circulation in the baroclinic wave and the mountain. Simulations of a stationary cold front interacting with a mountain



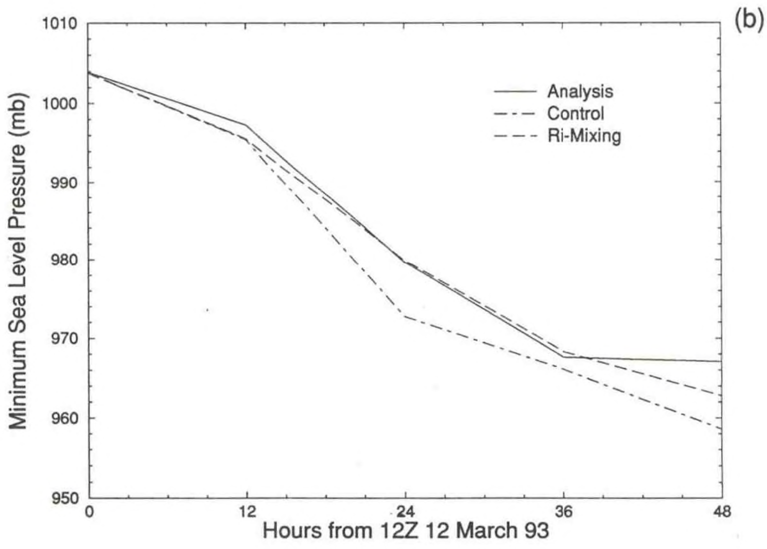


Fig. 7.2 Results from simulations of the Blizzard of '93. (a) Sea level pressure distribution at 00Z 14 March (36h) from a simulation using an experimental Ri-number-based vertical mixing scheme. The storm's path/position is shown by the heavy lines for both the analysis (A) and simulation (S) every 12h. (b) Evolution of the minimum sea level pressure for the analysis, control simulation, and "Ri-mixing" simulation.

ridge show that warm southerly flow ahead of the front is diverted westward by the mountain ridge, intensifying the strong hydrostatic pressure gradient between the mountain anticyclone and the developing cyclone to the south. In contrast, cold northerly flow is diverted eastward as it approaches the mountain and effectively broadens the mountain anticyclone towards the north. This produces the characteristic pressure dipole observed in orographic cyclogenesis. It is concluded that mature baroclinic eddies approaching the mountain ridge should have a strong frontal zone with a considerable temperature contrast and strong circulation for an intense response (tf).

7.3.2 Frontal Interaction with Topography

The modification of a front as it interacts with an isolated mountain ridge has been associated with the generation of lee cyclones (tf) and cold surges east of the world's principal mountain ranges. A clarification of the principal physical mechanisms responsible for this frontal modification is undertaken by means of nonlinear three-dimensional simulations using the hydrostatic Boussinesq version of the zeta model. In these simulations, the front evolves as part of a developing nonlinear baroclinic wave and propagates towards an isolated mountain ridge.

It is shown that when the front reaches the ridge, cold postfrontal air at the surface decelerates and produces a high pressure anomaly on the windward slope. If this anomaly is strong enough, it accelerates air over the ridge peak in a shallow ageostrophic flow that possesses many features found in a gravity current. This current provides relatively strong surface frontogenesis through convergence, but cannot transport enough mass across the peak to weaken the anomalous high pressure. The cold air and pressure anomaly on the windward slope propagate eastward in a manner similar to a topographic Rossby wave. When the east ridge end is reached, the anomalous pressure gradient accelerates the flow around the ridge end and into the lee, where intense frontogenesis occurs from shearing motion (Fig. 7.3b). Blocking, as measured by the ratio of the mass flux around the ridge end to that over the peak, is determined by a Froude number that depends on the propagation speed of the front (*i.e.*, the strength of the baroclinic wave) and the mountain height. Higher mountains or weaker waves tend to produce total blocking of the front, resulting in flow only around the east ridge end (Fig. 7.3c). Lower mountains and stronger waves produce frontogenesis patterns and frontal distortions that more closely resemble passive scalar simulations (Fig. 7.3a) (uo).

7.3.3 Blocking and Frontogenesis Due to Topography

The "high-drag" state of stratified flow over terrain has been a challenge for linear and steady-state nonlinear estimation of topographic wave drag. Linear theory completely misses the transition to the asymmetrical high-drag configuration, while

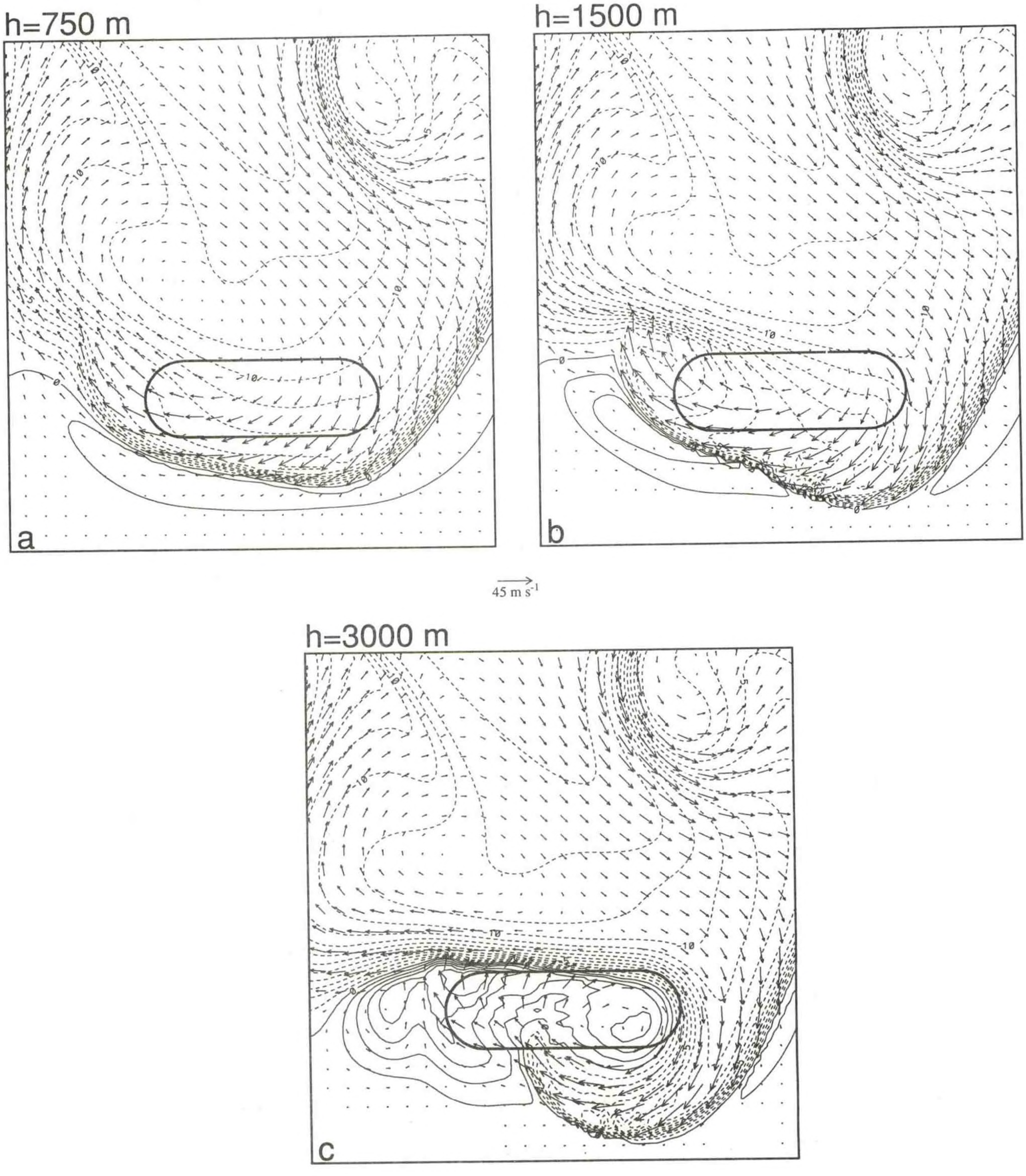


Fig. 7.3 Simulated interaction of a cold front with mountain ridges with heights (a) 750 m, (b) 1500 m, and (c) 3000 m. Surface potential temperature contoured every 1 K, with negative values dashed. The maximum horizontal velocity at the surface is 45 ms^{-1}. The mountain half-height is indicated by the bold closed contour, and is 1600 km x 600 km in extent.

steady-state nonlinear models use boundary conditions that may be inconsistent with the upstream conditions established by transients. A terrain-following numerical model with open boundaries has been used to obtain high-drag states that are consistent with slowly varying initial wind and static stability.

For mountains that are just tall enough to produce breaking waves, most of the drag enhancement is due to the pressure drop in the severe downslope windstorm. Permanent changes in far-upstream conditions are important mainly in allowing a steady cascade over much taller mountains than predicted by hydraulic theory. Contrary to a common assumption, the upstream influence is mostly due to an initial surge that is not directly related to wavebreaking. An empirical formula for the total drag as a function of mountain amplitude has been obtained for use in wave-drag parameterizations (ui).

By introducing background rotation into the terrain-following model, the nature of orographic blocking in a baroclinic atmosphere has been investigated. It was found that warm advection suppresses the effect of background rotation, which otherwise tends to weaken the upstream disturbance. Hence, blocked solutions are easily found for sufficiently narrow ridges. The shallow fronts that form as a consequence bear some resemblance to observed phenomena.

7.3.4 Gravity Waves Generated by an Eady-Type Front

A study of gravity-wave generation in fronts using a fully Lagrangian numerical model has led to a nonlinear diagnostic calculation that accurately filters inertial oscillations from small-wavelength two-dimensional Eady waves. This calculation uses higher-order balance to distinguish inertia-gravity waves from motions that do not participate in geostrophic adjustment. This is expected to be a useful tool for analyzing a variety of quasi-two-dimensional mesoscale phenomena.

7.3.5 The Role of Moisture in Cyclogenesis

Latent heating and cooling can have a dramatic impact on cyclogenesis through the direct effect on the potential vorticity distribution and through the indirect dynamical response to a given distribution. A simple quasi-geostrophic spectral model based on an idea of Eady has been developed to study the indirect effect on non-normal-mode cyclogenesis. A permanent saturated layer is placed between rigid top and bottom boundaries and no other potential vorticity anomalies are introduced. Hence, the model can be solved as a pair of coupled two-dimensional problems. A nonlinear version of this model, minus the rigid boundaries, was used earlier to study two-dimensional equilibration mechanisms (1109). The rate of growth of three-dimensional disturbances is dramatically altered by the saturated layer, as lifecycles can become irreversible. Of particular interest is the alteration of rectified heat and momentum fluxes due to the implicit heating and cooling in the saturated layer. Preliminary development has focussed on nonlinear behavior at critical latitudes with only one boundary. This is a simpler context for assessing the dependence of reversibility on model resolution.

PLANS FY94

Studies of the mesoscale circulation generated by the interaction of the planetary circulation with topography will continue. The role of moisture in cyclogenesis, as well as in the generation of gravity waves by mesoscale systems, will be investigated.

7.4 MODEL DEVELOPMENT

B. Gross *L. Polinsky*
I. Orlanski *J. Sheldon*

ACTIVITIES FY93

7.4.1 The Zeta Model

The primitive equation zeta model uses the terrain-following coordinate

$$\zeta = e^{-\varepsilon\left(\frac{z-h(x,y)}{H-h(x,y)}\right)}, \tag{1}$$

where *h(x,y)* represents the topographic height and *H* is the height of the rigid lid. The current version of the model is dry, inviscid, and adiabatic (except that weak second-order diffusion is included to control noise), and employs the hydrostatic and Boussinesq approximations. A complete description of the model is provided in (tf). Several modeling considerations have been investigated in preparation for extending this model to include compressible, nonhydrostatic, and moisture effects.

7.4.2 Improved Accuracy in the Pressure Gradient Term

One of the principal problems associated with terrain-following coordinate models is that the pressure gradient force is expressed as the difference between two large terms, a consequence of sloping coordinate surfaces piercing nearly horizontal pressure levels. Errors in evaluating these terms can generate spurious circulations near topography. It was found that the errors can be substantially reduced by removing a profile $\theta(z)$ that is representative of the potential temperature in the domain. The errors may also be reduced by evaluating the pressure gradient on level height surfaces. Both methods require interpolation in the vertical, and interpolation by means of fast Fourier transforms produced the best compromise between accuracy and computational speed.

7.4.3 Accuracy in the Advection Terms

The current version of the zeta model employs a leapfrog integration scheme that is second-order accurate in space and time. Several experiments have been performed to assess the feasibility of using alternate advection schemes in the compressible nonhydrostatic version of the model. All of these schemes are based on calculating upstream departure points of air parcels and using interpolation to derive the value of the required field that will reach the arrival point, usually designated a gridpoint. The principal advantage of these schemes is that they circumvent the traditional Courant-Friedrichs-Lewy (CFL) stability criterion based on advecting velocities; they require only that the interpolation be based on the gridpoints nearest the departure points. Excellent accuracy has been achieved with 6th-order (in space) polynomial interpolation. Monotonicity and shape preservation may be incorporated by introducing a form of flux-corrected transport. These schemes are, however, relatively expensive: 6th-order interpolation in three dimensions requires 57 one-dimensional interpolations to evaluate the variable at each departure point.

7.4.4 Surface Flux Parameterization

To support the sensitivity experiments discussed above in sections 7.2.1 and 7.2.2, the LAHM model was modified, replacing the E2 mixing length based vertical turbulent mixing of heat, moisture, and momentum with a mixing coefficient which depends on the local Richardson number.

PLANS FY94

Additional modifications to the surface flux parameterizations will be performed to determine both the LAHM's sensitivity to such fluxes and prospects for improved performance. The Richardson number dependent vertical flux option will be tested further to better characterize its stronger coupling between the constant flux layer and the lower portion of the free atmosphere. Moist physics and boundary layer physics will be incorporated into the zeta model, and provisions for including non-hydrostatic effects are being considered. The inclusion of a high order polynomial interpolation for the advection scheme in the Zeta model will be performed.

8. SYSTEM AND COMPUTING SERVICES

GOAL

To provide a computational facility to support research conducted at GFDL with emphasis on supercomputing and interactive capabilities for developing, running, and analyzing numerical models and on file serving capabilities for managing large amounts of data.

P. Baker	*T. Taylor*
C. Kranz	*L. Umscheid*
L. Lewis	*R. White*
B. Ross	*W. Yeager*

ACTIVITIES FY93

GFDL's computer facility includes: a Cray Research, Inc. Y-MP super-computer with eight processors, 32 million words of central memory, 256 million words of solid state storage, and 5.6 billion words of rotating storage; three Sun Microsystems and two Silicon Graphics servers; and a variety of text and graphics printers. Distributed throughout GFDL are 112 desktop workstations including 61 Sun 3/50s, 5 SPARCstation 1s, 34 Silicon Graphics 4D/25s, and 12 Silicon Graphics 4D/35s. The workstations, servers, and Y-MP are inter-connected by eight Ethernet segments and a Network Systems Corporation router.

Modifications to the existing contract for Silicon Graphics workstations were negotiated to replace the discontinued Personal Iris 4D/25 with various Iris Indigo models. Twenty Indigo R4000 XZ desktop workstations were ordered, and delivery is expected during autumn 1993. These workstations will be the most powerful yet installed at GFDL, with computational performance 2.5 times faster than the current performance leader and graphics performance 3 to 6 times faster.

Two new color PostScript printers were installed that offer improved speed, better quality, and less costly output than the existing color printers. Additional local disk space was acquired for some of the workstations. A dial-out modem was installed, enabling workstation users to connect with remote systems and bulletin boards not accessible via the Internet.

Several graphical, mathematical, and statistical software packages were installed that further enhance GFDL's data analysis capabilities. A comprehensive source code analyzer/debugger and program optimizer that uses an interactive graphical interface was installed for use on the Silicon Graphics workstations. Public domain text formatting and editing programs that are widely used outside GFDL also were made available.

The network disk capacity available to users was increased by reconfiguring the disks on two file servers. A comprehensive network management software package was installed and is under evaluation. RFPs (Request for Proposals) for maintenance of the Sun workstations and the network were issued, and contract awards are expected by the end of FY93. Work on the acquisition of a high-speed backbone network continued.

Two Cray Y-MP disk subsystems were upgraded with newer technology to improve reliability and future expandability. Planning was begun for an upgrade to the Y-MP tape subsystems that will allow twice as much data to be written on a tape cartridge. Software that automatically manages disk space for temporary files was implemented, and users were given guidelines for effective use of temporary files.

Table 8.1 User Processor Time and Amount of Total Archive Data

Month	Hours	Gigabytes
Oct 92	4,958	6,303
Nov 92	4,981	6,542
Dec 92	5,332	6,590
Jan 93	5,413	6,936
Feb 93	4,714	7,235
Mar 93	5,226	7,589
Apr 93	5,014	7,764
May 93	5,334	8,032
Jun 93	5,234	8,207
Jul 93	5,307	8,554
Aug 93	5,473	8,865
Sep 93	5,297	9,210

The number of user processor hours for each month and the accumulative amount of total archive data in millions of bytes are shown in Table 8.1. The excellent system utilization indicated in the table is an improvement over the already high amount achieved in the previous year. The table also shows the rapid growth of the Laboratory's data archive.

A major effort was undertaken to improve computer security. Access to the computer room and to root passwords was further restricted. Smart card technology was implemented to protect against unauthorized system access through the Internet. The GFDL Scientific Computing Facility was formally accredited following an Information Technology (IT) Security Review conducted by Department of Commerce and NOAA IT personnel, revision of GFDL's security plan, and completion of a risk analysis and a disaster recovery plan.

Because of insufficient FY94 funding from the HPCC (High Performance Computing and Communications) initiative, the planned acquisition of a small parallel system did not proceed. However, preliminary work started on the acquisition of a next generation high performance computer system. GFDL is receiving on-going input from computer vendors as the result of a request-for-comment announcement in the Commerce Business Daily which made the SKYHI atmospheric model available to vendors. The resulting technical collaborations are leading to a code design suitable for use as a benchmark in a planned future procurement.

PLANS FY94

GFDL will continue to pursue cost-effective ways to improve the utility of the Cray Y-MP and the workstation environment in support of its research mission. The Y-MP tape subsystems will be upgraded to double the capacity of tape cartridges and an effort will be undertaken to rewrite most of the data archive, effectively doubling the Laboratory's total data storage capacity. The process of acquiring and installing an FDDI (Fiber Distributed Data Interface) backbone will continue. An additional color PostScript printer will be acquired to provide photographic-quality output. Older Sun workstations will be phased out as new Silicon Graphics workstations are installed. New operating software will be installed for the Y-MP, print server, and Silicon Graphics workstations. Implementation of the new network management software will be completed and a network monitoring console will be installed for the computer operators. Additional public domain and third-party software packages, including NCAR Graphics version 3.2, will be installed for the various hardware platforms. Subject to the availability of funds, the procurement process for a balanced high performance computer system will begin for planned delivery in FY95.

