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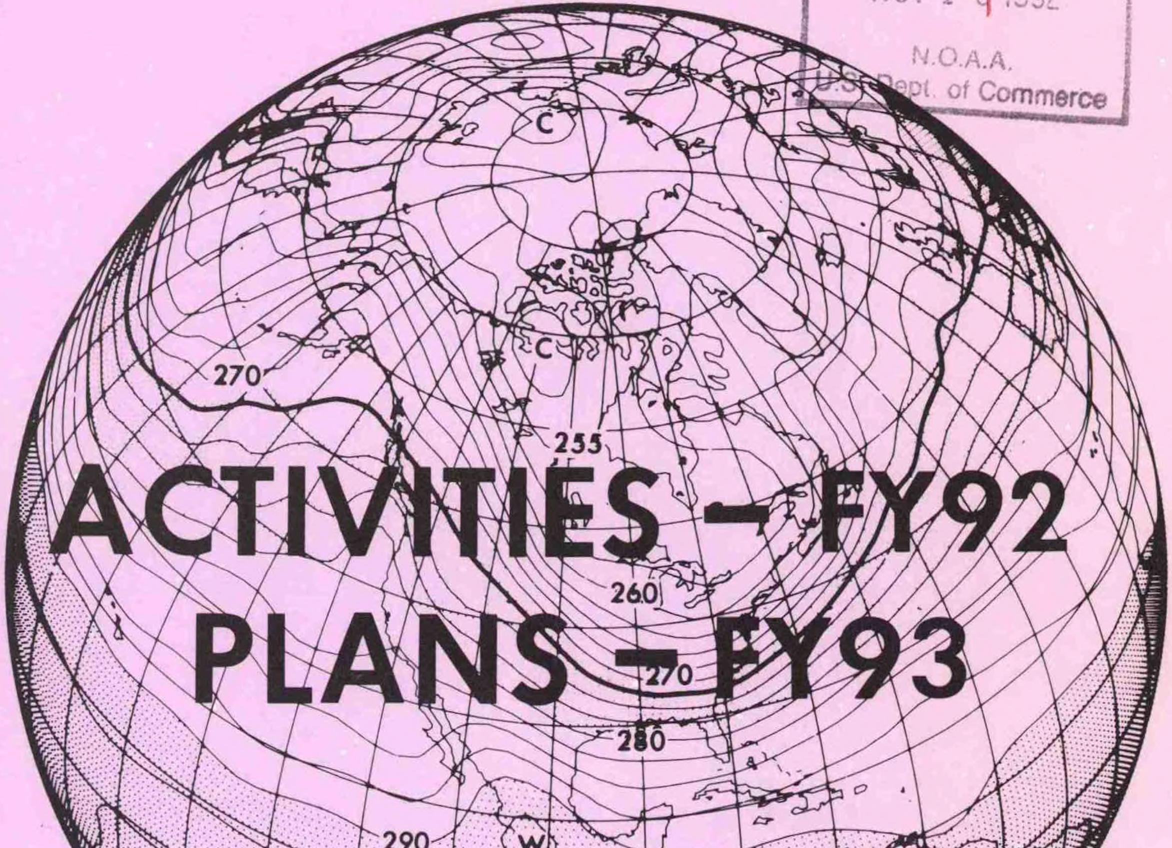
GFDL ACTIVITIES & PLANS FY92/93

GEOPHYSICAL FLUID DYNAMICS LABORATORY



ACTIVITIES – FY92
PLANS – FY93

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

GEOPHYSICAL FLUID DYNAMICS LABORATORY

ACTIVITIES - FY92

PLANS - FY93

OCTOBER 1992

GEOPHYSICAL FLUID DYNAMICS LABORATORY
PRINCETON, NEW JERSEY

UNITED STATES
DEPARTMENT OF COMMERCE

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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 1992; 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 FY93; a listing of seminars presented at GFDL during Fiscal Year 1992; a list of seminars and talks presented during Fiscal Year 1992 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 1992 Annual Report was co-edited by Joseph Sirutis and Betty M. Williams. Special thanks to Wendy Marshall for her patience and expertise in typing this report. Also, thanks to Gail Haller for painstakingly proofreading the report.

September 1992

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AN OVERVIEW

SCOPE OF THE LABORATORY'S WORK

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

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

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

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

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

HIGHLIGHTS OF FY92

and

IMMEDIATE OBJECTIVES

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

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

I. WEATHER SERVICE

GOALS

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

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

ACCOMPLISHMENTS OVER THE PAST YEAR (FY92)

* The simulated distributions of precipitation, clouds, and soil moisture have been dramatically improved by using filtering techniques to reduce the Gibbs phenomena associated with the spectral representation of model orography. The Lanczos filter was applied to the model orography, as well as to the cumulus parameterization results. As a result, negative values of mixing ratio, which have been an annoying problem for spectral models, have been eliminated for the most part, and the ripples in the surface pressure, produced by the Andes and the Antarctic highlands, have been largely removed (3.1.1).

* Major efforts have been expended on the improvement of the air-sea coupled model, focusing on two aspects of its simulation capability, *i.e.*, the El Nino/Southern Oscillation and the global SST distribution. Model sensitivity tests involving atmospheric parameters, such as surface winds, evaporation, and incoming shortwave radiation have been made. So far, the surface wind stress in the eastern tropical Pacific has been found to be the most influential parameter for reproducing the annual cycle and interannual variability of SST. Also, the impact of the horizontal resolution of the atmospheric GCM on the reduction of the SST bias has been

established. For example, the cold bias at the equator has been reduced by a factor of 1.7 by increasing the resolution from R21L9 to T42L18 (3.2.2, 3.2.3).

* One of the requirements for a useful ensemble forecast is that the ensemble members should cluster about the true solution. To achieve this objective, the dynamical and thermodynamical balancing of the initial conditions which are perturbed, based on the Monte Carlo method, is an important process. For this purpose, the capability of two methods of initialization have been tested; one is a nudging method and the other is a full-fledged data assimilation approach (3.4.1).

* An automated GFDL hurricane prediction system has been established by assembling the procedures of data acquisition, model initialization, and time integration of the hurricane model into one system. This system can now run in near real time mode. Hurricane prediction experiments using the automated system have been performed for seven cases of Atlantic hurricanes and for one case of a tropical cyclone in the Australian region. The results indicated dramatic improvement in track forecasts as well as the feasibility of forecasting storm intensity (6.1.1, 6.5.1, 6.5.2).

* The question of why tropical cyclones do not form over land surfaces, such as a tropical rainforest, a fundamental question in tropical cyclogenesis, has been studied through a series of idealized experiments using the hurricane model with improved treatment of radiation and land surface conditions. It was found that the smallness of the thermal property, defined as the square root of the product of the heat capacity and the thermal conductivity, of the soil hindered the storm formation (6.2).

* Using a joint hurricane-ocean model, the impact of hurricane ocean feedback processes on the behavior of tropical cyclones has been investigated. Over the ocean, with the sea surface temperature set to 302 K at the initial time, the storms in different basic easterly flows deepened to nearly the same intensity when the interaction was included (6.4).

* The importance of downstream development for baroclinic waves has been demonstrated in recent studies. Using a three-dimensional primitive equation model, it has been shown that the convergence/divergence of ageostrophic geopotential fluxes provides 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 (7.1.1, 7.1.3).

* The success with which geopotential fluxes have been used in case studies to indicate regions of kinetic energy growth and decay suggest that they offer considerable potential as a powerful diagnostic tool for predicting the growth and decay of systems (7.1.1, 7.1.2, 7.1.3).

* Recent simulations of storm tracks using an idealized model have shown that the existence of a localized source of enhanced baroclinicity does not necessarily lead to a localization of eddy activity. Energy radiated downstream by eddies generated in the high-baroclinicity region will trigger and sustain eddies in the low-baroclinicity region downstream. These results represent a fundamental difference between downstream development and normal-mode life cycles (7.1.3).

* A new mechanism for lee cyclogenesis has been proposed, based on a series of experiments in which it was found that the interruption of the warm ascending branch of a baroclinic wave by a topographic barrier will produce a low pressure system south of the barrier, due to the warm advection induced by the mountain anticyclone (7.3.1).

SOME PLANS FOR FUTURE RESEARCH

* The investigation of the Gibbs reduced scheme for cumulus convection will be continued. Three experiments on atmospheric subgrid-scale parameterization will be summarized. The bucket versus the SiB hydrology will be pursued.