APPENDIX A

GFDL STAFF MEMBERS

and

AFFILIATED PERSONNEL

during

Fiscal Year 1993

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 J.	Sr. Research Associate	FTP
Chen, Yang	Graduate Student	PU*
Delworth, Thomas L.	Sr. Research Associate	FTP
Dismukes, Jr., Gerard C.	Student	PTT*
Donner, Leo J.	Research Scientist	FTP
Freidenreich, Stuart M.	Research Associate	FTP
Hayashi, Yoshikazu	Research Scientist	FTP
Golder, Donald G.	Sr. Research Associate	FTP
Held, Isaac M.	Sr. Research Scientist	FTP
Hansen, Frank	Program Scientist	PU*
Larichev, Vitaly	Program Scientist	PU
Martino, Rocco	Graduate Student	PU*
Pavan, Valentina	Graduate Student	PU
Pelz, Richard	Program Scientist	PU
Phillipps, Peter J.	Research Associate	FTP
Sun, Dezheng	Program Scientist	PU
Zhang, Jiawei	Graduate Student	PU
Ip, Chi Fong	Program Scientist	PU
Knutson, Thomas R.	Sr. Research Associate	FTP
Lofgren, Brent M.	Graduate Student	PU*
Milly, P.C.D.	Research Scientist	RA**
Dunne, Krista	Research Associate	RA**
Ramaswamy, V.	Research Scientist	PU
Chen, Cheng-Ta	Graduate Student	PU
Orris, Rebecca	Graduate Student	PU
Soden, Brian	Program Scientist	PU
Schwarzkopf, M. Daniel	Sr. Research Associate	FTP
Seman, Charles J.	Research Associate	FTP
Spelman, Michael J.	Sr. Research Associate	FTP
Stouffer, Ronald J.	Sr. Research Associate	FTP
Vinnikov, Konstantin	Program Scientist	PU*
Wetherald, Richard T.	Sr. Research Associate	FTP
Williams, Gareth P.	Sr. Research Scientist	FTP

*Affiliation terminated prior to September 30, 1993.
**United States Geological Survey (USGS) on detail to GFDL.

MIDDLE ATMOSPHERE DYNAMICS AND CHEMISTRY

Mahlman, Jerry D.	Director	FTP
Goldberg, Charles	Program Scientist	PU
Hamilton, Kevin P.	Research Scientist	FTP
Hall, Alexander	Graduate Student	PU
Nakamura, Noboru	Program Scientist	PU*
Wilson, Robert J.	Research Associate	FTP
Yuan, Li	Graduate Student	PU*
Hemler, Richard S.	Sr. Research Associate	FTP
Goldberg, David	Student	PTT
Levy II, Hiram	Research Scientist	FTP
Kasibhatla, Prasad	Georgia Tech. Res. Scientist	GIT
Klonecki, Andrzej	Graduate Student	PU
Moxim, Walter J.	Sr. Research Associate	FTP
Richardson, Jennifer	Georgia Tech. Grad. Student	GIT*
Yienger, James J.	Technical Staff	PU
Zimmerman, Jorg	Program Scientist	PU
Perliski, Lori	Program Scientist	PU
Strahan, Susan E.	Program Scientist	PU*

EXPERIMENTAL PREDICTION

Miyakoda, Kikuro	Sr. Research Scientist	FTP
Anderson, Jeffrey L.	Research Scientist	FTP
Gordon, Charles T.	Research Scientist	FTP
Gudgel, Richard G.	Research Associate	FTP
Ploshay, Jeffrey J.	Sr. Research Associate	FTP
Rosati, Anthony J.	Sr. Research Associate	FTP
Sirutis, Joseph J.	Sr. Research Associate	FTP
Smith, Robert G.	Computer Assistant	FTP
Stern, William F.	Sr. Research Associate	FTP
Ballos, Constanti K.	Student	PTT
Wyman, Bruce L.	Research Associate	FTP

*Affiliation terminated prior to September 30, 1993.

OCEANIC CIRCULATION

Bryan, Kirk	Sr. Research Scientist	FTP
Dixon, Keith W.	Sr. Research Associate	FTP
Griffies, Stephen	UCAR Fellow	PU
Harrison, Matthew	Research Associate	NOAA**
Hsieh, William	Visiting Fellow	PU*
Hu, Ding Ming	UCAR Fellow	PU
Hurlin, William J.	Research Associate	FTP
Pacanowski, Ronald C.	Sr. Research Associate	FTP
Toggweiler, John R.	Research Scientist	FTP
Carson, Steven R.	Research Associate	FTP
Mix, Alan	Visiting Fellow	PU*
Samuels, Bonita L.	Research Associate	FTP
Tziperman, Eli	Program Scientist	PU

OBSERVATIONAL STUDIES

Oort, Abraham H.	Sr. Research Scientist	FTP
Dritt, L. Pasha	Graduate Student	PU
Lanzante, John	Research Associate	FTP
Lau, Ngar-Cheung	Sr. Research Scientist	FTP
Crane, Mark	Research Associate	FTP
Nakamura, Hisashi	Program Scientist	PU*
Nath, Mary Jo	Research Associate	FTP
Zhang, Yunqing	Graduate Student	PU
Lindberg, Craig R.	Program Scientist	PU
Raval, Ameet	Research Associate	INT
Rosenstein, Melvin	Research Assistant	FTP

*Affiliation terminated prior to September 30, 1993.
**NOAA Corps on assignment to GFDL.

HURRICANE DYNAMICS

Kurihara, Yoshio	Sr. Research Scientist	FTP
Bender, Morris A.	Sr. Research Associate	FTP
Ginis, Isaac	Program Scientist	PU*
Ross, Rebecca J.	Research Associate	FTP*
Tuleya, Robert E.	Sr. Research Associate	FTP
Rears, Patrick J.	Student	PTT
Wu, Chun-Chieh	Program Scientist	PU

MESOSCALE DYNAMICS

Orlanski, Isidoro	Sr. Research Scientist	FTP
Chang, Kar-Man	Graduate Student	PU*
Garner, Stephen	Research Scientist	FTP
Gross, Brian	Research Associate	FTP
Mak, Mankin	Program Scientist	PU
Polinsky, Larry	Research Associate	FTP
Sheldon, John	Research Associate	FTP

*Affiliation terminated prior to September 30, 1993.

CENTRALIZED SUPPORT SERVICES

Administrative and Technical Support

Mahlman, Jerry D.	Director	FTP
Ross, Bruce B.	Assistant Director	FTP
Haller, Gail T.	Library Technician	PTP
Lewis, Lawrence J.	Supv. Computer Systems Analyst	FTP
Marshall, Wendy H.	Editorial Assistant	FTP
Pege, Joan M.	Administrative Support Asst.	FTP
Amend, Beatrice E.	Office Automation Clerk	INT
Tunison, Philip G.	Supv. Scientific Illustrator	FTP*
Raphael, Catherine	Scientific Illustrator	PTP
Varanyak, Jeffrey	Scientific Illustrator	FTP
Umscheid, Ludwig J.	Major Systems Specialist	FTP
Urbani, Elaine B.	Travel Clerk	FTP
Uveges, Frank J.	Supv. Computer Specialist	FTP
Byrne, James S.	Jr. Technician	FTP
Shearn, William F.	Operations Manager	FTP
Williams, Betty M.	Secretary	FTP
Kennedy, Joyce Y.	Editorial Assistant	FTP

SYSTEMS AND SUPPORT GROUP

Lewis, Lawrence J.	Supv. Computer Systems Analyst	FTP
Baker, Philip L.	Computer Systems Analyst	FTP
Heyman, Kimberlee S.	Computer Clerk	PTT*
Kranz, Christopher L.	Computer Systems Analyst	FTP*
Taylor III, Thomas E.	Computer Assistant	FTP
White, Robert K.	Computer Systems Analyst	FTP
Yeager, William T.	Computer Systems Analyst	FTP

*Affiliation terminated prior to September 30, 1993.

COMPUTER OPERATIONS SUPPORT

Shearn, William F.	Operations Manager	FTP
Hopps, Frank K.	Supv. Computer Operator	FTP
Davis, Manuel H.	Computer Operator	FTP*
Deuringer, James A.	Computer Operator	FTP
Dutton, Tania	Computer Operator	FTP
King, John T.	Lead Computer Operator	FTP
Ledden, Jay H.	Computer Operator	FTP
Silva, Paula G.	Computer Operator	FTP*
Hand, Joseph S.	Supv. Computer Operator	FTP
Blakemore, Geneve	Computer Operator	FTP
Brandbergh, Gerald C.	Computer Operator	FTP
Cordwell, Clara L.	Computer Operator	FTP
Krueger, Scott R.	Computer Operator	FTP
Pinter, Kristina D.	Computer Operator	PTT
Heinbuch, Ernest C.	Supv. Computer Operator	FTP
Conover, Leonard J.	Lead Computer Operator	FTP
Harrold, Renee M.	Computer Operator	FTP
Schulze, Howard P.	Computer Operator	FTP
Henne, Ronald N.	Computer Assistant	FTP

*Affiliation terminated prior to September 30, 1993.

ATMOSPHERIC AND OCEANIC SCIENCES PROGRAM

Philander, S.G.H.	Professor, Program Director	PU
Callan, Johann V.	Technical Research Secretary	PU
Goddard, Lisa M.	Graduate Student	PU
Gu, Daifang	Program Scientist	PU
Koberle, Cornelia	Visiting Research Staff	PU*
Lambert, Gregory	Technical Staff	PU
Li, Jingdong	Graduate Student	PU*
Li, Tianming	Program Scientist	PU
Liu, Zhengyu	UCAR Fellow	PU*
Nicoletti, Mary Ann	Program Manager	PU
Ravelo, Christina	Program Scientist	PU*
Valerio, Anna	Technical Research Secretary	PU
Wunsch, Carl	Program Scientist	PU
Xie, Shang-Ping	Program Scientist	PU*
Mellor, George	Professor	PU
Ezer, Tal	Research Staff	PU
Kim, Namsoug	Technical Staff	PU
McCarthy, Robert	Program Scientist	PU*
Sarmiento, Jorge	Professor	PU
Anderson, Laurence A.	Graduate Student	PU*
Armstrong, Robert	Program Scientist	PU
Bryan, Frank	Visiting Fellow	PU
Figueroa, Horacio	Research Staff	PU
Key, Robert M.	Research Scientist	PU
LeQuere, Corrine	Technical Staff	PU
McDonald, Gerard	Technical Staff	PU
Murnane, Richard J.	Research Staff	PU
Olszewski, Jason	Research Assistant	PU
Orr, James	Research Staff	PU*
Rayner, Peter	Research Staff	PU
Rossmassler, Julie E.	Technical Staff	PU
Rotter, Richard	Technical Staff	PU
Sabine, Christopher L.	Research Staff	PU
Slater, Richard D.	Technical Staff	PU
Webb, Vincent	Graduate Student	PU

*Affiliation terminated prior to September 30, 1993.

CRAY RESEARCH INCORPORATED

Siebers, Bernard	Analyst in Charge
Braunstein, Mark	Field Engineer
Kerr, Christopher L.	Senior Physical Scientist
Rao, Ramesh	Applications Analyst
Weiss, Ed	Engineer in Charge

PERSONNEL SUMMARY

September 30, 1993

GFDL/NOAA	
Full Time Permanent (FTP)	84
Part Time Permanent (PTP)	2
Part Time Temporary (PTT)	1
Intermittent (INT)	2
National Oceanic and Atmospheric Administration (NOAA) Corps	1
Students	3
PRINCETON UNIVERSITY (PU)	
Program Scientists	16
Graduate Students	10
Professors	3
Research Scientists	2
Research Staff	6
Support Staff	3
Technical Staff	8
UCAR Fellows	2
Visiting Fellow	1
OTHER INSTITUTIONS	
Georgia Tech Research Associates (GIT)	1
U.S. Geological Survey	2
CRAY RESEARCH INC.	
Computer Support Staff	5
TOTAL	**152**

APPENDIX B

GFDL

BIBLIOGRAPHY

1988-1993

GFDL PUBLICATIONS

This is a partial listing of GFDL publications. A copy of the complete bibliography can be obtained by calling 609-452-6502, or by writing to:

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

* (849) Galperin, B., L.H. Kantha, S. Hassid, and A. Rosati, A Quasi-Equilibrium Turbulent Energy Model for Geophysical Flows, Journal of the Atmospheric Sciences, 45(1):55-62, 1988.

* (850) Savijarvi, H.I., The Maintenance Mechanisms of Transient Large-Scale Variations in the Atmosphere, Part I: Potential Temperature and Moisture, 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.

(852) Williams, G.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, S.B., Reply to A Parameterization of Scale-Dependent Radiative Damping in the Middle Atmosphere, Journal of the Atmospheric Sciences, 44(24):3829-3832, 1988.

* (855) Boning, C.W., and M.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 Rawinsonde Data, Monthly Weather Review, 116(2):417-430, 1988.

(857) Levitus, S., Ekman Volume Fluxes for the World Ocean and Individual Ocean Basins, Journal of Physical Oceanography, 18(2):271-279, 1988.

* (858) Panetta, R.L., I.M. Held, and R.T. Pierrehumbert, External Rossby Waves in the Two-Layer Model, Journal of the Atmospheric Sciences, 44(20):2924-2933, 1988.

** In collaboration with other organizations*

(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, B., Another Look at CISK in Polar Oceanic Air Masses, Tellus, 39A:179-186, 1988.

* (861) Neelin, J.D., 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, S., I.M. Held, and S.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, G.P., The Dynamical Range of Global Circulations-I, Climate Dynamics, 2:205-260, 1988.

(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, F.B., R.S. Hemler, and B.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-J148, 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.A., 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, R.E., A Numerical Study of the Genesis of Tropical Storms Observed during the FGGE Year, Monthly Weather Review, 116(5):1188-1208, 1988.

** In collaboration with other organizations*

* (872) Sarmiento, J.L., J.R. Toggweiler, and R.G. Najjar, Ocean Carbon-Cycle Dynamics and Atmospheric P_{co2}, Philosophical Transactions of the Royal Society of London, A325:3-21, 1988.

(873) Toggweiler, J.R., Deep-Sea Carbon, A Burning Issue, Nature, 334:468, 1988.

* (874) Zhu, X., 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, N., and A.H. Oort, Atmospheric Heat Budgets of the Polar Regions, Journal of Geophysical Research, 93(D8):9510-9524, 1988.

(877) Oort, A.H., Climate Observations and Diagnostics, 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.L., and S. Manabe, The Influence of Potential Evaporation on the Variabilities of Simulated 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 the 1982-83 El Niño, Journal of Physical Oceanography, 18(6):926-931, 1988.

* (880) Sarmiento, J.L., T.D. Herbert, and J.R. Toggweiler, Causes of Anoxia in the World Ocean, Global Biogeochemical Cycles, 2(2):115-128, 1988.

* (881) Mesinger, F., Z.I. Janjic, S. Nickovic, D. Gavrilov, and D.G. 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, N.-C., 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, G.P., The Dynamical Range of Global Circulations-II, Climate Dynamics, 3:45-84, 1988.

(885) Lipps, F.B., and R.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.

* *In collaboration with other organizations*

* (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, K.H., and I.M. Held, Stationary Waves of the Ice Age Climate, Journal of Climate, 9(8):807-819, 1988.

(888) Oort, A.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, Louvain-la-Neuve, Belgium, 1-28, 1988.

(889) Lau, N.-C., Variability of the Observed Midlatitude Storm Tracks in Relation to Low-Frequency Changes in the Circulation Pattern, Journal of the Atmospheric Sciences, 45(19):2718-2743, 1988.

* (890) Lin, S.-J., and R.T. Pierrehumbert, Does Ekman Friction Suppress Baroclinic Instability? Journal of the Atmospheric Sciences, 45(20):2920-2933, 1988.

* (891) Nakamura, N., Scale Selection of Baroclinic Instability - Effects of Stratification and Nongeostrophy, 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, Journal of the Atmospheric Sciences, 45(21):3017-3033, 1988.

* (893) Hamilton, K., 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.L., and I.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, J.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, 1989.

(898) Rosati, A., and K. Miyakoda, A General Circulation Model for Upper Ocean Simulation, Journal of Physical Oceanography, 18(11):1601-1626, 1988.

** In collaboration with other organizations*

(899) Levitus, S., Decadal and Pentadal Distributions of Hydrographic Stations at 1000m Depth for the World Ocean, Progress in Oceanography, 20(2):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.D. Herbert, and J.R. Toggweiler, Mediterranean Nutrient Balance and Episodes of Anoxia, Global Biogeochemical Cycles, 2(4):427-444, 1988.

* (902) Snieder, R.K., and S.B. Fels, The Flywheel Effect in the Middle Atmosphere, Journal of the Atmospheric Sciences, 45(24):3996-4004, 1988.

* (903) Lau, N.-C., I.M. Held, and J.D. Neelin, The Madden-Julian Oscillation in an Idealized General Circulation Model, Journal of the Atmospheric Sciences, 45(24):3810-3832, 1988.

* (904) Held, I.M., S.W. Lyons, and S. Nigam, Transients and the Extratropical Response to El Niño, 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, 1988.

(906) Toggweiler, J.R., Are Rising and Falling Particles Microbial Elevators? Nature, 337:691-692, 1989.

(907) Lau, N.-C., 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", 1:139-154, 1989.

* (908) Boning, C.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, M., G.L. Mellor, and M.G. McPhee, Role of the Molecular Sublayer in the Melting or Freezing of Sea Ice, Journal of Physical Oceanography, 19(1):139-147, 1989.

* (910) Thompson, S.L., V. Ramaswamy, and C. 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, 1988.

* (911) Oort, A.H., S.C. Ascher, S. Levitus, J.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, P., and S.G.H. Philander, Rossby Wave Packets in Baroclinic Mean Currents, Deep-Sea Research, 36(1):17-37, 1989.

** In collaboration with other organizations*

(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, Pure and Applied Geophysics, 130(2/3):421-443, 1989.

(916) Levy II, H., 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, K., 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, 1988.

(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, 1988.

(919) Stern, W.F., and K. Miyakoda, Systematic Errors in GFDL's Extended Range Prediction Spectral GCM, Proceedings of Workshop on Systematic Errors in Models of the Atmosphere, Toronto, Canada, 19-23 September 1988, WMO/TD No. 273, 78-122, 1988.

* (920) Kantha, L.H., and G.L. Mellor, A Numerical Model of the Atmospheric Boundary Layer Over a Marginal Ice Zone, Journal of Geophysical Research, 94(C4):4959-4970, 1989.

* (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, K., 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, X., Radiative Cooling Calculated by Random Band Models with $S^{-1-\beta}$ Tailed Distribution, Journal of the Atmospheric Sciences, 46(4):511-520, 1989.

* *In collaboration with other organizations*

(926) Levy II, H., and W.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, 1. Steady State, Prebomb 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, 2. Distributions of Bomb-Produced Carbon-14, Journal of Geophysical Research, 94(C6):8243-8264, 1989.

(929) Levy II, H., and W.J. Moxim, Simulated Global Distribution and Deposition of Reactive Nitrogen Emitted by Fossil Fuel Combustion, Tellus, 41B:256-271, 1989.

* (930) Karoly, D.J., Northern Hemisphere Temperature Trends: A Possible Greenhouse Gas Effect? Geophysical Research Letters, 16(5):465-468, 1989.

(931) Levy II, H., Tracers of Atmospheric Transport, Nature, 325(6107):761-762, 1988.

(932) Levitus, S., Interpentadal Variability of Temperature and Salinity at Intermediate Depths of the North Atlantic Ocean, 1970-1974 Versus 1955-1959, Journal of Geophysical Research, 94(C5):6091-6131, 1989.