* A random cloud model will be tested. The development of a working version of the meso-scale eta-model with cloud physics will be completed. A long time integration with specified ISCCP clouds will be carried out.

* A C-grid option will be added to the grid point model.

* A version of the GFDL Modular Ocean Model (MOM) with an implicit free surface will be implemented. Lateral boundary conditions will be added to the MOM.

* The Gibbs reduced model of T30L18 resolution, coupled with the ocean GCM, will be investigated. The 1° x 1° latitude grid size ocean model will be tested in the air-sea coupled mode.

* The compatibility of the MOM's surface pressure with that derived from satellite altimeter data will be investigated. An algorithm to assimilate altimeter data will be developed. The ocean data assimilation will be repeated with TOGA data combined.

* The nine runs using the atmospheric T42L18 GCM will be completed, and the results will be analyzed and compared with observations. The study on the reproducibility of multiple-runs will be repeated, using a 40 year SST data set. The investigation of methods to estimate the uncertainty in the atmospheric analysis will be continued. Ensemble forecasts are to be performed, using a set of about 300 perturbed initial conditions. As a reasonable way of stratifying the ensemble, two

states of atmospheric circulation, the *zonal flow* and the *blocked* patterns, will be investigated.

* The automated hurricane prediction system will be further evaluated by its application to the Atlantic and Eastern Pacific hurricanes in the 1992 season.

* A study to investigate the effects of tropical cyclones on the evolution of the surrounding environment will be carried out. This issue is one side of the two-fold aspect of scale interaction.

* Additional case studies will be initiated to better understand the role of geopotential fluxes and baroclinic conversion in the development of cyclones. From the new perspective gained so far, the explosive development of storms will be analyzed to identify the roles played by localized baroclinicity and the decay of upstream systems.

* Alternative time filtering approaches will be employed in order to identify the role of downstream development in the formation and maintenance of storm tracks.

* The role of surface heat and momentum fluxes in the intensification of extratropical cyclones will continue. New case studies will be performed to assess the relative importance of these fluxes in atmospheric preconditioning and cyclone evolution.

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 (FY92)

* Analysis of a 1000 year integration of the coupled ocean-atmosphere model indicates:

* (1) substantial interdecadal variability of the model thermohaline circulation in the North Atlantic Ocean. These fluctuations, with a time scale of approximately 40-50 years, are related to large scale changes in the temperature, salinity, and density structure of the model North Atlantic, and may have important implications for atmospheric variability on interdecadal time scales (1.1.2).

* (2) surface temperature variability tends to be larger and more persistent in the neighborhood of deep and intermediate water formation in the ocean (1.1.1).

* Radiative-convective equilibria have been obtained using a two-dimensional model with resolved moist convection, in which the radiative transfer is fully interactive with the predicted moisture and cloud fields. The model produces a basic flow oscillation with a period of approximately 60 days. The predicted planetary albedo decreases with increasing surface temperature. This implies a possible positive cloud-radiation feedback in the climate system (1.3.1).

* Experiments designed to measure the feedback between the earth's climate and vegetation on land have revealed positive feedback at low latitudes due to the vegetation's surface albedo effect, but not at middle and high latitudes. There is also some positive feedback due to the surface roughness at all latitudes, and little feedback due to field capacity (1.2.2).

* The GFDL SKYHI model has been completely rewritten in a fully modular form. This new version allows for far simpler user access, full separability of physics packages, use of higher order advection and diffusion schemes, and a completely separable multiple-trace constituent package for climate and chemistry studies. This recoding has been put in a form that allows access of this model to the new generation of massively parallel processor (MPP) systems (2.2.1).

* The climatology of the SKYHI model has been extensively evaluated at 1°, 2°, and 3° latitude grid spacing versions. The comparison with observations shows generally good agreement that improves as the grid size is decreased. Overall, the winter stratosphere agreement with observations is remarkably good in the Northern Hemisphere, but important deficiencies remain in the Southern Hemisphere (2.2.2).

*	The SKYHI 3° resolution model shows a highly realistic interannual climatology of sudden stratospheric warming events (Fig. 2.2). Extended forecast experiments show that global sudden warming events become quite unpredictable if the model is initialized a month or more before the peak of the warming event (2.2.5).