* (933) Savijarvi, H.I., and H.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.

** In collaboration with other organizations*

(938) Levy II, H., and W.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, Y., and M.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, S., Interpentadal Variability of Salinity in the Upper 150m of the North Atlantic Ocean, 1970-74 Versus 1955-59, Journal of Geophysical Research, 94(C7):9679-9685, 1989.

* (941) Kantha, L.H., and G.L. Mellor, 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, S.-J., The Instability Mechanism of Synoptic-Scale Eddies, Ph.D. Dissertation, Atmospheric and Oceanic Science Program, Princeton University, 1989.

* (943) Chang, P., Oceanic Adjustment in the Presence of Mean Currents, Ph.D. Dissertation, Atmospheric and Oceanic Sciences Program, Princeton University, 1989.

* (944) Nakamura, N., Dynamics of Baroclinic Instability in Rapid Cyclogenesis, Ph.D. Dissertation, Atmospheric and Oceanic Sciences Program, Princeton University, 1989.

* (945) 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, 70(6):620-622, 1989.

* (946) Mellor, G.L., and L.H. Kantha, An Ice Coupled Model, Journal of Geophysical Research, 94(C8):10,937-10,954, 1989.

* (947) Karoly, D.J., R.A. Plumb, and M. Ting, Examples of the Horizontal Propagation of Quasi-Stationary Waves, Journal of the Atmospheric Sciences, 46(18):2802-2811, 1989.

* (948) Nakamura, N., and I.M. Held, Nonlinear Equilibration of Two-Dimensional Eady Waves, Journal of the Atmospheric Sciences, 46(19):3055-3064, 1989.

(949) Oort, A.H., Angular Momentum Cycle in the Atmosphere-Ocean-Solid Earth System, Bulletin of the American Meteorological Society, 70(10):1231-1242, 1989.

(950) Derber, J., and A. Rosati, A Global Oceanic Data Assimilation System, Journal of Physical Oceanography, 19(9):1333-1347, 1989.

(951) Philander, S.G.H., El Niño and La Niña, American Scientist, 77:451-459, 1989.

* *In collaboration with other organizations*

(952) Mahlman, J.D., Mathematical Modeling of Greenhouse Warming: How Much Do We Know? Proceedings of the National Research Council Forum on Global Change and Our Common Future, 2-3 May 1989, Washington, DC, 62-72, 1989.

* (953) Feldstein, S.B., and I.M. Held, Barotropic Decay of Barotropic Waves in a Two-Layer Beta-Plane Model, Journal of the Atmospheric Sciences, 46(22):3416-3430, 1989.

(954) Levitus, S., Interpentadal Variability of Temperature and Salinity in the Deep North Atlantic, 1970-74 Versus 1955-59, Journal of Geophysical Research, 94(C11):16,125-16,131, 1989.

(955) 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, Philosophical Transactions of the Royal Society of London, A329:167-178, 1989.

(956) Cox, M.D., An Idealized Model of the World Ocean, Part I: The Global-Scale Water Masses, Journal of Physical Oceanography, 19(11):1730-1752, 1989.

(957) Derber, J.C., A Variational Continuous Assimilation Technique, Monthly Weather Review, 117(11):2437-2446, 1989.

(958) Delworth, T., and S. Manabe, The Influence of Soil Wetness on Near-Surface Atmospheric Variability, Journal of Climate, 2(12):1447-1462, 1989.

(959) Kurihara, Y., C.L. Kerr, and M.A. Bender, An Improved Numerical Scheme to Treat the Open Lateral Boundary of a Regional Model, Monthly Weather Review, 117(12):2714-2722, 1989.

* (960) Orlanski, I., M. Marino, C. Menendez, and J. Katzfey, The Role of Cyclones in the Daily Variability of Antarctic Ozone, from the Third International Conference on Southern Hemisphere Meteorology and Oceanography, November 13-17, 1989, Buenos Aires, Argentina, American Meteorological Society, Boston, MA, 416-420, 1989.

(961) Stouffer, R.J., S. Manabe, and K. Bryan, Interhemispheric Asymmetry in Climate Response to a Gradual Increase of Atmospheric CO_2, Nature, 342:660-662, 1989.

(962) Manabe, S., and A.J. Broccoli, Mountains and Arid Climates of Middle Latitudes, Science, 247:192-195, 1990.

* (963) Karoly, D.J., The Role of Transient Eddies in Low Frequency Zonal Variations of the Southern Hemisphere Circulation, Tellus, 42A(1):41-50, 1990.

* (964) Fyfe, J., and I.M. Held, The Two-Fifths and One-Fifth Rules for Rossby Wave Breaking in the WKB Limit, Journal of the Atmospheric Sciences, 47(6):697-706, 1990.

* (965) Held, I.M., and M. Ting, Orographic Versus Thermal Forcing of Stationary Waves: The Importance of the Mean Low-Level Wind, Journal of the Atmospheric Sciences, 47(4):495-500, 1990.

** In collaboration with other organizations*

(966) Levitus, S., Interpentadal Variability of Steric Sea Level and Geopotential Thickness of the North Atlantic Ocean, 1970-74 Versus 1955-59, Journal of Geophysical Research, 95(C4):5233-5238, 1990.

(967) Moxim, W.J., Simulated Transport of NO_y to Hawaii during August: A Synoptic Study, Journal of Geophysical Research, 95(D5):5717-5729, 1990.

(968) Toggweiler, J.R., Diving Into the Organic Soup, Nature, 345:203-204, 1990.

(969) Bryan, K., Climate Response to Greenhouse Warming: The Role of the Ocean, In Climate and the Geosciences, A. Berger, S. Schneider, J.C. Duplessy (eds.), Kluwer Academic Publishers, 435-446, 1989.

(970) Bryan, K., The Design of Numerical Models of the Ocean Circulation, In Oceanic Circulation Models: Combining Data and Dynamics, Kluwer Academic Publishers, 465-500, 1989.

(971) Bryan, K., A Review of "Mathematical Modelling of Ocean Circulation" by G.I. Marchuk and A.S. Sarkisyan, Bulletin of the American Meteorological Society, 71(2):209-210, 1990.

(972) Held, I.M., and P.J. Phillipps, A Barotropic Model of the Interaction between the Hadley Cell and a Rossby Wave, Journal of the Atmospheric Sciences, 47(7):856-869, 1990.

* (973) Chang, P., and S.G.H. Philander, Quasi-Geostrophic Oceanic Adjustment in the Presence of Mean Currents, Dynamics of Atmospheres and Oceans, (14):387-414, 1990.

* (974) Murnane, R.J., and R.F. Stallard, Germanium and Silicon in Rivers of the Oronoco Drainage Basin, Nature, 344:749-752, 1990.

(975) Manabe, S., and T. Delworth, The Temporal Variability of Soil Wetness and its Impact on Climate, Climatic Change, 16(2):185-192, 1990.

(976) Hamilton, K., A Look at the Recently Proposed Solar-QBO-Weather Relationship, Journal of Climate, 3(4):497-503, 1990.

* (977) Zhu, X., Carbon Dioxide 15-μm Band Cooling Rates in the Upper Middle Atmosphere Calculated by Curtis Matrix Interpolation, Journal of the Atmospheric Sciences, 47(6):755-774, 1990.

* (978) Sheng, J., and Y. Hayashi, Observed and Simulated Energy Cycles in the Frequency Domain, Journal of the Atmospheric Sciences, 47(10):1243-1254, 1990.

* (979) Sheng, J., and Y. Hayashi, Estimation of Atmospheric Energetics in the Frequency Domain during the FGGE Year, Journal of the Atmospheric Sciences, 47(10):1255-1268, 1990.

** In collaboration with other organizations*

(980) Lau, N.-C., 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, BMRC Research Report No. 21, 1-8, 1990.

(981) Manabe, S., K. Bryan, and M.J. Spelman, Transient Response of a Global Ocean-Atmosphere Model to a Doubling of Atmospheric Carbon Dioxide, Journal of Physical Oceanography, 20(5):722-749, 1990.

* (982) Thiele, G., and J.L. Sarmiento, Tracer Dating and Ocean Ventilation, Journal of Geophysical Research, 95(C6):9377-9391, 1990.

(983) Lipps, F.B., On the Anelastic Approximation for Deep Convection, Journal of the Atmospheric Sciences, 47(14):1794-1798, 1990.

* (984) Najjar, R., Simulations of the Phosphorus and Oxygen Cycles in the World Ocean Using a General Circulation Model, Ph.D. Dissertation, Atmospheric and Oceanic Sciences, Princeton University, 1990.

* (985) Ting, M., The Stationary Wave Response to Tropical and Midlatitude SST Anomalies, Ph.D. Dissertation, Atmospheric and Oceanic Sciences Program, Princeton University, 1990.

* (986) Ma, C.-C., Models of Planetary Wave Propagation in the Middle Atmosphere, Ph.D. Dissertation, Atmospheric and Oceanic Sciences Program, Princeton University, 1990.

(987) Sirutis, J., and K. Miyakoda, Subgrid Scale Physics in 1-Month Forecasts, Part I: Experiment with Four Parameterization Packages, Monthly Weather Review, 118(5):1043-1064, 1990.

(988) Miyakoda, K., and J. Sirutis, Subgrid Scale Physics in 1-Month Forecasts, Part II: Systematic Error and Blocking Forecasts, Monthly Weather Review, 118(5):1065-1081, 1990.

* (989) Saravanan, R., Mechanisms of Equatorial Superrotation: Studies with Two-Level Models, Ph.D. Dissertation, Atmospheric and Oceanic Sciences Program, Princeton University, 1990.

* (990) Chao, Y., Seasonal and Interannual Variability in the Tropical Pacific Ocean, Ph.D. Dissertation, Atmospheric and Oceanic Sciences Program, Princeton University, 1990.

* (991) Anderson, J.L., Low Frequency Variability and the Instability of Zonally Varying Atmospheric Flows, Ph.D. Dissertation, Atmospheric and Oceanic Sciences Program, Princeton University, 1990.

(992) Cook, K.H., The Atmosphere's Response to the Ice Sheets of the Last Glacial Maximum, Annals of Glaciology, 14:32-38, 1990.

* *In collaboration with other organizations*

* (993) Peixoto, J.P., and A.H. Oort, The Water Cycle and the Climate, La Recherche, 21(221):570-579, Special Issue on "Water", 1990.

* (994) Hou, A.Y., S.B. Fels, and R.M. Goody, Zonal Superrotation Above Venus' Cloud Base Induced by the Semidiurnal Tide and the Mean Meridional Circulation, Journal of the Atmospheric Sciences, 47(15):1894-1901, 1990.

(995) Levy II, H., The Regional and Global Transport and Distribution of Trace Species Released at the Earth's Surface, Proceedings of Long Range Transport of Pesticides Symposium, Toronto, Canada, June 1988, D.A. Kurtz (ed.), Lewis Publishers, Inc., 83-95, 1990.

(996) Toggweiler, J.R., Bombs and Ocean Carbon Cycles, Nature, (347):122-123, 1990.

* (997) Mahlman, J.D., A.F. Tuck, and I. Galbally, The Role of Greenhouse Gases in Global Chemical-Dynamical Processes, Report of the Tenth Session of the Joint Scientific Committee, Villefranche-Sur-Mer, France, 13-18 March 1989, WMO/TD 314, 1989.

* (998) Murnane, R.J., J.L. Sarmiento, and M.P. Bacon, Thorium Isotopes, Particle Cycling Models, and Inverse Calculations of Model Rate Constants, Journal of Geophysical Research, 95(C9):16,195-16,206, 1990.

* (999) Hakkinen, S., Models and Their Applications to Polar Oceanography, In Polar Oceanography, W. Smith (ed.), Academic Press, 335-384, 1990.

* (1000) 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, 95(C9):15,959-15,969, 1990.

* (1001) Bretherton, F.P., K. Bryan, J.D. Woods, Time-Dependent Greenhouse-Gas-Induced Climate Change, In Climate Change, the IPCC Scientific Assessment, J.T. Houghton, G.J. Jenkins, and J.J. Ephraums (eds.), Cambridge University Press, 179-193, 1990.

* (1002) Matano, R.P., A Numerical Study of the Circulation in the South Atlantic Ocean, Ph.D. Dissertation, Atmospheric and Oceanic Sciences Program, Princeton University, 1991.

* (1003) Pan, Y.H., and A.H. Oort, Correlation Analyses between Sea Surface Temperature Anomalies in the Eastern Equatorial Pacific and the World Ocean, Climate Dynamics, 4:191-205, 1990.

* (1004) Tao, X., Atmospheric Responses to Lower Tropospheric Forcing in a Multi-Layer Isentropic Model, Ph.D. Dissertation, Atmospheric and Oceanic Sciences Program, Princeton University, 1991.

* (1005) Lau, K.-H., and N.-C. Lau, Observed Structure and Propagation Characteristics of Tropical Summertime Synoptic Scale Disturbances, Monthly Weather Review, 118(9):1888-1913, 1990.

* *In collaboration with other organizations*

* (1006) Zhu, X., and D.F. Strobel, On the Role of Vibration-Vibration Transitions in Radiative Cooling of the CO_2 15 μm Band Around the Mesopause, Journal of Geophysical Research, 95(D4):3571-3577, 1990.

(1007) Wetherald, R.T., and S. Manabe, Hydrologic Sensitivity to CO_2-Induced Global Warming, Civil Engineering Practice, 5(1):33-36, 1990.

* (1008) Lau, K.-H., and N.-C. 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, 1990.

(1009) Broccoli, A.J., and S. Manabe, Can Existing Climate Models be Used to Study Anthropogenic Changes in Tropical Cyclone Climate? Geophysical Research Letters, 17(11):1917-1920, 1990.

* (1010) Detwiler, A., and V. Ramaswamy, Radiative Heating Profiles in Simple Cirrus Cloud Systems, Journal of the Atmospheric Sciences, 47(18):2167-2176, 1990.

* (1011) Sarmiento, J.L., G. Thiele, R.M. Key, and W.S. Moore, Oxygen and Nitrate New Production and Remineralization in the North Atlantic Subtropical Gyre, Journal of Geophysical Research, 95(C10):18,303-18,315, 1990.

* (1012) 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, Estuarine, Coastal and Shelf Science, 31(3):231-253, 1990.

* (1013) 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, Estuarine, Coastal and Shelf Science, 31(3):255-281, 1990.

(1014) Lau, N.-C., and M.J. Nath, A General Circulation Model Study of the Atmospheric Response to Extratropical SST Anomalies Observed in 1950-79, Journal of Climate, 3(9):965-989, 1990.

* (1015) Kantha, L.H., and A. Rosati, The Effect of Curvature on Turbulence in Stratified Fluids, Journal of Geophysical Research, 95(C11):20,313-20,330, 1990.

(1016) Kurihara, Y., M.A. Bender, R.E. Tuleya, and R.J. Ross, Prediction Experiments of Hurricane Gloria (1985) Using a Multiply Nested Movable Mesh Model, Monthly Weather Review, 118(10):2185-2198, 1990.

* (1017) Saravanan, R., A Multiwave Model of the Quasi-biennial Oscillation, Journal of the Atmospheric Sciences, 47(21):2465-2474, 1990.

* (1018) Ting, M., and I.M. Held, The Stationary Wave Response to a Tropical SST Anomaly in an Idealized GCM, Journal of the Atmospheric Sciences, 47(21):2546-2566, 1990.

** In collaboration with other organizations*

* (1019) Lau, K.-H., An Observational Study of Tropical Summertime Synoptic Scale Disturbances, Ph.D. Dissertation, Atmospheric and Oceanic Sciences Program, Princeton University, 1991.

* (1020) Zhu, X., Spectral Parameters in Band Models with Distributed Line Intensity, Journal of Quantitative Spectroscopy and Radiative Transfer, 45(1):33-46, 1991.

* (1021) Xue, H.-J., Numerical Studies of Gulf Stream Meanders in the South Atlantic Bight, Ph.D. Dissertation, Atmospheric and Oceanic Sciences Program, Princeton University, 1991.

* (1022) Milly, P.C.D., A Refinement of the Combination Equations for Evaporation, Surveys in Geophysics, 12:145-154, 1991.

(1023) Bryan, K., and R.J. Stouffer, A Note on Bjerknes's Hypothesis for North Atlantic Variability, Journal of Marine Systems, 1:229-241, 1991.

* (1024) Bard, E., M. Arnold, J.R. Toggweiler, P. Maurice, and J.-C. Duplessy, Bomb ^{14}C in the Indian Ocean Measured by Accelerator Mass Spectrometry: Oceanographic Implications, Radiocarbon, 31(3):510-522, 1991.

* (1025) Garner, S.T., The Nongeostrophic Structure of Baroclinic Waves and its Relation to Fronts and Jet Streaks, Journal of the Atmospheric Sciences, 48(1):147-162, 1991.

* (1026) Randel, W.J., and I.M. Held, Phase Speed Spectra of Transient Eddy Fluxes and Critical Layer Absorption, Journal of the Atmospheric Sciences, 48(5):688-697, 1991.

* (1027) Wetherald, R.T., V. Ramaswamy, and S. Manabe, A Comparative Study of the Observations of High Clouds and Simulations by an Atmospheric General Circulation Model, Climate Dynamics, 5:135-143, 1991.

(1028) Tuleya, R.E., Sensitivity Studies of Tropical Storm Genesis Using a Numerical Model, Monthly Weather Review, 119(3):721-733, 1991.

* (1029) Lee, S., and I.M. Held, Subcritical Instability and Hysteresis in a Two-Layer Model, Journal of the Atmospheric Sciences, 48(8):1071-1077, 1991.

* (1030) Ramaswamy, V., M.D. Schwarzkopf, and S.C. Liu, Preface to JGR-ICRCCM Issue, Journal of Geophysical Research, 96(D5):8921-8923, 1991.

* (1031) Ramaswamy, V., and S.M. Freidenreich, Solar Radiative Line-by-Line Determination of Water Vapor Absorption and Water Cloud Extinction in Inhomogeneous Atmospheres, Journal of Geophysical Research, 96(D5):9133-9157, 1991.

* (1032) Fouquart, Y., B. Bonnel, and V. Ramaswamy, Intercomparing Shortwave Radiation Codes for Climate Studies, Journal of Geophysical Research, 96(D5):8955-8968, 1991.

* (1033) Ellingson, R.G., J. Ellis, and S. Fels, The Intercomparison of Radiation Codes Used in Climate Models: Long Wave Results, Journal of Geophysical Research, 96(D5):8929-8953, 1991.

** In collaboration with other organizations*

(1034) Schwarzkopf, M.D., and S.B. Fels, The Simplified Exchange Method Revisited: An Accurate, Rapid Method for Computation of Infrared Cooling Rates and Fluxes, Journal of Geophysical Research, 96(D5):9075-9096, 1991.

* (1035) Feigelson, E.M., B.A. Fomin, I.A. Gorchakova, E.V. Rozanov, Yu. M. Timofeyev, A.N. Trotsenko, and M.D. Schwarzkopf, Calculation of Longwave Radiation Fluxes in Atmospheres, Journal of Geophysical Research, 96(D5):8985-9001, 1991.