*	A radiative model study has revealed that the effects of volcanic aerosol can modify the amount of surface climatic forcing on the interdecadal time scale by an amount that is large relative to the incremental greenhouse gas forcing. This shows that volcanic effects must be carefully considered when observational evidence of global warming signals is being sought (2.4.2).

*	A major study has been completed, showing that the marked decrease of lower stratospheric ozone during the 1980's implies a significant negative climate forcing for the earth's surface. While only a modest correction to the net increased greenhouse forcing during this period, the ozone loss effect does roughly cancel the greenhouse warming effect of the increased CFCs, probably the root cause of the substantial ozone decreases (Fig. 2.4). This finding was a highlighted new result in the IPCC 1992 Supplement (2.4.5).

*	The book "Physics of Climate" by José P. Peixoto and Abraham H. Oort, which was in preparation during many years, was finally published in January 1992 by the American Institute of Physics. This 520-page long book describes, among other topics, the basic equations governing the climate system, the observed state of the atmosphere, ocean and cryosphere, the global angular momentum, water, energy and entropy cycles, interannual and interdecadal variations, and the mathematical simulation of climate. It can be used as a graduate textbook on climate. This publication represents a major investment of time and research effort by the Observational Studies Group at GFDL. So far, it has been favorably reviewed; a second printing is already in progress (5.2.6).

*	The global tropospheric and lower stratospheric temperature analyses for the period May 1958 through December 1989, produced at GFDL during the last two decades have been adopted as the standard atmospheric data to describe the state of the atmosphere and its temporal evolution for the 1992 Supplement to the IPCC Scientific Assessment (5.2.1).

*	A series of GCM experiments, performed as part of a NOAA/Universities collaborative effort, yield several phenomena which bear considerable resemblance to the observations. Of particular interest are the temporal and spatial development of the Asian summer monsoon, the differences between the atmospheric circulation in various parts of the globe during the spring and autumn seasons, and the decadal-scale variability in the occurrence of the teleconnection pattern associated with El Niño. The appearance of such features in the model atmosphere offers promise that

diagnosis of the model output and additional integrations of the GCMs will enhance our understanding of the mechanisms contributing to these phenomena (5.2.3, 5.2.4).

* Intercomparison of the output from a suite of GCM runs, which incorporate different aspects of the air-sea interactions, indicates that a substantial portion of the coupling between the SST and meteorological anomalies in the extratropics may be attributed to the atmosphere driving the ocean, whereas the influence of the ocean on the atmosphere appears to play a secondary role (5.4.1).

SOME PLANS FOR FUTURE RESEARCH

* The analysis of low-frequency variability in the coupled model of the atmosphere-ocean system will be continued. Special emphasis will be placed on the role of the oceans in the interdecadal variability of climate.

* A detailed analysis of the direct sensitivity of surface water balance to soil-water holding capacity will be conducted.

* A series of calculations will be performed with the resolved-convection radiative-convective equilibrium model, testing the model's sensitivity to resolution, sub-grid scale parametrization, domain size, and microphysical assumptions.

* To explore the confusing issue of how the atmosphere responds to perturbations in sea surface temperature, a series of low resolution integrations will be performed with the R15 GCM, using models with both realistic and idealized geometries.

* Calculations will be conducted with the dry dynamical cores of several GCMs (both spectral and gridpoint) at several resolutions, as a starting point in a systematic study of the merits and deficiencies of alternative atmospheric modeling frameworks.

* Further development of the modular version of SKYHI will continue, with emphasis on generalizing it for climate studies and for computational testing on massively parallel systems.

* New control integrations will be started with the SKYHI model that incorporate improved distributions of ozone and clouds, along with inclusion of updated radiative transfer algorithms.

* Extensive analysis of the interannual variability of the simulated Northern Hemisphere stratospheric circulation in SKYHI will be conducted.

* Analysis of the climatic implications of stratospheric ozone loss will continue. Whenever possible, comparisons will be made with observed temperature trends.

* The study of the three dimensional structure of the observed trends in temperature and humidity, and their possible connection with the greenhouse gases warming during the last 26 years, will continue.