(1036) Manabe, S., Studies of Glacial Climates by Coupled Atmosphere-Ocean Models: How Useful are Coupled Models? In Global Changes of the Past, R.S. Bradley (ed.), 1989 OIES Global Change Institute, Snowmass, CO, 24 July-4 August 1989, UCAR/Office for Interdisciplinary Earth Studies, Boulder, CO, 421-448, 1991.

* (1037) Peixoto, J.P., A.H. Oort, M. de Almeida, and A. Tome, Entropy Budget of the Atmosphere, Journal of Geophysical Research, 96(D6):10,981-10,988, 1991.

* (1038) Fels, S.B., J.T. Kiehl, A.A. Lacis, and M.D. Schwarzkopf, Infrared Cooling Rate Calculations in Operational General Circulation Models: Comparisons with Benchmark Computations, Journal of Geophysical Research, 96(D5):9105-9120, 1991.

* (1039) Karoly, D.J., and D.S. Graves, On Data Sources and Quality for the Southern Hemisphere Stratosphere, In Dynamics, Transport and Photochemistry in the Middle Atmosphere of the Southern Hemisphere, A. O'Neill (ed.), NATO ASI Series C321, Kluwer Academic Press, 19-32, 1990.

* (1040) Lee, S., Baroclinic Wave Pockets in Models and Observations, Ph.D. Dissertation, Atmospheric and Oceanic Sciences Program, Princeton University, 1991.

* (1041) Mitchell, J.F.B., S. Manabe, V. Meleshko, and T. Tokioka, Equilibrium Climate Change - and Its Implications for the Future, In Climate Change, the IPCC Scientific Assessment, J.T. Houghton, G.J. Jenkins and J.J. Ephraums (eds.), Cambridge University Press, 137-164, 1990.

(1042) Manabe, S., R.J. Stouffer, M.J. Spelman, and K. Bryan, Transient Responses of a Coupled Ocean-Atmosphere Model to Gradual Changes of Atmospheric CO_2, Part I: Annual Mean Response, Journal of Climate, 4(8):785-818, 1991.

* (1043) Wallace, J.M., D.J. Baker, M.L. Blackmon, J.D. Mahlman, J. Blackmon, and J. Shukla, Prospects for Extending the Range of Prediction of the Global Atmosphere, National Research Council, National Academy Press, 33 pp., 1991.

* (1044) Mellor, G.L., and T. Ezer, A Gulf Stream Model and an Altimetry Assimilation Scheme, Journal of Geophysical Research, 96(C5):8779-8795, 1991.

* (1045) Mellor, G.L., An Equation of State for Numerical Models of Oceans and Estuaries, Journal of Atmospheric and Oceanic Technology, 8:609-611, 1991.

* *In collaboration with other organizations*

* (1046) Milly, P.C.D., Some Current Themes in Physical Hydrology of the Land-Atmosphere Interface, In Hydrological Interactions Between Atmosphere, Soil, and Vegetation, International Association of Hydrological Sciences, G. Kienitz, P.C.D. Milly, M. Genuchten, D. Rosbjerg and W.J. Shuttleworth (eds.), 3-10, 1991.

* (1047) Joos, F., J.L. Sarmiento, and U. Siegenthaler, Estimates of the Effect of Southern Ocean Iron Fertilization on Atmospheric CO_2 Concentrations, Nature, 349(6312):772-775, 1991.

(1048) Sarmiento, J.L., Slowing the Buildup of Fossil CO_2 in the Atmosphere by Iron Fertilization: A Comment, Global Biogeochemical Cycles, 5(1):1-2, 1991.

* (1049) Nuttle, W.K., J.S. Wroblewski, and J.L. Sarmiento, Advances in Modeling Ocean Primary Production and Its Role in the Global Carbon Cycle, Advanced Space Research, 11(3):367-376, 1991.

* (1050) Joos, F., U. Siegenthaler, and J.L. Sarmiento, Possible Effects of Iron Fertilization in the Southern Ocean on Atmospheric CO_2 Concentration, Global Biogeochemical Cycles, 5(2):135-150, 1991.

* (1051) Kasibhatla, P.S., H. Levy II, W.J. Moxim, and W.L. Chameides, The Relative Impact of Stratospheric Photochemical Production on Tropospheric NO_y Levels: A Model Study, Journal of Geophysical Research, 96(D10):18,631-18,646, 1991.

(1052) Lipps, F.B., and R.S. Hemler, Numerical Modeling of a Midlatitude Squall Line: Features of the Convection and Vertical Momentum Flux, Journal of the Atmospheric Sciences, 48(17):1909-1929, 1991.

(1053) Orlanski, I., and J. Katzfey, The Life Cycle of a Cyclone Wave in the Southern Hemisphere, Part I: Eddy Energy Budget, Journal of the Atmospheric Sciences, 48(17):1972-1998, 1991.

* (1054) Cook, K.H., and A. Gnanadesikan, Effects of Saturated and Dry Land Surfaces on the Tropical Circulation and Precipitation in a General Circulation Model, Journal of Climate, 4(9):873-889, 1991.

(1055) Bryan, K., Michael Cox (1941-1989): His Pioneering Contributions to Ocean Circulation Modeling, Journal of Physical Oceanography, 21(9):1259-1270, 1991.

(1056) Hamilton, K., Climatological Statistics of Stratospheric Inertia-Gravity Waves Deduced from Historical Rocketsonde Wind and Temperature Data, Journal of Geophysical Research, 96(D11):20,831-20,839, 1991.

* (1057) Toggweiler, J.R., K. Dixon, and W.S. Broecker, The Peru Upwelling and the Ventilation of the South Pacific Thermocline, Journal of Geophysical Research, 96(C11): 20,467-20,497, 1991.

* (1058) Ramaswamy, V., and J.D. Mahlman, Climatic Effects of Trace Gases in the Atmosphere, Proceedings of the CFC Issue and Greenhouse Effect, Asia-Pacific Conference, Singapore, 172-185, 1991.

** In collaboration with other organizations*

* (1059) Boer, G.J., K. Arpe, M. Blackburn, M. Deque, W.L. Gates, T.L. Hart, H. le Treut, E. Roeckner, D.A. Sheinin, I. Simmonds, R.N.B. Smith, T. Tokioka, R.T. Wetherald, and D. Williamson, An Intercomparison of the Climates Simulated by 14 Atmospheric General Circulation Models, CAS/JSC Working Group on Numerical Experimentation, WCRP-58, WMO/TD-425, 1991.

* (1060) Orlanski, I., J. Katzfey, C. Menendez, and M. Marino, Simulation of an Extratropical Cyclone in the Southern Hemisphere: Model Sensitivity, Journal of the Atmospheric Sciences, 48(22):2293-2311, 1991.

(1061) Orlanski, I., Atmospheric Fronts, In Encyclopedia of Earth System Science, Vol.1, 201-216, Academic Press, 1992.

* (1062) Manzini, E., A Numerical Study of the Middle Atmosphere Response to Tropical and Subtropical Tropospheric Heat Sources, Ph.D. Dissertation, Atmospheric and Oceanic Sciences Program, Princeton University, 1992.

(1063) Lau, N.-C., and M.J. Nath, Variability of the Baroclinic and Barotropic Transient Eddy Forcing Associated with Monthly Changes in the Midlatitude Storm Tracks, Journal of the Atmospheric Sciences, 48(24):2589-2613, 1991.

(1064) Hemler, R.S., F.B. Lipps, and B.B. Ross, A Simulation of a Squall Line Using a Nonhydrostatic Cloud Model with a 5-km Horizontal Grid, Monthly Weather Review, 119(12):3012-3033, 1991.

* (1065) Peixoto, J.P., and A.H. Oort, Physics of Climate, American Institute of Physics, New York, NY, 520 pp., 1992.

(1066) Cook, K.H., and I.M. Held, The Stationary Response to a Large-Scale Orography in a General Circulation Model and a Linear Model, Journal of the Atmospheric Sciences, 49(6):525-539, 1992.

(1067) Manabe, S., M.J. Spelman, and R.J. Stouffer, Transient Responses of a Coupled Ocean-Atmosphere Model to Gradual Changes of Atmospheric CO_2, Part II: Seasonal Response, Journal of Climate, 5(2):105-126, 1992.

* (1068) Blain, C.A., and P.C.D. Milly, Development and Application of a Hillslope Hydrologic Model, Advances in Water Resources, 14(4):168-174, 1991.

* (1069) Najjar, R.G., J.L. Sarmiento, and J.R. Toggweiler, Downward Transport and Fate of Organic Matter in the Ocean: Simulations with a General Circulation Model, Global Biogeochemical Cycles, 6(1):45-76, 1992.

* (1070) Milly, P.C.D., Potential Evaporation and Soil Moisture in General Circulation Models, Journal of Climate, 5(3):209-226, 1992.

* (1071) Ramaswamy, V., M.D. Schwarzkopf, and K.P. Shine, Radiative Forcing of Climate from Halocarbon-Induced Global Stratospheric Ozone Loss, Nature, 355: 810-812, 1992.

(1072) Toggweiler, J.R., Catalytic Conversions, Nature, 356:665-666, 1992.

** In collaboration with other organizations*

* (1073) Milly, P.C.D., Land Surface Processes and Climate Variability, EOS, Transactions, American Geophysical Union, 73(15):163, 1992.

* (1074) Gordon, A.L., S.E. Zebiak, and K. Bryan, Climate Variability and the Atlantic Ocean, EOS, Transactions, American Geophysical Union, 73(15):161, 164-165, 1992.

(1075) Lau, N.-C., Book Review of "Teleconnections Linking Worldwide Climate Anomalies", Science, 256(5057):682, 1992.

* (1076) Lau, N.-C., S.G.H. Philander, and M.J. Nath, Simulation of ENSO-like Phenomena with a Low-Resolution Coupled GCM of the Global Ocean and Atmosphere, Journal of Climate, 5(4):284-307, 1992.

* (1077) Philander, S.G.H., R.C. Pacanowski, N.-C. Lau, and M.J. Nath, Simulation of ENSO with a Global Atmospheric GCM Coupled to a High-Resolution, Tropical Pacific Ocean GCM, Journal of Climate, 5(4):308-329, 1992.

* (1078) Kushnir, Y., and N.-C. Lau, The General Circulation Model Response to a North Pacific SST Anomaly: Dependence on Time Scale and Pattern Polarity, Journal of Climate, 5(4):271-283, 1992.

(1079) Mahlman, J.D., Understanding Climate Change, Science and Policy Associates, Inc., Report of Findings: Joint Climate Project to Address Decision Makers' Uncertainties, J.C. Bernabo and P.D. Eglinton (eds.), Appendix B, 16 pp., 1992.

* (1080) Tziperman, E., W.C. Thacker, and K. Bryan, Computing the Steady Oceanic Circulation Using an Optimization Approach, Dynamics of Atmospheres and Oceans, 16:379-403, 1992.

* (1081) Neelin, J.D., M. Latif, M.A.F. Allaart, M.A. Cane, U. Cubasch, W.L. Gates, P.R. Gent, M. Ghil, C. Gordon, N.-C. Lau, C.R. Mechoso, G.A. Meehl, J.M. Oberhuber, S.G.H. Philander, P.S. Schopf, K.R. Sperber, A. Sterl, T. Tokioka, J. Tribbia, and S.E. Zebiak, Tropical Air-Sea Interaction in General Circulation Models, Climate Dynamics, 7(2):73-104, 1992.

* (1082) Wu, G., and N.-C. Lau, A GCM Simulation of the Relationship Between Tropical-Storm Formation and ENSO, Monthly Weather Review, 120(6):958-977, 1992.

* (1083) Garner, S.T., and A.J. Thorpe, The Development of Organized Convection in a Simplified Squall-Line Model, Quarterly Journal of the Royal Meteorological Society, 118:101-124, 1992.

* (1084) Sarmiento, J.L., J.C. Orr, and U. Siegenthaler, A Perturbation Simulation of CO_2 Uptake in an Ocean General Circulation Model, Journal of Geophysical Research, 97(C3):3621-3645, 1992.

* (1085) Sarmiento, J.L., and U. Siegenthaler, New Production and the Global Carbon Cycle, In Primary Productivity and Biogeochemical Cycles in the Sea, P. Falkowski (ed.), Plenum Press, New York, NY, 317-322, 1992.

* *In collaboration with other organizations*

* (1086) Sarmiento, J.L., and E. Sundquist, Revised Budget for the Oceanic Uptake of Anthropogenic Carbon Dioxide, Nature, 356:589-593, 1992.

* (1087) Sarmiento, J.L., and J.C. Orr, Three-Dimensional Simulations of the Impact of Southern Ocean Nutrient Depletion on Atmospheric CO_2 and Ocean Chemistry, Limnology and Oceanography, 36(8):1928-1950, 1992.

* (1088) Sarmiento, J.L., Oceanic Uptake of Anthropogenic CO_2: The Major Uncertainties, Global Biogeochemical Cycles, 5(4):309-313, 1991.

* (1089) Herbert, T.D., and J.L. Sarmiento, Ocean Nutrient Distribution and Oxygenation: Limits on the Formation of Warm Saline Bottom Water in the Oceans over the Past 90 Years, Geology, 19:702-705, 1992.

* (1090) Orr, J.C., and J.L. Sarmiento, Potential of Marine Macroalgae as a Sink for CO_2: Constraints from a 3-D General Circulation Model of the Global Ocean, Water, Air and Soil Pollution, 64:405-421, 1992.

(1091) Bryan, K., Poleward Heat Transport in the Ocean - A Review of a Hierarchy of Models of Increasing Resolution, A Contribution to the Friiberghs Herrgard Symposium, Tellus, 43AB:104-115, 1991

* (1092) Ezer, T., and G.L. Mellor, A Numerical Study of the Variability and the Separation of the Gulf Stream, Induced by Surface Atmospheric Forcing and Lateral Boundary Flows, Journal of Physical Oceanography, 22(6):660-682, 1992.

* (1093) Ezer, T., G.L. Mellor, and D.-S. Ko, Nowcasting the Gulf Stream Structure with a Primitive Equation Model and Assimilation of Altimetry and SST Data, Proceedings of MTS '91, Marine Technology Society Meeting, 10-14 November 1991, New Orleans, LA, 236-241, 1991.

(1094) Holloway, L., Atmospheric Sun Protection Factor on Clear Days: Its Observed Dependence on Solar Zenith Angle and Its Relevance to the Shadow Rule for Sun Protection, Photochemistry and Photobiology, (56)2:229-234, 1992.

* (1095) Ramaswamy, V., and S.M. Freidenreich, A Study of Broadband Parameterizations of the Solar Radiative Interactions with Water Vapor and Water Drops, Journal of Geophysical Research, 97(D11):11,487-11,512, 1992.

(1096) Stern, W.F., and J.J. Ploshay, A Scheme for Continuous Data Assimilation, Monthly Weather Review, 120(7):1417-1432, 1992.

(1097) Gordon, C.T., Comparison of 30-Day Integrations with and without Cloud-Radiation Interaction, Monthly Weather Review, 120(7):1244-1277, 1992.

* (1098) Verma, R.K., ENSO-Monsoon Linkages as Evidenced from Pacific SST Correlations with Monsoon Precipitation, TOGA Notes, 6:1-4, 1992.

(1099) Broccoli, A.J., and S. Manabe, Reply to Evans, Geophysical Research Letters, 19(14):1525-1526, 1992.

* *In collaboration with other organizations*

(1100) Mahlman, J.D., Assessing Global Climate Change: When Will We Have Better Evidence? Global Climate Change: Its Mitigation Through Improved Production and Use of Energy, LANL #LA-UR-92-502, Los Alamos, NM, L. Rosen and R. Glasser (eds.), American Institute of Physics, NY, 17-31, 1992.

(1101) Ross, R.J., and Y. Kurihara, A Simplified Scheme to Simulate Asymmetries Due to the Beta Effect in Barotropic Vortices, Journal of the Atmospheric Sciences, 49(17):1620-1628, 1992.

* (1102) Oltmans, S.J., and H. Levy II, Seasonal Cycle of Surface Ozone Over the Western North Atlantic, Nature, 358:392-394, 1992.

(1103) Lipps, F.B., and R.S. Hemler, On the Downward Transfer of Tritium to the Ocean by a Cloud Model, Journal of Geophysical Research, 97(D12):12,889-12,900, 1992.

* (1104) Ezer, T., D.-S. Ko, and G.L. Mellor, Modeling and Forecasting the Gulf Stream, Marine Technology Society Journal, 26(2):5-14, 1992.

* (1105) Oey, L.-Y., T. Ezer, G.L. Mellor, and P. Chen, A Model Study of "Bump" Induced Western Boundary Current Variabilities, Journal of Marine Systems, 3:321-342, 1992.

(1106) Ploshay, J.J., W.F. Stern, and K. Miyakoda, FGGE Reanalysis at GFDL, Monthly Weather Review, 120(9):2083-2108, 1992.

* (1107) Held, I.M., and E. O'Brien, Quasigeostrophic Turbulence in a Three-Layer Model: Effects of Vertical Structure in the Mean Shear, Journal of the Atmospheric Sciences, 49(19):1861-1870, 1992.

* (1108) Stephenson, D., and K. Bryan, Large-Scale Electric and Magnetic Fields Generated by the Oceans, Journal of Geophysical Research, 97(C10):15,467-15,480, 1992.

* (1109) Garner, S.T., N. Nakamura, and I.M. Held, Nonlinear Equilibration of Two-Dimensional Eady Waves: A New Perspective, Journal of the Atmospheric Sciences, 49(22):1984-1996, 1992.

(1110) Mahlman, J.D., A Looming Arctic Ozone Hole?, Nature, 360:209-210, 1992.

* (1111) Lau, K.-H., and N.-C. Lau, The Energetics and Propagation Dynamics of Tropical Summertime Synoptic Scale Disturbances, Monthly Weather Review, 120(11):2523-2539, 1992.

(1112) Delworth, T., S. Manabe, and R. Stouffer, Interdecadal Variability of the Thermohaline Circulation in a Coupled Ocean-Atmosphere Model, Proceedings from the Principal Investigators Meeting, University of Miami, Miami, Florida, March 9-11, 1992, The Atlantic Climate Change Program, NOAA Climate and Global Change Program, Special Report #7, 1992.

* (1113) Lofgren, B., Sensitivity and Feedbacks Associated with Vegetation-Related Land Surface Parameters in a General Circulation Model, Ph.D. Dissertation, Atmospheric and Oceanic Sciences Program, Princeton University, 1993.

* *In collaboration with other organizations*

* (1114) Chang, E.K.M., Downstream Development of Baroclinic Waves, Ph.D. Dissertation, Atmospheric and Oceanic Sciences Program, Princeton University, 1993.

* (1115) Hamilton, K., and L. Yuan, Experiments on Tropical Stratospheric Mean-Wind Variations in a Spectral General Circulation Model, Journal of the Atmospheric Sciences, 49(24):2464-2483, 1992.

* (1116) Orlanski, I., and E.K.M. Chang, Ageostrophic Geopotential Fluxes in Downstream and Upstream Development of Baroclinic Waves, Journal of the Atmospheric Sciences, 50(2):212-225, 1993.

* (1117) Anderson, L.A., The Determination of Redfield Ratios for Use in Global Oceanic Nutrient Cycle Models, Ph.D. Dissertation, Atmospheric and Oceanic Sciences Program, Princeton University, 1993.

(1118) Hayashi, Y., and D.G. Golder, Tropical 40-50- and 25-30-Day Oscillations Appearing in Realistic and Idealized GFDL Climate Models and the ECMWF Dataset, Journal of the Atmospheric Sciences, 50(3):464-494, 1993.

(1119) Ploshay, J., W. Stern, and K. Miyakoda, A Summary Report on FGGE Re-analysis at GFDL, Data Assimilation Systems, BMRC Research Report No. 27, Melbourne, Australia, 29-53, 1991.

(1120) Hamilton, K., What We Can Learn from General Circulation Models about the Spectrum of Middle Atmospheric Motions, In Coupling Processes in the Lower and Middle Atmosphere, E. Thrane et al. (eds.), Kluwer Academic Publishers, 161-174, 1992.

(1121) Manabe, S., and R.J. Stouffer, Reply, Journal of Climate, 6(1):178-179, 1993.

* (1122) Schwarzkopf, M.D., and V. Ramaswamy, Radiative Forcing due to Ozone in the 1980s: Dependence on Altitude of Ozone Change, Geophysical Research Letters, 20(3):205-208, 1993.

(1123) Broccoli, A.J., and S. Manabe, The Effects of Orography on Midlatitude Northern Hemisphere Dry Climates, Journal of Climate, 5(11):1181-1201, 1992.

* (1124) Oort, A.H., and H. Liu, Upper-Air Temperature Trends Over the Globe, 1958-1989, Journal of Climate, 6(2):292-307, 1993.

* (1125) Chang, E.K.M., and I. Orlanski, On the Dynamics of a Storm Track, Journal of the Atmospheric Sciences, 50(7):999-1015, 1993.

(1126) Bryan, K., Ocean Circulation Models, In Strategies for Future Climate Research, M. Latif (ed.), Max Planck Institute fur Meteorologie, Hamburg, Germany, 265-285, 1991.

(1127) Lau, N.-C., Climate Variability Simulated in GCMs, In Climate System Modeling, K.E. Trenberth (ed.), Cambridge University Press, 617-642, 1992.

** In collaboration with other organizations*

(1128) Lanzante, J.R., A Comparison of the Stationary Wave Responses in Several GFDL Increased CO_2 GCM Experiments, Proceedings of the Sixteenth Annual Climate Diagnostics Workshop, Lake Arrowhead, CA, 241-246, 1991.

* (1129) Milly, P.C.D., Sensitivity of the Global Water Cycle to the Water-Holding Capacity of Soils, Proceedings of the Yokohama Symposium, Yokohama, Japan, 495-501, 1993.

* (1130) Savoie, D.L., J.M. Prospero, S.J. Oltmans, W.C. Graustein, K.K. Turekian, J.T. Merrill, and H. Levy II, Sources of Nitrate and Ozone in the Marine Boundary Layer of the Tropical North Atlantic, Journal of Geophysical Research, 97(D11):11,575-11,589, 1992.

(1131) Held, I.M., Large-Scale Dynamics and Global Warming, Bulletin of the American Meteorological Society, 74(2):228-241, 1993.

* (1132) Imbrie, J., E.A. Boyle, S.C. Clemens, A. Duffy, W.R. Howard, G. Kukla, J. Kutzbach, D.G. Martinson, A. McIntyre, A.C. Mix, B. Molfino, J.J. Morley, L.C. Peterson, N.G. Pisias, W.L. Prell, M.E. Raymo, N.J. Shackleton, and J.R. Toggweiler, On the Structure and Origin of Major Glaciation Cycles, 1. Linear Responses to Milankovitch Forcing, Paleoceanography, 7(6):701-738, 1992.

(1133) Donner, L.J., A Cumulus Parameterization Including Mass Fluxes, Vertical Momentum Dynamics, and Mesoscale Effects, Journal of the Atmospheric Sciences, 50(6):889-906, 1993.

(1134) Mahlman, J.D., Modeling Perspectives on Global Monitoring Requirements, Proceedings of the NOAA Workshop on "Assuring the Quality and Continuity of NOAA's Environmental Data", Silver Spring, MD, December 1991, 19-26, 1993.

* (1135) Murray, J.W., M.W. Leinen, R.A. Feely, J.R. Toggweiler, and R. Wanninkhof, EqPac: A Process Study in the Central Equatorial Pacific, Oceanography, 5(3):134-142, 1993.

* (1136) Freidenreich, S.M., and V. Ramaswamy, Solar Radiation Absorption by CO_2, Overlap with H_2O, and a Parameterization for General Circulation Models, Journal of Geophysical Research, 98(D4):7255-7264, 1993.

* (1137) Kasibhatla, P.S., H. Levy II, and W.J. Moxim, Global NO_x, HNO_3, PAN, and NO_y Distributions from Fossil Fuel Combustion Emissions: A Model Study, Journal of Geophysical Research, 98(D4):7165-7180, 1993.

(1138) Held, I.M., and P.J. Phillipps, Sensitivity of the Eddy Momentum Flux to Meridional Resolution in Atmospheric GCMs, Journal of Climate, 6(3):499-507, 1993.

(1139) Kurihara, Y., M.A. Bender, R.E. Tuleya, and R.J. Ross, Hurricane Forecasting with the GFDL Automated Prediction System, Proceedings of the 20th Conference on Hurricanes and Tropical Meteorology, 10-14 May 1993, San Antonio, TX, Published by American Meteorological Society, Boston, MA, 323-326, 1993.

* *In collaboration with other organizations*

(1140) Ross, R.J., and Y. Kurihara, Hurricane-Environment Interaction in Hurricanes Gloria and Gilbert, Proceedings of the 20th Conference on Hurricanes and Tropical Meteorology, 10-14 May 1993, San Antonio, TX, Published by American Meteorological Society, Boston, MA, 27-30, 1993.

* (1141) Hakkinen, S., L.H. Kantha, and G.L. Mellor, Modeling Deep Convection in the Greenland Sea, Journal of Geophysical Research, 97(C4):5389-5408, 1992.

* (1142) Sarmiento, J.L., Biogeochemical Ocean Models, In Climate System Modeling, K.E. Trenberth (ed.), Cambridge University Press, Cambridge, MA, 519-549, 1992.

* (1143) Sarmiento, J.L., and J.C. Orr, The Iron Fertilization Strategy, Proceedings of the Conference "Oceans, Climate, Man," Fondazione, San Paolo, Italy, 1992.

* (1144) Lee, S., and I.M. Held, Baroclinic Wave Packets in Models and Observations, Journal of the Atmospheric Sciences, 50(10):1413-1428, 1993.

(1145) Delworth, T., and S. Manabe, Climate Variability and Land Surface Processes, Advances in Water Resources, 16:3-20, 1993.

(1146) Manabe, S., and R.J. Stouffer, Century-Scale Effects of Increased Atmospheric CO_2 on the Ocean-Atmosphere System, Nature, 364(6434):215-217, 1993.

(1147) Kurihara, Y., M.A. Bender, and R.J. Ross, An Initialization Scheme of Hurricane Models by Vortex Specification, Monthly Weather Review, 121(7):2030-2045, 1993.

(1148) Bender, M.A., R.J. Ross, R.E. Tuleya, and Y. Kurihara, Improvements in Tropical Cyclone Track and Intensity Forecasts Using the GFDL Initialization System, Monthly Weather Review, 121(7):2046-2061, 1993.

(1149) Anderson, J.L., The Climatology of Blocking in a Numerical Forecast Model, Journal of Climate, 6(6):1041-1056, 1993.

* (1150) Yuan, L., Statistical Equilibrium Dynamics in a Forced-Dissipative f-plane Shallow-Water Model, Ph.D Dissertation, Atmospheric and Oceanic Sciences Program, Princeton University, 1993.

* (1151) Levy II, H., W.J. Moxim, and P.S. Kasibhatla, Impact of Global NO_x Sources on the Northern Latitudes, In The Tropospheric Chemistry of Ozone in the Polar Regions, H. Niki and K.H. Becker (eds.), NATO, ASI Series, Vol. 17, Springer-Verlag, Berlin, Heidelberg, 77-88, 1993.

(1152) Kurihara, Y., Hurricanes and Atmospheric Processes, In Relating Geophysical Structures and Processes: The Jeffreys Volume, K. Aki and R. Dmowska (eds.), IUGG, Vol. 16, American Geophysical Union, 19-26, 1993.

* (1153) Manzini, E., and K. Hamilton, Middle Atmospheric Traveling Waves Forced by Latent and Convective Heating, Journal of the Atmospheric Sciences, 50(14):2180-2200, 1993.

* *In collaboration with other organizations*

* (1154) Chang, E.K.M., Downstream Development of Baroclinic Waves as Inferred from Regression Analysis, Journal of the Atmospheric Sciences, 50(13):2038-2053, 1993.

* (1155) Sarmiento, J.L., R.D. Slater, M.J.R. Fasham, H.W. Ducklow, J.R. Toggweiler, and G.T. Evans, A Seasonal Three-Dimensional Ecosystem Model of Nitrogen Cycling in the North Atlantic Euphotic Zone, Global Biogeochemical Cycles, 7(2):417-450, 1993.

(1156) Toggweiler, J.R., and B. Samuels, Is the Magnitude of the Deep Outflow from the Atlantic Ocean Actually Governed by Southern Hemisphere Winds? In The Global Carbon Cycle, M. Heimann (ed.), NATO ASI Series, Springer-Verlag, Berlin, 303-331, 1993.

(1157) Toggweiler, J.R., and B. Samuels, New Radiocarbon Constraints on the Upwelling of Abyssal Water to the Ocean's Surface, In The Global Carbon Cycle, M. Heimann (ed.), NATO ASI Series, Springer-Verlag, Berlin, 333-366, 1993.

* (1158) Matano, R.P., On the Separation of the Brazil Current from the Coast, Journal of Physical Oceanography, 23(1):79-90, 1993.

* (1159) Matano, R.P., and S.G.H. Philander, Heat and Mass Balances of the South Atlantic Ocean Calculated from a Numerical Model, Journal of Geophysical Research, 98(C1):977-984, 1993.

* (1160) Ezer, T., G.L. Mellor, D.-S. Ko, and Z. Sirkes, A Comparison of Gulf Stream Sea Surface Height Fields Derived from Geosat Altimeter Data and Those Derived from Sea Surface Temperature Data, Journal of Atmospheric and Oceanic Technology, 10(1):76-87, 1993.

* (1161) Hakkinen, S., and G.L. Mellor, Modeling the Seasonal Variability of a Coupled Arctic Ice-Ocean System, Journal of Geophysical Research, 97(C12):20,285-20,304, 1992.

* (1162) Nakamura, N., Momentum Flux, Flow Symmetry, and the Nonlinear Barotropic Governor, Journal of the Atmospheric Sciences, 50(14):2159-2179, 1993.

* (1163) Gerdes, R., A Primitive Equation Ocean Circulation Model Using a General Vertical Coordinate Transformation, 1. Description and Testing of the Model, Journal of Geophysical Research, 98(C8):14,683-14,701, 1993.

* (1164) Gerdes, R., A Primitive Equation Ocean Circulation Model Using a General Vertical Coordinate Transformation, 2. Application to an Overflow Problem, Journal of Geophysical Research, 98(C8):14,703-14,726, 1993.

* (1165) Sarmiento, J.L., Ocean Carbon Cycle, Chemical and Engineering News, 71:30-43, 1993.

* (1166) Fasham, M.J.R., J.L. Sarmiento, R.D. Slater, H.W. Ducklow, and R. Williams, Ecosystem Behavior at Bermuda Station "1" and Ocean Weather Station "India": A General Circulation Model and Observational Analysis, Global Biogeochemical Cycles, 7(2):379-415, 1993.

* *In collaboration with other organizations*

* (1167) Kasibhatla, P.S., NO_y from Sub-sonic Aircraft Emissions: A Global Three-Dimensional Model Study, Geophysical Research Letters, 20(16):1707-1710, 1993.

(1168) Hamilton, K., A General Circulation Model Simulation of El Niño Effects in the Extratropical Northern Hemisphere Stratosphere, Geophysical Research Letters, 20(17):1803-1806,1993.

* (1169) Ting, M., and N.-C. Lau, A Diagnostic and Modeling Study of the Monthly Mean Wintertime Anomalies Appearing in a 100-Year GCM Experiment, Journal of the Atmospheric Sciences, 50(17):2845-2867, 1993.

* (1170) Armstrong, R.A., A Comparison of Index-Based and Pixel-Based Neighborhood Simulations of Forest Growth, Ecology, 74(6):1707-1712, 1993.

* *In collaboration with other organizations*

MANUSCRIPTS SUBMITTED FOR PUBLICATION

* (re) Murnane, R.J., Determination of Thorium and Particulate Matter Cycling Parameters at Station P: A Re-Analysis and Comparison of Least Squares Techniques, Journal of Geophysical Research, January 1992.

* (rj) Chao, Y., and S.G.H. Philander, On the Structure of the Southern Oscillation, Journal of Climate, February 1992.

* (ru) Shaffer, G., and J.L. Sarmiento, A New Ocean Chemistry Model for Studies of Global Biogeochemical Cycling, Journal of Geophysical Research, July 1992.

* (rv) Murnane, R.J., J.K. Cochran, and J.L. Sarmiento, Estimates of Particle and Thorium Cycling Rate Constants in the Northwest Atlantic Ocean, Journal of Geophysical Research, July 1992.

* (sc) Ezer, T., On the Interaction Between the Gulf Stream and the New England Seamounts Chain, Journal of Physical Oceanography, June 1992.

* (se) Karoly, D.J., J.A. Cohen, G.A. Meehl, J.F.B. Mitchell, A.H. Oort, R.J. Stouffer, and R.T. Wetherald, An Example of Fingerprint Detection of Greenhouse Climate Change, Climate Dynamics, April 1991.

* (sg) Ramaswamy, V., Perturbation of the Climate System due to Stratospheric Ozone Depletion, Proceedings of the Symposium on the Chemistry of the Atmosphere, American Chemical Society, Washington, DC, August 23-28, 1992.

* (sh) Ramaswamy, V., Volcanic Super-Eruptions and Climate Change, Nature, August 1992.

* (si) Strahan, S.E., and J.D. Mahlman, Evaluation of the GFDL "SKYHI" General Circulation Model using Aircraft N_2O Measurements: 1. Polar Winter Stratospheric Meteorology and Tracer Morphology, Journal of Geophysical Research-Atmospheres, September 1992.

* (sj) Strahan, S.E., and J.D. Mahlman, Evaluation of the GFDL "SKYHI" General Circulation Model using Aircraft N_2O Measurements: 2. Tracer Variability and Diabatic Meridional Circulation, Journal of Geophysical Research-Atmospheres, September 1992.

(sk) Milly, P.C.D., An Analytic Solution of the Stochastic Storage Problem Applicable to Soil Water, Water Resources Research, September 1992.

* (sl) Lau, N.-C., and K.-H. Lau, Simulation of the Asian Summer Monsoon in a 40-Year Experiment with a General Circulation Model, Proceedings of Second International Conference on East Asia and Western Pacific Meteorology and Climate, National Taiwan University, Taipei, Taiwan, September 1992.

(sm) Delworth, T., S. Manabe, and R.J. Stouffer, North Atlantic Interdecadal Variability in a Coupled Model, Proceedings of "Decade to Century Time Scales of Natural Climate Variability" Workshop, September 1992.

* *In collaboration with other organizations*

* (so) Stephenson, D.B., and I.M. Held, GCM Response of Northern Winter Stationary Waves and Stormtracks to Increasing Amounts of Carbon Dioxide, Journal of Climate, October 1992.

(sp) Hamilton, K., An Examination of Observed Southern Oscillation Effects in the Northern Hemisphere Stratosphere, Journal of the Atmospheric Sciences, October 1992.

* (sq) Wu, G., and N.-C. Lau, Reply to Comments on "A GCM Simulation of the Relationship between Tropical-Storm Formation and ENSO", Monthly Weather Review, October 1992.

* (st) Bryan, K., and F.C. Hansen, A Toy Model of North Atlantic Climate Variability on a Decade to Century Time-Scale, Proceedings of a National Academy Workshop, October 1992.

* (sv) Held, I.M., R.S. Hemler, and V. Ramaswamy, Radiative-Convective Equilibrium with Explicit Two-Dimensional Moist Convection, Journal of the Atmospheric Sciences, November 1992.

* (sw) Tziperman, E., J.R. Toggweiler, Y. Feliks, and K. Bryan, Instability of the Thermohaline Circulation with Respect to Mixed Boundary Conditions: Is it Really a Problem for Realistic Models? Journal of Physical Oceanography, December 1992.

* (sy) Ramaswamy, V., and C.-T. Chen, An Investigation of the Global Solar Radiative Forcing due to Changes in Cloud Liquid Water Path, Journal of Geophysical Research-Atmospheres, December 1992.

* (sz) Pierrehumbert, R.T., I.M. Held, and K.L. Swanson, Spectra of Local and Non-Local Two-Dimensional Turbulence, Physical Review Letters, January 1993.

* (ta) Raval, A., A.H. Oort, and V. Ramaswamy, Observed Dependence of Outgoing Longwave Radiation on Sea Surface Temperature and Moisture, Journal of Climate, January 1993.

* (tc) Armstrong, R.A., Grazing Limitations and Nutrient Limitation in Marine Ecosystems: Steady-State Solutions of an Ecosystem Model with Multiple Food Chains, Limnology and Oceanography, January 1993.

(td) Phillipps, P.J., and I.M. Held, On the Response to Orbital Perturbations in an Atmospheric Model Coupled to a Slab Ocean, Climate Dynamics, January 1993.

* (te) Oort, A.H., L.A. Anderson, and J.P. Peixoto, Estimates of the Generation of Available Potential and Kinetic Energy in the Oceans, Journal of Geophysical Research-Oceans, January 1993.

(tf) Orlanski, I., and B.D. Gross, Orographic Modification of Cyclone Development, Journal of the Atmospheric Sciences, February 1993.

(tg) Oort, A.H., Angular Momentum Cycle in Planet Earth, In The Encyclopedia of Planetary Sciences, February 1993.

* *In collaboration with other organizations*

(th) Kurihara, Y., Surface Conditions in Tropical Cyclone Models, Modelling Severe Weather, BMRC Research Report, February 1993.

(ti) Kurihara, Y., R.E. Tuleya, M.A. Bender, and R.J. Ross, Advanced Modeling of Tropical Cyclones, Proceedings of ICSU/WMO International Symposium on Tropical Cyclone Disasters, October 12-16, 1992, Beijing, China, February 1993.

* (tj) Mahlman, J.D, J.P. Pinto, and L.J. Umscheid, Transport, Radiative, and Dynamical Effects of the Antarctic Ozone Hole: A GFDL "SKYHI" Model Experiment, Journal of the Atmospheric Sciences, February 1993.

(tk) Orlanski, I., and J. Sheldon, A Case of Downstream Baroclinic Development over Western North America, Monthly Weather Report, February 1993.

(tl) Broccoli, A.J., and S. Manabe, Climate Model Studies of Interactions Between Ice Sheets and the Atmosphere-Ocean System, In Ice in the Climate System, Springer-Verlag, February 1993.

* (tm) Bryan, K., and W.W. Hsieh, The Steric Component of Sea Level Rise Associated with Enhanced Greenhouse Warming: A Model Study, Journal of Physical Oceanography, February 1993.

(tn) Hamilton, K., Modelling Middle Atmosphere Interannual Variability, Proceedings of the Fifth Cospar Colloquium, Pergamon Press, March 1993.