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 carbon dioxide, methane, nitrous oxide, and the chlorofluorocarbons (CFCs); 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 (FY92)

* The GFDL global chemical transport model has been used to investigate the sources and behavior of reactive nitrogen (NO_y) components NO_x, HNO_3, and PAN as transported species. This experiment reveals a number of new insights: (1) about 70-75% of fossil fuel emissions are deposited near their source regions, with the remainder exported to adjacent ocean basins; (2) fossil fuel sources dominate the observed HNO_3 surface deposition in the extratropical North Atlantic; (3) much of the mid-troposphere PAN and HNO_3 levels may be explained by fossil-fuel and stratosphere sources of NO_y; (4) the fossil-fuel source has only a minor impact on NO_y levels in the Southern Hemisphere and remote tropics; and (5) away from source regions, PAN is a major component of fossil-fuel NO_y and dominates north of 45°N (Fig. 2.1, 2.1.2).

* The effort continues on determining how much the ozone, at relatively unpolluted sites, is controlled by anthropogenic NO_y emissions. A detailed model and observational analysis has indicated that the Atlantic islands of Bermuda and Barbados have an ozone climatology that is essentially under the control of natural

processes, similar to that seen at Samoa in the South Pacific, a clearly remote site (2.1.3).

* A continued comparison of the 1° latitude resolution SKYHI model, with the recent polar stratospheric aircraft expeditions, has revealed further insights. The model does an excellent job of simulating the very sharp "wall" of N_2O gradient at the edge of the northern polar vortex. Unfortunately, the southern vortex edge is not as well simulated, paralleling other documented dynamical deficiencies in the model's Southern Hemisphere winter stratosphere. An indirect analysis leads to the additional conclusion that current chemical parameterizations of N_2O photochemical destruction in the stratosphere are too weak (2.2.12).

SOME PLANS FOR FUTURE RESEARCH

* SKYHI experiments with various levels of ozone chemistry will be started. These experiments will establish a baseline for an accelerated effort in tropospheric and lower stratospheric chemistry, and its connection to ozone-climate interactions.

* Reactive nitrogen simulations will be carried out in the GCTM for multiple species with all the nitrogen sources and hydrocarbon effects included.

* SKYHI transport studies will be performed with a suite of trace constituents: CFC-11 for evaluating interhemispheric transport; reactive nitrogen for comparison with the previous-generation GCTM; stratospheric ozone to test "natural" ozone effects; and a biomass burning source for testing transport in the tropics.

* The photochemistry of biomass NO_y emissions and O_3 over the tropical ocean will be examined in the context of regional transport.

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 (FY92)

* Results from numerical simulations of the Gulf Stream with a realistic regional model compared well with observations and contributed to the understanding of dynamical processes, such as the separation of the Stream from the coast and its interaction with topography. Forecast and nowcast skills have been demonstrated for the Gulf Stream region using a data assimilation scheme to assimilate satellite altimetry and SST data into the model (4.6).

* The ocean's capacity to take up anthropogenic CO_2 has been estimated with an ocean general circulation model. The uptake estimate for the 1980 to 1989 decade (1.9 GtC/yr) is in excellent agreement with other models, but significantly larger than the Tans et al. estimate of 0.3 to 0.8 GtC/yr based on observations and an atmospheric model. The discrepancy has been explained as arising primarily from the fact that Tans et al. ignored the substantial net flux of carbon into the ocean by rivers (4.5.1).

* A study of the potential response of atmospheric CO_2 to perturbations in the ocean carbon cycle, such as those that might result from enhancing new production by iron fertilization of the high latitude Southern Ocean, has been completed. The iron fertilization scenario could potentially have a significant impact on atmospheric CO_2, but the extreme conditions required to achieve a large impact would be difficult, if not impossible, to satisfy. The impact of the Southern Ocean iron fertilization scenario on atmospheric nitrous oxide levels is potentially quite large, increasing the flux by an order of 2.6 (0.1 to 15.4) TgN yr^{-1}, compared to the present flux of 1.4 to 2.6 TgN yr^{-1}. The same model was used to show that the potential growth of marine macroalgae as a sink for CO_2 is minor (4.5.2).

* An analysis of the ecosystem model of nitrogen cycling in the North Atlantic has been completed. This model can predict many of the observed features of the nutrient and chlorophyll distributions (4.5.3).