(to) Lanzante, J., Circulation Response in GFDL Increased CO_2 Experiments and Comparison with Observed Data, Proceedings of the Seventeenth Annual Climate Diagnostic Workshop, Norman, OK, October 1992.

(tp) Hamilton, K., Meteorology and Climatology, In Encyclopedia of Applied Physics, American Institute of Physics, March 1993.

(tq) Donner, L.J., A Parameterization for Ice Content in Convective Anvils for General Circulation Models, Journal of the Atmospheric Sciences, March 1993.

* (tr) Anderson, J.L., and H.M. van den Dool, Skill and Return of Skill in Dynamic Extended Range Forecasts, Monthly Weather Review, March 1993.

(ts) Hamilton, K., Aspects of Mesospheric Simulation in a Comprehensive General Circulation Model, The Upper Mesosphere and Lower Thermosphere, Geophysical Monographs, American Geophysical Union, April 1993.

* (tt) Branstator, G., and I.M. Held, Westward Propagating Normal Modes in the Presence of Stationary Background Waves, Journal of the Atmospheric Sciences, April 1993.

* (tu) Tziperman, E., and K. Bryan, Estimating Global Air-Sea Fluxes from Surface Properties and from Climatological Flux Data using an Oceanic General Circulation Model, Journal of Geophysical Research, April 1993.

* *In collaboration with other organizations*

(tw) Manabe, S., and R.J. Stouffer, Multiple Century Response of a Coupled Ocean-Atmosphere Model to an Increase of Atmospheric Carbon Dioxide, Journal of Climate, April 1993.

(tx) Milly, P.C.D., and K.A. Dunne, Sensitivity of the Global Water Cycle to the Water-Holding Capacity of Land, Journal of Climate, May 1993.

(tz) Manabe, S., R.J. Stouffer, and M.J. Spelman, Response of a Coupled Ocean-Atmosphere Model to Increasing Atmospheric Carbon Dioxide, AMBIO, Part of Proceedings of the IGBP meeting held in Ensenada, May 1993.

* (ua) Bender, M., I. Ginis, and Y. Kurihara, Numerical Simulations of the Tropical Cyclone-Ocean Interaction with a High Resolution Coupled Model, Journal of Geophysical Research, May 1993.

* (ub) Scanlon, B.R., and P.C.D. Milly, Water and Heat Fluxes in Desert Soils, 2. Numerical Simulations, Water Resources Research, May 1993.

* (uc) Chang, E.K.M., and I. Orlanski, Use of a Modified Energy Flux as a Diagnostic Tool of Zonal Wave Propagation in the Troposphere, Journal of the Atmospheric Sciences, May 1993.

(ud) Tuleya, R.E., Tropical Storm Development and Decay: Sensitivity to Surface Boundary Conditions, Monthly Weather Review, May 1993.

* (uf) Slater, R.D., J.L. Sarmiento, and M.J.R. Fasham, Some Parametric and Structural Simulations with a Three Dimensional Ecosystem Model of Nitrogen Cycling in the North Atlantic Euphoric Zone, In Towards a Model of Biogeochemical Processes, Springer-Verlag, May 1993.

* (ug) Siegenthaler, U., and J.L. Sarmiento, Atmospheric Carbon Dioxide and the Ocean, Nature, May 1993.

* (uh) Armstrong, R.A., A Model of Exact Compensation in Uptake of Nitrogenous Substrates by Marine Phytoplankton, Marine Ecology Progress Series, June 1993.

(ui) Garner, S.T., Development and Maintenance of the High-Drag State in Incompressible Stratified Flow Over a Ridge, Journal of the Atmospheric Sciences, June 1993.

* (uj) Ramaswamy, V., and M.M. Bowen, Effect of Changes in Radiatively Active Species upon the Lower Stratospheric Temperatures, Journal of Geophysical Research-Atmospheres, June 1993.

* (uk) Navarra, A., W.F. Stern, and K. Miyakoda, Reduction of the Gibbs Oscillation in Spectral Model Simulations, Journal of Climate, June 1993.

* (um) Mehta, V.M., and T. Delworth, Decadal Variability of the Tropical Atlantic Ocean Surface Temperature in Shipboard Measurements and in a Global Ocean-Atmosphere Model, Journal of Climate, June 1993.

* *In collaboration with other organizations*

(un) Hamilton, K., Model Simulation of the Stratospheric Penetration of the Southern Oscillation, Toga Notes, July 1993.

* (uo) Gross, B.D., Frontal Interaction with Isolated Orography, Journal of the Atmospheric Sciences, July 1993.

(up) Lau, N.-C., and M.J. Nath, A Modeling Study of the Relative Roles of Tropical and Extratropical SST Anomalies in the Variability of the Global Atmosphere-Ocean System, Journal of Climate, July 1993.

(uq) Oltmans, S.J., and H. Levy II, Surface Ozone Measurements from a Global Network, Atmospheric Environment, July 1993.

(ur) Xie, S.P., On Preferred Zonal Scale of Wave-CISK with Conditional Heating, Journal of the Meteorological Society of Japan, August 1993.

(us) Xie, S.P., and S.G.H. Philander, A Coupled Ocean-Atmosphere Model of Relevance to the ITCZ in the Eastern Pacific, Tellus, August 1993.

(ut) Xie, S.P., On the Equatorial Annual Variation, Journal of Climate, August 1993.

(uu) Xie, S.P., The Maintenance of an Equatorially Asymmetric State in a Hybrid Coupled GCM, Journal of the Atmospheric Sciences, August 1993.

* (uv) Lawrence, M.G., W.L. Chameides, P.S. Kasibhatla, H. Levy II, and W.J. Moxim, Lightning and Atmospheric Chemistry: The Rate of Atmospheric NO Production, Handbook of Atmospheric Electrodynamics, August 1993.

* (uw) Ezer, T., and G.L. Mellor, Continuous Assimilation of Geosat Altimeter Data into a Three-Dimensional Primitive Equation Gulf Stream Model, Journal of Physical Oceanography, August 1992.

* (ux) Xue, H.-J., and G.L. Mellor, Instability of the Gulf Stream Front in the South Atlantic Bight, Journal of Physical Oceanography, January 1992.

* (uy) Zavatarelli, M., and G.L. Mellor, A Numerical Study of the Circulation in the Mediterranean Sea, Journal of Physical Oceanography, February 1992.

* (uz) Mellor, G.L., T. Ezer, and L.-Y. Oey, On the Pressure Gradient Conundrum of Sigma Coordinate Ocean Models, Journal of Atmospheric and Oceanic Technology, February 1993.

* (va) Ezer, T., and G.L. Mellor, Diagnostic and Prognostic Calculations of the North Atlantic Circulation and Sea Level Using a Primitive Equation Ocean Model, Journal of Geophysical Research, September 1993.

(vb) Milly, P.C.D., Climate, Interseasonal Storage of Soil Water, and the Annual Water Balance, Advances in Water Resources, August 1993.

* *In collaboration with other organizations*

* (vc) Matano, R.P., and S.G.H. Philander, On the Decay of the Meanders of Eastward Currents, Journal of Physical Oceanography, August 1993.

* (vd) Liu, Z., and S.G.H. Philander, How Different Wind Stress Patterns Affect the Tropical-Subtropical Circulations of the Upper Ocean, Journal of Physical Oceanography, August 1993.

* (ve) Koberle, C., and S.G.H. Philander, On the Processes that Control Seasonal Variations of Sea Surface Temperatures in the Tropical Pacific Ocean, Tellus, August 1993.

* (vf) Xie, S.P., and S.G.H. Philander, A Coupled Ocean-Atmosphere Model of Relevance to the ITCZ in the Eastern Pacific, Tellus, August 1993.

(vg) Bryan, K., and K. Dixon, Deep Ocean Temperature Changes in the World Ocean, 1888-1988: A Model Study, Journal of Climate, August 1993.

(vi) Donner, L.J., Radiative Forcing by Parameterized Ice Clouds in a General Circulation Model, Proceedings of 8th Conference on Atmospheric Radiation, American Meteorological Society, September 1993.

* (vj) Figueroa, H., and J.L. Sarmiento, Mass and Tritium Subduction in a North Atlantic GCM, Journal of Physical Oceanography, September 1993.

* (vk) Anderson, L.A., and J.L. Sarmiento, The Determination of Redfield Ratios, 1. Nutrient Data Analysis, Global Biogeochemical Cycles, September 1993.

(vl) Milly, P.C.D., Climate, Soil Water Storage, and the Annual Water Balance, Water Resources Research, September 1993.

(vm) Stern, W.F., and K. Miyakoda, The Feasibility of Seasonal Forecasts Inferred from Multiple GCM Simulations, Journal of Climate, September 1993.

(vn) Broccoli, A.J., Climate Model Sensitivity, Paleoclimate and Future Climate Change, NATO Proceedings of Long-Term Climatic Variations, Data and Modeling, September 1993.

* *In collaboration with other organizations*

BIBLIOGRAPHY

1988-1993

CROSS REFERENCE BY AUTHOR

APPENDIX C

Seminars Given at GFDL

During Fiscal Year 1993

1 October 1992	Modeling Equatorial Kelvin Waves: Changes in Global Upwelling, by Dr. William Hsieh, University of British Columbia, Vancouver, BC, Canada
6 October 1992	Compensations in Climate Forcing: "Greenhouse" Gases, Ozone, and Aerosols, by Dr. V. Ramaswamy and M.M. Bowen, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
7 October 1992	Further Progress in Global Eddy-Resolving Ocean Modeling for Climate Study, by Dr. Albert J. Semtner, Department of the Navy, Naval Postgraduate School, Monterey, CA
8 October 1992	Experimenting with Topographic Stress in an Ocean GCM, by Dr. Gregg Holloway, Institute of Oceanographic Studies, Sydney, BC, Canada
13 October 1992	Sensitivity of Southern Ocean Sea Ice Simulations to Different Atmospheric Forcing Algorithms, by Dr. A. Stossel, Max Planck Institute for Meteorology, Hamburg, Germany
13 October 1992	Paleo-Implications to the Southern Hemisphere Winds Hypothesis, by Dr. J.R. Toggweiler, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
15 October 1992	Long-Term Effects of Fossil Fuel Burning, by Prof. James Kasting, Earth System Science Center, Pennsylvania State University, University Park, PA
16 October 1992	A New Perspective on the Observed Global Warming, by Dr. Thomas Karl, National Climatic Data Center, Asheville, NC
20 October 1992	The Role of Ageostrophic Waves in the Reflection of Rossby Waves from a Coast, by Dr. Vitaly Larichev, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
22 October 1992	Frontal Dynamics Near and Following Frontal Collapse, by Dr. Christopher Snyder, National Center for Atmospheric Research, Boulder, CO
23 October 1992	New Approaches to Cumulus Parameterization, by Prof. David Randall, Department of Atmospheric Science, Colorado State University, Fort Collins, CO
27 October 1992	On the Zonal Mean Distribution of the Extratropical Tropospheric Temperature and Wind: APV View, by Dr. D.-Z. Sun, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
2 November 1992	Dynamics of Localized Vortices on a β-plane, by Dr. Grigory Reznik, P.P. Shirshov Institute of Oceanology, Moscow, Russia
3 November 1992	A Milankovitch View of Ice-Age Carbon Isotopes and Deep-Sea Circulation, by Dr. Alan Mix, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ

4 November 1992	Reversal in the Earth's Magnetic Field, by Prof. Keith Runcorn, University of Alaska, Fairbanks, AK
12 November 1992	Modeling of the Interaction Between Bathymetry and Sea-Ice Concentration by Multivariate Adaptive Regression Splines, by Prof. Richard De Veaux, Department of Civil Engineering, Princeton University, Princeton, NJ
16 November 1992	A Decadal Normal Mode of the North Atlantic in a Stochastically Forced Ocean General Circulation Model, by Dr. Ralf Weisse, Max-Planck Institute for Meteorology, Hamburg, Germany
17 November 1992	A GCM Study of Tropical-Subtropical Upper Ocean Correlation: Their Connections and Response to Various Wind Forcing, by Z. Liu, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
19 November 1992	Modeling Lake-Atmosphere Interactions, by Dr. Steven Hostetler, Geological Survey, Water Resources Division, Boulder, CO
1 December 1992	Circulation Response in GFDL Increased CO_2 Experiments and Comparison with Observed Data, by Dr. John Lanzante, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
3 December 1992	Hemispheric Snow Cover in the Climate System, by Dr. David Robinson, Department of Geography, Rutgers University, New Brunswick, NJ
8 December 1992	Coupled Ocean-Atmosphere Models of Relevance to the ITCZ in the Eastern Pacific, by Shang Ping Xie and Dr. George Philander, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
11 December 1992	Progress Report on Parallel SKYHI Code, Part I: Discussion Group on Atmospheric GCM Development, by Dr. Christopher Kerr, Mr. Richard Hemler, and Mr. William Stern, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
14 December 1992	Dynamical Study of Greenland Ice Sheet, by Dr. Ayako Abe-Ouchi, Swiss Federal Institute of Technology, Zurich, Switzerland
15 December 1992	A Simulation Study of the Hurricane-Ocean-Interaction, by Dr. Isaac Ginis, Mr. Morris Bender, and Dr. Yoshio Kurihara, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
17 December 1992	"Breeding" the Growing Modes of the Atmosphere: Application to Ensemble Forecasting and Data Assimilation, by Dr. Eugenia Kalnay, National Meteorological Center, Washington, DC
17 December 1992	Current Research at NMC, by Dr. Eugenia Kalnay, National Meteorological Center, Washington, DC

18 December 1992	Seasonal Cycling of Oxygen in the World Ocean: Implication for the Marine Carbon Cycle, by Dr. Raymond Najjar, National Center for Atmospheric Research, Boulder, CO
18 December 1992	Progress Report on Parallel SKYHI Code, Part II: Discussion Group on Atmospheric GCM Development, by Dr. Christopher Kerr, Cray Inc., Princeton, NJ
21 December 1992	Precipitation and Snowfall Changes over North America during the Period of Instrumental Observations, by Dr. Pavel Groisman, National Climatic Data Center, Asheville, NC
22 December 1992	Surface Air Temperature Effects of the Pinatubo Eruption, by Dr. Pavel Groisman, National Climatic Data Center, Asheville, NC
5 January 1993	Real Time Hurricane Forecasting with the GFDL Forecasting System, by Mr. Morris Bender, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
6 January 1993	Results from a Coupled Ocean-Atmosphere Model, by Dr. David Neelin, University of California, Los Angeles, CA
7 January 1993	A Class of Semi-Lagrangian Approximations for Fluids, by Dr. Piotr K. Smolarkiewicz, Mesoscale & Microscale Meteorology Division, National Center for Atmospheric Research, Boulder, CO
19 January 1993	A New Look to Lee-Cyclogenesis (in the Zeta model), by Dr. Isidoro Orlanski and Dr. Brian Gross, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
27 January 1993	Boundary Layer Modeling of GCM, by Mr. Hanspeter Zinn, Aerospace and Mechanical Engineering Department, Rutgers University, New Brunswick, NJ
28 January 1993	Recent Developments in Tropical Cyclone Track Forecasting with the NMC Global Model, by Dr. Stephen Lord, National Meteorological Center, Washington, DC
29 January 1993	Sea-Ice Forcing and Atmospheric Variability in High Latitudes, by Dr. Valentin Meleshko, Main Geophysical Observatory, St. Petersburg, Russia
1 February 1993	Experiences in Running the Parallel Ocean Model on LANL's CM-5, by Dr. Richard Smith, CHAMMP, Los Alamos National Laboratories, Los Alamos, NM
2 February 1993	Reducing the Gibbs Oscillations in the Spectral Model, by Dr. Antonio Navarra and Mr. William Stern, Atmospheric and Oceanic Sciences Program, and Geophysical Fluid Dynamics Laboratory, Princeton NJ

4 February 1993	Variations in Tropospheric Humidity as Observed by Radiosondes: Separating Climate Signals from the Effects of Instrument Changes, by Dian Gaffen, Air Resources Laboratory, Silver Spring, MD
5 February 1993	Complex Quality Control of Rawinsonde Data at the National Meteorological Center, by Dr. Lev Gandin and Mr. William Collins, National Meteorological Center, Washington, DC
10 February 1993	Numerical Study of Fully Nonlinear Moist Symmetric Instability with CAPE, by Dr. Charles Seman, National Meteorological Center, Washington, DC
11 February 1993	Using GCMs to Calculate Present and Future River Runoff, by Dr. James R. Miller, Department of Meteorology, Rutgers University, New Brunswick, NJ
18 February 1993	Climate of the Polar Regions: Recent Variations and Model Projections, by Prof. John E. Walsh, Department of Atmospheric Sciences, University of Illinois, Urbana, IL
19 February 1993	Long-Term Predictions with a Coupled Ocean Atmosphere Model, by Dr. A. Leetmaa, National Meteorological Center, Washington, DC
23 February 1993	Tropical 40-50 and 25-30 Day Oscillations, by Dr. Yoshio Hayashi and Mr. Donald Golder, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
24 February 1993	Results of the UK Meteorological Office Unified Model, by Dr. Sean Milton, United Kingdom Meteorological Office, Bracknell, United Kingdom
25 February 1993	Subduction in the North Atlantic, by Dr. R.G. Williams, Massachusetts Institute of Technology, Cambridge, MA
25 February 1993	Ocean/Sea Ice Interaction in Climate, by Dr. Douglas Martinson, Lamont-Doherty Geological Laboratory, Palisades, NY
26 February 1993	Renormalization Group Studies of Turbulence and Waves on a Beta Plane, by Dr. Boris Galperin, Department of Marine Science, University of South Florida, St. Petersburg, FL
4 March 1993	Low-Frequency Variability of an Eddy-Resolving Oceanic Double-Gyre Model, by Dr. John D. McCalpin, College of Marine Studies, University of Delaware, Newark, DE
5 March 1993	Model Study of Hydrodynamics and Water Quality in the Rappahannock Estuary in Virginia, by Mr. Keyong Park, Virginia Institute of Marine Science, College of William and Mary, Williamsburg, VA

11 March 1993	From Toasters to Data Integrals: The Passive Tracer Problem in Turbulence, by Mr. Mark Holzer, Physics Department, Cornell University, Ithaca, NY
16 March 1993	Interannual Variability in the Mediterranean Sea, by Dr. Nadia Pinardi, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
22 March 1993	A New Scaling for Convective Boundary Layers, by Prof. Sergeij Zilitinkevich, Max Planck Institute, Hamburg, Germany
23 March 1993	The Sensitivity of the Terrestrial Biosphere to Changes in the Climatic Regime: A Model Based Study, by Mr. Jonathan Foley, University of Wisconsin, Madison, WI
24 March 1993	On the Global Warming Signal Detection Controversy: Is There Such a Thing as a Fingerprint?, by Dr. Stephen Schneider, Stanford University, Stanford, CA
25 March 1993	Water Vapor and Cloud Feedbacks on Climate: Do We Need to Worry about Both?, by Dr. Anthony Del Genio, Goddard Institute for Space Studies, New York, NY
9 April 1993	Global Chemical/Transport Models of the Troposphere and Stratosphere, by Dr. Guy P. Brasseur, National Center for Atmospheric Research, Atmospheric Chemistry Division, Boulder, CO
15 April 1993	A Study of Radiative-Convective Processes using a Two-Dimensional Cumulus Ensemble Model, by Dr. C.H. Sui, NASA/GSFC, Laboratory for Atmosphere, Greenbelt, MD
16 April 1993	Variability in the North Atlantic: Some Models/Data Studies, by Dr. Richard Greatbatch, Memorial University, St. Johns, Newfoundland
19 April 1993	Hadley, Walker, and Low-Level Tropical Circulations, by Dr. David Battisti, University of Washington, Seattle, WA
22 April 1993	On the Dynamics of Cumulus Entrainment, by Dr. Terry Clark, National Center for Atmospheric Research, Mesoscale and Microscale Division, Boulder, CO
26 April 1993	Understanding Hurricane Movement from the Potential Vorticity Perspective: Numerical Model and Observational Study, by Mr. Chun-Chieh Wu, Center for Meteorology & Physical Oceanography, Massachusetts Institute of Technology, Cambridge, MA
30 April 1993	Issues in Cloud Remote Sensing, by Dr. Bruce A. Wielicki, NASA Langley Research Center, Hampton, VA

4 May 1993	Destabilization of Thermohaline by Deep Water, by Dr. Zhengyu Liu, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
6 May 1993	Paleoceanographic Constraints on Changes in pCO_2 in the Late Quaternary Subantarctic Southern Ocean, by Dr. Will Howard, Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY
7 May 1993	Statistical Mechanical Tendencies in β-Plane and Topographic Basins, by Patrick Cummins, Institute of Oceanographic Sciences, Sydney, BC, Canada
11 May 1993	Secular Variation of Annual and ENSO Cycle During the Past Century, by Dr. Daifang Gu, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
12 May 1993	Global Atmospheric and Ocean Modeling on the Connection Machine, by Ms. Susan R. Atlas, Thinking Machines Corporation, New York, NY
13 May 1993	Trade-Offs and Options in Object-Oriented Model Development, by Ms. Paula Reid, University of Oklahoma, Norman, OK
14 May 1993	Effects of Solar UV on Primary Productivity in the Ocean, by Dr. Patrick Neale, Photobiology Laboratory, Smithsonian Environmental Research Center, Edgewater, MD
18 May 1993	A Model of the Ocean Nitrous Oxide Source, by Ms. Parvadha Suntharalingam, Atmospheric and Oceanic Program, Princeton University, Princeton, NJ
19 May 1993	Wave-Mean Flow Interaction in the Radiative Convective Equilibrium Model, by Mr. Rocco Martino, Atmospheric and Oceanic Program, Princeton University, Princeton, NJ
20 May 1993	On the Thermohaline Circulation of the Oceans, by Ms. Simona Masina, Atmospheric and Oceanic Program, Princeton University, Princeton, NJ
21 May 1993	Creating an Ozone Climatology Using Observations and Models, by Ms. Rebecca Orris, Atmospheric and Oceanic Program, Princeton University, Princeton, NJ
21 May 1993	A Model for Atmospheric CO_2 Over the Past 600 Million Years, by Prof. Robert Berner, Department of Geology and Geophysics, Yale University, New Haven, CT
24 May 1993	PV Inversion Electrostatics and Testing Dynamical Theories Against Data, by Dr. Craig Bishop, University of Reading, Reading, Berkshire, United Kingdom
25 May 1993	Development of a Global Step-Mountain Model, by Mr. Bruce Wyman, Geophysical Fluid Dynamics Laboratory, Princeton, NJ

27 May 1993	Geochemical Implication of the Uncertainties in Parameterizing Air-Sea Gas Exchange, by Mr. Vincent Webb, Atmospheric and Oceanic Program, Princeton University, Princeton, NJ
27 May 1993	Diagnosis of Frontal Circulation in Two and Three Dimensions, by Dr. Dan Keyser, Department of Atmospheric Science, State University of New York, Albany, NY
1 June 1993	Response of the Tropical Atmosphere to a Gradual Increase of Atmospheric CO_2, by Mr. Tom Knutson, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
3 June 1993	Global Chaotic Mixing on Isentropic Surface, by Dr. Huijun Yang, Department of Geophysical Sciences, University of Chicago, Chicago, IL
7 June 1993	Biases in the Measurements of Precipitation over the Globe, by Dr. David Legates, University of Oklahoma, Department of Geography, Norman, OK
8 June 1993	Surface Geostrophic Flows and Generalized 2-D Turbulence, by Dr. Isaac Held, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
10 June 1993	Benchmark Calculations for the Dynamical Cores of GCMs: Spectral vs. Grid Comparison, Dr. Isaac Held, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
11 June 1993	Regimes and Scaling of Deep Ocean Convection, by Mr. Barry Klinger, Department of Earth & Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA
15 June 1993	Model Comparisons with a Global Step-Mountain Model, by Mr. Bruce Wyman and Dr. Kikuro Miyakoda, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
17 June 1993	Surface Windfields in Landfalling Hurricanes, by Dr. Mark Powell, Hurricane Research Division, Atlantic Oceanographic and Meteorological Laboratory, Miami, FL
22 June 1993	High Amplitude Circulation Anomalies in the Northern Hemisphere Winter, by Dr. H. Nakamura, Atmosphere and Oceanic Sciences Program, Princeton University, Princeton, NJ
24 June 1993	"Hurricane Like" Mesoscale Vortices Within Extratropical Marine Cyclones, by Dr. Melvyn Shapiro, Wave Propagation Laboratory, Boulder, CO
25 June 1993	Toward a Potential Vorticity Perspective on Tropospheric Dynamics, by Dr. Melvyn Shapiro, Wave Propagation Laboratory, Boulder, CO

2 July 1993	Simple Models of the Indonesian Throughflow, by Dr. Roxana Wajsowicz, USRA/NASA, Goddard Space Flight Center, Greenbelt, MD
6 July 1993	3-D Modeling of Ozone over North America and its Export to the Global Atmosphere, by Dr. Daniel Jacob, Center for Earth and Planetary Physics, Harvard University, Cambridge, MA
6 July 1993	On the Natural Variability of Climate, by Dr. Konstantin Vinnikov, Atmosphere and Oceanic Sciences Program, Princeton University, Princeton, NJ
15 July 1993	Unstable Ocean-Atmosphere Interaction in the Seasonal Cycle, by Dr. Ping Chang, Texas A & M University, Austin, TX
10 August 1993	Growing Solitary Waves in Baroclinic Boundary Currents, by Dr. Atsushi Kubokawa, National Center for Atmospheric Research, Boulder, CO
19 August 1993	State of ERL Address (audio visual link from Boulder), by Dr. Alan Thomas, Boulder, CO
20 August 1993	Heat Transport in a Model of the Indian Ocean, by Dr. S. Wacongne, University of Brest, France
31 August 1993	Representation of Topography in Spectral Climate Models and its Effects on Simulated Precipitation, by Dr. Craig Lindberg, Atmospheric and Oceanic Sciences Program, Princeton University, and Mr. Anthony Broccoli, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
2 September 1993	Entropy and the Climate System, by Prof. Jośe P. Peixoto, University of Lisbon, Lisbon, Portugal
7 September 1993	A Simple Model of El Niño's Chaos, by Dr. Eli Tziperman, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
9 September 1993	An Empirical Rossby Wave Propagation Formula, by Dr. Huug M. van den Dool, Climate Analysis Center, Washington, DC
24 September 1993	Convectively Generated Gravity Waves in the Venusian Atmosphere, by Stephen S. Leroy, California Institute of Technology, Pasadena, CA
28 September 1993	Satellite Measurements of Upper Tropospheric Water Vapor, by Dr. Brian Soden, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
29 September 1993	The Influence of the Air-Sea Interaction on the Evolution and Motion of a Pair of Tropical Cyclones, by Dr. Aleksandr Falkovich, formerly of the Hydrometeorological Center of Russia, Moscow, Russia

Addendum:

22 September 1992	Climatology and Climate Drift of Blocking in the MRF Model, by Dr. Jeffrey Anderson, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
24 September 1992	Seasonal Redistribution and Conservation of Atmospheric Mass, and the Role of Water in the Continuity Equation, by Dr. Huug M. van den Dool, Climate Analysis Center, Washington, DC
29 September 1992	The Role of Ageostrophic Waves in the Reflection of Rossby Waves from a Coast, by Dr. Vitaly Larichev, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ

APPENDIX D

Talks, Seminars, and Papers Presented Outside GFDL

During Fiscal Year 1993

1 October 1992	Mr. Anthony J. Broccoli "Climate Sensitivity to CO_2 and Ice Sheet Forcings", North Atlantic Treaty Organization Advanced Study Institute on "Long-Term Climatic Variations: Data and Modeling", Siena, Italy
2 October 1992	Dr. Jerry D. Mahlman "Transport, Radiative, and Dynamical Effects of the Antarctic Ozone Hole: A GFDL "SKYHI" Model Experiment", Colorado State University, Fort Collins, CO
5 October 1992	Dr. Kikuro Miyakoda "The Feasibility of Seasonal Atmospheric Prediction Speculated from SS7 Forced Decadal Simulations", Kyoto University, Kyoto, Japan
7 October 1992	Dr. Jerry D. Mahlman "NOAA's High Performance Computing and Communications Initiative for FY 1994", OMB Budget Hearing, Washington, DC
8 October 1992	Dr. Yoshio Kurihara 1. "A Tropical Cyclone Prediction System", and 2. "A Typhoon and its Environment", Institute for Atmospheric Physics, Beijing, China
13 October 1992	Dr. Yoshio Kurihara "Advanced Modeling of Tropical Cyclones", International Council of Scientific Unions/World Meteorological Organization, International Symposium on Tropical Cyclone Disasters, Beijing, China
13 October 1992	Dr. Isidoro Orlanski "The Importance of Downstream Development in Cyclogenesis", Cyclone Workshop, Val-Morin, Quebec, Canada
14 October 1992	Dr. Jerry D. Mahlman "The Science of Climate Change: Where do We Stand?", Symposium on "Global Warming: Understanding the Forecast", American Museum of Natural History, New York, NY
16 October 1992	Dr. Ngar-Cheung Lau "Variability of the Transient Eddy Forcing Associated with Monthly Changes in the Midlatitude Storm Tracks", Goddard Institute for Space Studies, Columbia University, New York, NY
17 October 1992	Dr. Yoshio Kurihara "Tropical Cyclone-Ocean Interaction", National Research Center for Marine Environmental Forecasts, Beijing, China
19 October 1992	Dr. John R. Lanzante "Circulation Response in GFDL Increased CO_2 Experiments and Comparison with Observed Data", Seventeenth Annual Climate Diagnostics Workshop, University of Oklahoma, Norman, OK

19 October 1992	Dr. Jeffrey L. Anderson "Return of Skill in Extended Range Numerical Forecasts", Seventeenth Annual Climate Diagnostics Workshop, University of Oklahoma, Norman, OK
19 October 1992	Dr. Abraham H. Oort "Observed Temperature and Humidity Trends in the Atmosphere", Seventeenth Annual Climate Diagnostics Workshop, University of Oklahoma, Norman, OK
19 October 1992	Mr. Thomas Knutson "Toward Improved Climate Model Information for Impact Studies", Workshop on Global Change Assessment for Forestry, Agriculture, and Water Resources, State College, PA
20 October 1992	Dr. V. Ramaswamy "Does Ozone Cool or Warm the Climate?", Center for Energy and Environmental Studies, Princeton University, Princeton, NJ
21 October 1992	Dr. Jerry D. Mahlman "GFDL: Research Plans and Budget Coping Strategies", ERL Headquarters, Silver Spring, MD
22 October 1992	Dr. Yoshio Kurihara "A System of Tropical Cyclone Prediction", Bureau of Meteorology Research Center, Melbourne, Australia
23 October 1992	Dr. Yoshio Kurihara "Tropical Cyclones and Fronts", Bureau of Meteorology Research Center, Melbourne, Australia
27 October 1992	Mr. Anthony J. Broccoli "Precipitation Simulation in GFDL Climate Models", GEWEX/WGNE Workshop on Global Observations, Analyses and Simulation of Precipitation, Camp Springs, MD
27 October 1992	Dr. Yoshio Kurihara "Surface Conditions in Tropical Cyclone Models", Bureau of Meteorology Research Center, Workshop on Severe Weather Modeling, Melbourne, Australia
28 October 1992	Mr. Thomas L. Delworth "North Atlantic Interdecadal Climate Variability in a Coupled Ocean-Atmosphere Model", Lamont-Doherty Geological Observatory, Palisades, NY

5 November 1992	Dr. Syukuro Manabe "The Role of Oceans in Greenhouse Warming and Interdecadal Variability of Climate-Building the Theory of Climate Systems", Climate Research Committee Meeting of the National Research Council, National Academy of Sciences, Washington, DC
11 November 1992	Dr. Leo J. Donner "Role of FIRE in Development of GCM Parameterization for Ice Clouds", FIRE Science Team Meeting, Fairfax, VA
16 November 1992	Dr. Kevin P. Hamilton "Comprehensive General Circulation Modeling of the Mesosphere", American Geophysical Union "Chapman Conference on the Upper Mesosphere and Lower Thermosphere", Asilomar, CA
18 November 1992	Dr. Jerry D. Mahlman "Scientific and Societal Implications of Greenhouse Warming", Special AOSP Student Seminar, Sayre Hall, Princeton University, Princeton, NJ
23 November 1992	Dr. John R. Toggweiler "Is the Ocean's Thermohaline Circulation a Wind-Driven Process After All?", Old Dominion University, Norfolk, VA
4 December 1992	Dr. Syukuro Manabe "The Role of Oceans in the Interdecadal Variability of Climate", Goddard Institute of Space Studies, New York, NY
9 December 1992	Dr. Jerry D. Mahlman "The Role of Science in Guiding Greenhouse Warming Policy Decisions", National Academy of Sciences "Workshop on Greenhouse Warming Policy", Washington, DC
10 December 1992	Dr. Tal Ezer "Assimilation of Geosat Altimetry Data into a Three-Dimensional Primitive Equation Gulf Stream Model", AGU Fall Meeting, San Francisco, CA
15 December 1992	Mr. Richard T. Wetherald "Overview of Climate Impacts", NOAA Coastal Impacts Workshop, Washington, DC
6 January 1993	Dr. Jerry D. Mahlman "Hurricane Prediction Research at GFDL", Weather Research Meeting for FY95 ERL Budget Planning, Silver Spring, MD
12 January 1993	Mr. Robert E. Tuleya "Hurricane Forecasts in the 1992 Season with the GFDL Prediction System", Hurricane Research Meeting, National Meteorological Center, Washington, DC

17 January 1993	Dr. Hiram Levy II "The Role of Synoptic-Scale Transport in the Variability of Tropospheric NO_x in the Northern Hemisphere", 73rd American Meteorological Society's Annual Meeting, Conference on Atmospheric Chemistry, Anaheim, CA
18 January 1993	Mr. Morris A. Bender "Hurricane Forecasting with the GFDL Prediction System", 73rd American Meteorological Society's Annual Meeting, Anaheim, CA
21 January 1993	Dr. P.C.D. Milly "Sensitivity of the Global Water Cycle to the Water-Holding Capacity of Soils", American Meteorological Society Conference on Hydroclimatology, Anaheim, CA
25 January 1993	Dr. Syukuro Manabe "The Role of Oceans in Global Warming and Interdecadal Variability of Climate", Third Scientific Advisory Council Meeting of the International Geosphere-Biosphere Program, Ensenada, Baja, California, Mexico
27 January 1993	Dr. Ngar-Cheung Lau "On the Nature of Model-Simulated Large-Scale Air-Sea Interactions in the Tropics and Extratropics", Winter Meeting of the EPOCS Advisory Committee, Miami, FL
2 February 1993	Dr. Jerry D. Mahlman "Future Challenges and Opportunities for NOAA", OAR Retreat, Silver Spring, MD
3 February 1993	Dr. Kikuro Miyakoda "A Perspective of Seasonal Prediction", Colorado State University, Fort Collins, CO
9 February 1993	Dr. Syukuro Manabe "Effects of Orography on Middle Latitude Dry Climate in the Northern Hemisphere", Goddard Space Flight Center/NASA, Greenbelt, MD
9 February 1993	Dr. P.C.D. Milly "Continental Hydrology and Global Climate", Princeton University Department of Ecology and Evolutionary Biology, Princeton, NJ
16 February 1993	Dr. P.C.D. Milly "Continental Hydrology and Global Climate: Scientific Progress, U.S. Geological Survey, Reston, VA
22 February 1993	Mr. Morris A. Bender "Hurricane Forecasting with the GFDL Automated Prediction System", 47th Interdepartmental Hurricane Conference, Miami, FL

22 February 1993	Dr. Jerry D. Mahlman "Global Warming and the Greenhouse Effect: A Modeling Perspective", First Annual Scientific Workshop for NOAA's Earth Watch Service (NEWS), Silver Spring, MD
25 February 1993	Dr. Jerry D. Mahlman "Perspectives on Improving the Priorities Within the U.S. Global Change Research Program", Congress of the United States Office of Technology Assessment Workshop "EOS and the U.S. GCRP: Are We Asking and Answering the Right Questions?", Washington, DC
1 March 1993	Dr. Ngar-Cheung Lau "Role of the Tropical SST Anomalies in the Variability of the Extratropical Ocean/Atmosphere System", GOALS Study Conference, Climate Research Committee, National Academy of Sciences, Honolulu, HI
1 March 1993	Dr. Kikuro Miyakoda "Perspective of Seasonal Prediction at the Extratropics", GOALS Study Conference, Climate Research Committee, National Academy of Sciences, Honolulu, HI
5 March 1993	Dr. Hiram Levy II "Tropospheric Ozone: Past, Present, and Future", University of Iowa, Iowa City, IA
14 March 1993	Dr. Jeffrey L. Anderson "Correction of Bias in the DERF90 Experiment by Post Processing", Workshop on "Errors in Atmospheric Model Climate", National Meteorological Center, Camp Springs, MD
15 March 1993	Mr. Joseph J. Sirutis "Comparison of Model Integrations with 3 Different Subgrid Scale Parameterization Formulations", Workshop on "Errors in Atmospheric Model Climate", National Meteorological Center, Camp Springs, MD
26 March 1993	Dr. Hiram Levy II "Tropospheric O_3 and NO_x: Past, Present and Future", Harvard University, Department of Earth and Planetary Sciences, Cambridge, MA
29 March 1993	Dr. Kevin Hamilton "Wave-Mean Flow Interaction in the Tropical Stratosphere", Princeton University Program in Applied and Computational Mathematics, Princeton, NJ
30 March 1993	Dr. Jerry D. Mahlman "Climate Modeling: How Much Do Scientists Currently Know?", U.S. Senate Energy and Natural Resources Committee Hearing on Global Climate Change, Washington, DC

2 April 1993	Dr. Isaac M. Held "Radiative-Convective Equilibrium with Explicit Two-Dimensional Moist Convection", Massachusetts Institute of Technology, Cambridge, MA
8 April 1993	Dr. P.C.D. Milly "Climate, Soil-Water Storage, and the Annual Water Balance", Colloquium on Hydroclimatology and Global Hydrology, Massachusetts Institute of Technology, Cambridge, MA
9 April 1993	Dr. Leo J. Donner "The Problem of Clouds in the Atmospheric General Circulation", Department of Geology and Geophysical Sciences, Princeton University, Princeton, NJ
12 April 1993	Dr. Isaac M. Held "Some Problems in the Dynamics of Global Warming", Program in Applied and Computational Mathematics Colloquium, Princeton University, Princeton, NJ
16 April 1993	Dr. Jerry D. Mahlman "Greenhouse Warming: Current Science and Long-Term Implications", Department of Geological and Geophysical Sciences, Princeton University, Princeton, NJ
19 April 1993	Dr. Kirk Bryan "The Role of the Grand Banks in North Atlantic Climate Variability", North Atlantic Current Meeting, Woods Hole, MA
19 April 1993	Dr. Jerry D. Mahlman "NOAA's Potential Role in a Global Environmental Monitoring System", Second NOAA Data Quality and Continuity Workshop, Rockville, MD
20 April 1993	Dr. Isidoro Orlanski "A New Look at Downstream Baroclinic Development", National Meteorological Center, Washington, DC
23 April 1993	Mr. Anthony J. Rosati "Global Ocean Data Assimilation", Ocean Forecasting Conference, Acquafredda di Naratea, Italy
26 April 1993	Dr. Isidoro Orlanski "Unstable Waves that Shape our Weather", Spring 1993 Colloquium, Program in Applied and Computational Mathematics, Princeton University, Princeton, NJ
27 April 1993	Mr. Anthony J. Rosati "Initialization for ENSO Predictions", TOGA-NEG Conference, Hamburg, Germany

28 April 1993	Dr. Isaac M. Held "Benchmark Calculations for the Dynamical Cores of Atmospheric GCMs: A Preliminary Comparison of Spectral and Grid Models", CHAMMP Meeting, Oak Ridge, TN
30 April 1993	Mr. Anthony J. Rosati "ENSO Forecasts with a Coupled GCM", Forecasting Short-Range Climate Variations Conference, Hamburg, Germany
3 May 1993	Dr. Jerry D. Mahlman "Climate Change and the Stratosphere", SPARC Session of the European Geophysical Society, Wiesbaden, Germany
4 May 1993	Mr. Anthony J. Rosati "Assimilating Altimetry Data in Global Ocean GCM", Data Assimilation in Marine Science Conference, Liege, Belgium
10 May 1993	Dr. Isaac M. Held "Generalized 2-D Flows and Surface Quasigeostrophic Turbulence", Ninth Conference on Atmospheric and Oceanic Waves and Stability, sponsored by the American Meteorological Society, San Antonio, TX
10 May 1993	Mr. William F. Stern Results from an Ensemble of Decadal Simulations with GFDL's DERF GCM", Atmospheric Model Intercomparison Program Meeting, Bologna, Italy
10 May 1993	Dr. Yoshikazu Hayashi "Tropical 40-50 and 25-30 Day Oscillations Appearing in Realistic and Idealized GFDL Climate Models and the ECMWF Dataset", Ninth Conference on Atmospheric and Oceanic Waves and Stability, sponsored by the American Meteorological Society, San Antonio, TX
10 May 1993	Dr. Yoshio Kurihara "Hurricane Forecasting with the GFDL Automated Prediction System" 20th Conference on Hurricanes and Tropical Meteorology, sponsored by the American Meteorological Society, San Antonio, TX
10 May 1993	Mr. Robert E. Tuleya "Sensitivity Studies of Tropical Cyclone Development to Surface Conditions" 20th Conference on Hurricanes and Tropical Meteorology, sponsored by the American Meteorological Society, San Antonio, TX
10 May 1993	Dr. Abraham H. Oort "Physics of Global Climate Phenomena", Netherlands Organization for Scientific Research, The Hague, The Netherlands
11 May 1993	Dr. Leo J. Donner "The Role of Satellite Observations in Representing Clouds in General Circulation Models", National Meteorological Center, Washington, DC

13 May 1993	Dr. Isaac M. Held "Radiative-Convective Equilibrium with Explicit 2-D Moist Convection", Tropical Meteorology Conference, San Antonio, TX
17 May 1993	Dr. Yoshio Kurihara "Hurricanes: Modeling and Prediction", 13th Annual Conference "Modeling the Forces of Nature", Los Alamos National Laboratory, Los Alamos, NM
17 May 1993	Dr. Abraham H. Oort "Observed Humidity Trends in the Atmosphere", Royal Netherlands Meteorological Institute, De bilt, The Netherlands
17 May 1993	Dr. Jerry D. Mahlman "The Science of Global Warming: Implications for Policymakers", World Resources Institute, Washington, DC
18 May 1993	Mr. Ronald J. Stouffer "Double Equilibria in a Coupled Ocean-Atmosphere GCM", 13th Annual Conference "Modeling the Forces of Nature", Los Alamos National Laboratory, Los Alamos, NM
19 May 1993	Mr. Thomas L. Delworth "Interdecadal Variability of the North Atlantic in a Coupled Model", NASA/Goddard, College Park, MD
19 May 1993	Dr. Tal Ezer "Meso-scale Variability Inferred from Altimetric Data Assimilation using a Primitive Equation Model", Navy Geosat Follow-on Meeting, Applied Physics Laboratory, Laurel, MD
20 May 1993	Dr. George L. Mellor "A Sigma Coordinate Numerical Ocean Model", Los Alamos National Laboratory, Los Alamos, NM
24 May 1993	Dr. Tal Ezer "Simulations and Data Assimilation Studies of the East Coast and the North Atlantic with Princeton's Coastal Ocean Numerical Model", Annual American Geophysical Union Spring Meeting, Baltimore, MD
26 May 1993	Dr. Jerry D. Mahlman "Dynamics and Chemistry of Polar Ozone Depletion", Annual American Geophysical Union Spring Meeting, Baltimore, MD
28 May 1993	Dr. George L. Mellor "Arctic Ocean Modeling", Nansen Centennial Symposium, Solstand, Norway
2 June 1993	Ms. Rebecca Ross "The Initialization Scheme for the GFDL Hurricane Model", Air Resources Laboratory, Silver Spring, MD

2 June 1993	Mr. Ronald J. Stouffer "Latest Results from the GFDL Coupled Climate Model", Finnish National Program on Climate Change (SILMU), Helsinki, Finland
7 June 1993	Mr. Ronald J. Stouffer 1. "Latest Results from the GFDL Coupled Climate Model", 2. "Philosophy of Setting Up a Coupled Model Experiment at GFDL", Hadley Center, Bracknell, England
8 June 1993	Dr. Kikuro Miyakoda 1. "GFDL Activity in 1992/93", 2. "The Initial Conditions for Soil Moisture", Numerical Extended Range Weather Prediction Workshop, Airlie, VA
8 June 1993	Dr. Jeffrey L. Anderson "Impacts of Systematic Errors on Numerical Extended Range Weather Prediction", Numerical Extended Range Weather Prediction Workshop, Airlie, VA
9 June 1993	Dr. Kevin P. Hamilton "General Circulation Modeling of Stratospheric Interannual Variability", Annual Congress of the Canadian Meteorological and Oceanographic Society, Fredericton, New Brunswick, Canada
11 June 1993	Mr. Anthony J. Broccoli "Greenhouse Warming", NOAA Colloquium on Operational Environmental Prediction, Silver Spring, MD
14 June 1993	Dr. Isaac M. Held "Idealized Models of the Extratropical Response to Global Warming", Stanstead Seminar, Lennoxville, Quebec, Canada
25 June 1993	Dr. Leo J. Donner "Ice Clouds", Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
28 June 1993	Dr. Leo J. Donner "Ice Clouds in Community Climate Model", NCAR Community Climate Model Workshop, Boulder, CO
28 June 1993	Mr. Robert J. Wilson "Three-Dimensional Numerical Simulation of Thermal Tides in the Martian Atmosphere", Workshop on Atmospheric Transport on Mars, Corvallis, OR
29 June 1993	Dr. Tal Ezer "Coastal Ocean Circulation Modeling", 2nd NOAA Colloquium on Operational Environmental Prediction, National Ocean Service, Silver Spring, MD

2 July 1993	Dr. John R. Toggweiler "Integrating Chemistry and Biology into Physical Models", 2nd NOAA Colloquium on Operational Environmental Prediction, National Ocean Service, Silver Spring, MD
12 July 1993	Dr. Syukuro Manabe "Greenhouse Gas-Induced Evolution of the Coupled Ocean-Atmosphere Land Surface System Over Several Centuries", International Association of Meteorology Atmospheric Physics/International Association of Hydrological Sciences Meeting, Yokohama, Japan
12 July 1993	Dr. Leo J. Donner "Parameterization of Convection for GCM's", NCAR Summer Colloquium on "Clouds and Climate", Boulder, CO
12 July 1993	Dr. John R. Toggweiler "Equatorial Pacific Biogeochemical Models", Joint Global Ocean Fluid Study Equatorial Pacific Workshop, Seattle, WA
15 July 1993	Dr. P.C.D. Milly "Sensitivity of the Global Water Cycle to the Water-Holding Capacity of Soils", International Association of Hydrological Science, International Association Meteorological Atmospheric Physics, Joint Symposium on Exchange Processes at the Land Surface for a Range of Time and Space Scales, Yokohama, Japan
19 July 1993	Dr. P.C.D. Milly 1. "Some Suggestions for Comparing Simple and Complex Land-Surface Parameterization Schemes", 2. "Water and Energy Balances Computed for a Land-Surface with a Single Water Store and No Heat Capacity", International Association Hydrological Science/International Association of Meteorological Atmospheric Physics, Joint Symposium on GEWEX Continental-Scale International Project, Yokohama, Japan
27 July 1993	Mr. Bruce Wyman "Global Model Development and Comparisons using the Vertical Eta Coordinate", National Meteorological Center, Camp Springs, MD
28 July 1993	Dr. Jerry D. Mahlman "Global Warming: Current Understanding, Remaining Uncertainties", World Resources Institute briefing on "Current Understanding of Global Warming and Ozone Depletion: A Briefing on Global Change", Washington, DC
9 August 1993	Dr. John R. Toggweiler "Wind-Driven Aspects of the Global Thermohaline Circulation", Summer Course "Atmosphere-Ocean Dynamics and Interannual Climate Variability", Friday Harbor, Washington
12 August 1993	Dr. Syukuro Manabe "Modeling Climate Change", Jet Propulsion Laboratory, Pasadena, CA

16 August 1993	Dr. Leo J. Donner "Assimilation of Precipitation Observations", International Summer School on Assimilation of Meteorological and Oceanographical Observations, La Garde, France
25 August 1993	Dr. Ngar-Cheung Lau "Use of Satellite Cloud Data to Depict Characteristics of Atmospheric Circulation Systems", Joint Institute for the Study of Atmosphere and Ocean, University of Washington, Seattle, WA
26 August 1993	Dr. Ngar-Cheung Lau "Modeling of Air-Sea Interaction in the Extratropics", Joint Institute for the Study of Atmosphere and Ocean, University of Washington, Seattle, WA
30 August 1993	Dr. Jerry D. Mahlman "The Case for Serious Climate and Chemical Change Monitoring", National Research Council Board on Global Change Meeting, Woods Hole, MA
6 September 1993	Dr. Jerry D. Mahlman "Tracer Transport in the GFDL SKYHI Model", NATO Advanced Research Workshop on Stratosphere-Troposphere Exchange, Cambridge, England
8 September 1993	Dr. Leo J. Donner "Recent Developments in Parameterizing Cirrus Clouds and Cumulus Convection in General Circulation Models", Workshop on General-Circulation-Model Cloud Parameterization, Colorado State University, Fort Collins, CO
8 September 1993	Dr. Syukuro Manabe "Multi-Century Response of the Coupled Ocean-Atmosphere System to Increasing Atmospheric CO_2", Lamont-Doherty Geological Observatory, Palisades, NY
10 September 1993	Dr. John R. Toggweiler "Rethinking the Thermohaline Component of Global Biogeochemical Cycles", International JGOFS (Joint Global Ocean Flux Study) Scientific Steering Committee Meeting, Carqueiranne, France
13 September 1993	Mr. Ronald J. Stouffer "Update on the Coupled Modeling Activities at GFDL", World Climate Research Programme Steering Group on Global Climate Modeling, Institute of Ocean Sciences, Sidney, British Columbia, Canada
14 September 1993	Mr. Anthony J. Rosati "Overview of TOGA-NEG and GFDL ENSO Forecasts", World Climate Research Programme Steering Group on Global Climate Modeling, Institute of Ocean Sciences, Sidney, British Columbia, Canada

14 September 1993	Dr. Tal Ezer "Modeling the Separation of the Gulf Stream", WOCE Numerical Experimentation Group Meeting, Institute of Ocean Sciences, Sidney, British Columbia, Canada
28 September 1993	Dr. Jerry Mahlman "Long-Term Implications of Greenhouse Warming", Center for Energy and Environmental Studies, von Neumann Hall, Princeton University, Princeton, NJ

Addendum

15 September 1992	Dr. Kevin Hamilton "The Ozone Layer", Princeton Environmental Action, Princeton University, Princeton, NJ
18 September 1992	Dr. Jerry D. Mahlman "A State of the Science Report on Climate Change", Senate Foreign Relations Committee Hearing on "The United Nations Framework Convention on Climate Change", Washington, DC
22 September 1992	Dr. Syukuro Manabe "The Influence of Orography upon the Arid Climates in the Northern Middle Latitudes", Japan-China Workshop on Monsoons, Environmental Research Institute, Tokyo, Japan
23 September 1992	Dr. Syukuro Manabe "The Role of Oceans in the Interdecadal Variability of Climate", Center for Climatic Research, University of Tokyo, Tokyo, Japan
26 September 1992	Dr. Kikuro Miyakoda "Toward GCM Seasonal Predictions", University of Tokyo, Tokyo, Japan
28 September 1992	Dr. Kikuro Miyakoda "Toward GCM Seasonal Predictions", World Climate Research Program Symposium "Clouds and Ocean in Climate", Nagoya, Japan
28 September 1992	Dr. John R. Toggweiler 1. "Is the Outflow of Deep Water from the Atlantic Ocean Driven by Southern Hemisphere Winds?", 2. "Transport of Atlantic Salt (and $\delta^{13}C$) to the Southern Ocean", Woods Hole Oceanographic Institution, Woods Hole, MA
29 September 1992	Dr. Isidoro Orlanski "A New Look at Lee Cyclogenesis", Sixth Conference on Mountain Meteorology, Portland, OR

APPENDIX E

ACRONYMS

ACRONYMS

AASE	Arctic Airborne Stratospheric Experiment
ABLE	Atmospheric Boundary Layer Experiment
AMEX	Australian Monsoon Experiment
AMIP	Atmospheric Model Intercomparison Project
AOML	Atlantic Oceanographic and Meteorological Laboratory/NOAA
AOU	Apparent Oxygen Utilization
ARL	Atmospheric Research Laboratory/NOAA
A92/P93	GFDL Activities FY92, Plans FY93
CCN	Cloud Condensation Nuclei
CEM	Cumulus Ensemble Model
CFC	Chlorofluorocarbon
CHAMMP	Computer Hardware, Advanced Mathematics and Model Physics project
CIRA	COSPAR International Reference Atmosphere
CLIPER	A simple model combining CLImatology and PERsistence used in hurricane prediction.
CMDL	Climate Monitoring and Diagnostics Laboratory/NOAA
COADS	Comprehensive Ocean-Atmosphere Data Set
COARE	Coupled Ocean-Atmosphere Response Experiment
COSPAR	Congress for Space Research
CRAY	Cray Research, Inc.
CSIRO	Commonwealth Scientific & Industrial Research Organization

DAMEE	Data Assimilation and Model Evaluation Experiments
DJF	December, January, February (winter)
E	A physical parametrization package in use at GFDL. E physics includes a high-order closure scheme for subgrid turbulence.
ECMWF	European Centre for Medium-Range Weather Forecasts
E"n"	Horizontal model resolution corresponding to "n" points between a pole and the equator on the E-grid.
ENSO	El Niño - Southern Oscillation
EPOCS	Equatorial Pacific Ocean Climate Studies
ERBE	Earth Radiation Budget Experiment
FDDI	Fiber Distributed Data Interface
FDH	Fixed Dynamic Heating model
FIRE	First ISCCP Regional Experiment
FY"yy"	Fiscal Year "yy" where "yy" are the last two digits of the year.
GARP	Global Atmospheric Research Program
GATE	GARP Atlantic Tropical Experiment
GCM	General Circulation Model
GCTM	Global Chemical Transport Model
GEOSAT	Geodetic Satellite
GFDL	Geophysical Fluid Dynamics Laboratory/NOAA
GMT	Greenwich Mean Time
GOES	Geostationary Operational Environmental Satellite

GTE	Global Tropospheric Experiment
HIBU	Federal Hydrological Institute and Belgrade University
HPCC	High Performance Computing and Communications
HRD	Hurricane Research Division/AOML
IPCC	Intergovernmental Panel on Climate Change
ISCCP	International Satellite Cloud Climatology Project
IT	Information Technology
ITCZ	Intertropical Convergence Zone
JGOFS	Joint Global Ocean Flux Study
JJA	June, July, August (summer)
JPL	Jet Propulsion Laboratory
KFA	Forschungszentrum Julich
LAHM	Limited Area HIBU Model
LBL	Line By Line
LIMS	Limb Infrared Monitor of the Stratosphere
L"n"	Vertical model resolution of "n" levels.
LWP	Liquid Water Path
MMM	Multiply-nested Movable Mesh
MOM	Modular Ocean Model
MOODS	Master Oceanographic Observations Data Set
MPP	Massively Parallel Processor
NABE	North Atlantic Bloom Experiment

NADW	North Atlantic Deep Water
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCDC	National Climate Data Center/NOAA
NH	Northern Hemisphere
NMC	National Meteorological Center/NOAA
NOAA	National Oceanic and Atmospheric Administration
NODC	National Oceanographic Data Center/NOAA
OLR	Outgoing Longwave Radiation
OTL	Ocean Tracers Laboratory/Princeton University
PCMDI	Program for Climate Model Diagnosis and Intercomparison
PFC	Perfluorocarbon
PILPS	Project for Intercomparison of Land-Surface Parameterization Schemes
PMEL	Pacific Marine Environmental Laboratory
PNA	Pacific-North American
QBO	Quasi-Biennial Oscillation
RFP	Request for Proposal
R"n"	Horizontal resolution of spectral model with rhomboidal truncation at wave numbers "n".
SAGE	Stratospheric Aerosol and Gases Experiment
SAMS	Stratospheric Aerosol Measurement System
SAVE	South Atlantic Ventilation Experiment

SBUV	Solar Backscatter Ultraviolet (satellite)
SH	Southern Hemisphere
SiB	Simple Biosphere
SKYHI	The GFDL Troposphere-Stratosphere-Mesosphere GCM
SME	Solar Mesosphere Explorer
SPCZ	South Pacific Convergence Zone
SST	Sea Surface Temperature
SUN	Sun Microsystems, Inc.
THC	Thermohaline Circulation
T"n"	Horizontal resolution of spectral model with triangular truncation at wave number "n".
TOGA	Tropical Ocean and Global Atmosphere (project)
TOMS	Total Ozone Mapping Spectrometer
TOVS	Tiros Operational Vertical Sounder
TTO	Transient Tracers in the Oceans
WGNE	Working Group on Numerical Experimentation
WMO	World Meteorological Organization
WOCE/HP	World Ocean Circulation Experiment/Hydrographic Program
XBT	Expendable Bathythermograph

☆U.S. GOVERNMENT PRINTING OFFICE:1993-731-461/80048