* A new set of simulations of the biological and chemical cycling of carbon throughout the water column were initiated with a model of carbon's solubility pump, driven by the increase in the solubility of CO_2 in cold water. The combined effect of the solubility pump with the biological pump, which is driven by organic carbon cycling, is in the process of being simulated at the present time. The model of the solubility pump explicitly includes total carbon and the ^{13}C isotope, gas exchange, the carbonate species H_2CO_3, HCO_3^-, and $CO_3^=$, as well as the contributions to total alkalinity of dissolved silica, phosphate, water, and borate species (4.5.4).

* A re-analysis of thorium data from Station P in the North Pacific provided realistic estimates of the concentration of sinking particles and of the magnitude of particle cycling rate constants. A compilation of thorium and particle data from the Nares Abyssal Plain in the NW Atlantic was used to determine particle cycling rate constants throughout the water column (4.5.4).

* A new carbon system measurement program was established this year to support the World Ocean Circulation Experiment/Hydrographic Program (WOCE/HP) by providing high precision carbon system measurements on their cruises (4.5.5).

* Final processing of ^{228}Ra samples collected by the Ocean Tracers Laboratory during the North Atlantic TTO experiment is nearly complete. Interpretation of these results is now underway, including both classical methods as well as with numerical models. At the present time, the Ocean Tracers Laboratory is the primary laboratory for collection and interpretation of ^{14}C in the U.S. Pacific World Ocean Circulation Experiment. During FY92, members of the lab participated in 7 sampling cruises, mostly in mid-latitude eastern Pacific waters (4.7.2, 4.7.3).

SOME PLANS FOR FUTURE RESEARCH

* The construction and evaluation of an operational coastal ocean prediction system for the U.S. east coast will continue. Modeling of climatic effects on coastal regions and sea level change will be initiated.

* A set of simulations of oceanic anthropogenic CO_2 uptake will be carried out using the new ocean carbon system model that is being developed with a more realistic representation of the biological and solubility pumps than used for the previous studies.

* A project will be initiated in collaboration with the Climate Dynamics group to calculate oceanic uptake of anthropogenic CO_2 in coupled air-sea models of the climate response to increased atmospheric CO_2.

* Results of the tropical Pacific portion of the global equatorial ecosystem model will be analyzed and the impact of El Niño will be simulated.

* A new effort is being undertaken to examine the feasibility of assimilating satellite ocean color observations into the ecosystem model as a technique for using such data to obtain information on carbon fluxes in the ocean.

* An inversion of ^{234}Th, ^{228}Th, nitrogen, and carbon data from the Joint Global Ocean Flux Study (JGOFS) North Atlantic Bloom Experiment (NABE) will be attempted. This data set provides estimates of the change with time of the activity of

thorium isotopes and concentration of nitrogen and carbon. This data should help to provide more precise estimates of carbon and particle cycling rate constants.

* The ongoing re-analysis of oceanic nutrient observations will be completed in order to obtain new estimates of Redfield ratios.

* The North Atlantic thermocline ventilation studies will be continued, with the possibility of extending the analysis to the South Atlantic, particularly to the region of the Agulhas retroflection and southwestern Atlantic.

* The Ocean Tracers Laboratory (OTL) will continue to participate in the WOCE program. OTL is currently scheduled for approximately 300 days of sea time for FY93.

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 (FY92)

* A high resolution global coupled ocean-atmosphere model has been developed, which exhibits realistic ENSO oscillations in a decade-long integration with no significant model drift (4.1.4).

* A new hypothesis has been developed to explain the unique character of the Atlantic overturning "conveyor belt" circulation. Mechanical forcing by westerly winds over the Southern Oceans may be equally as important in forcing pole to pole overturning as the effect of thermohaline density gradients in North Atlantic deep water formation (4.3.1).

* A retrospective calculation has been carried out for a global ocean model using the historical record of temperature over the past century as input. Predicted

subsurface temperature changes compare favorably to observations in the North Atlantic (4.3.3).

SOME PLANS FOR FUTURE RESEARCH

* The high resolution global coupled ocean-atmosphere model will be used to study the seasonal cycle and the ENSO oscillations to predicted clouds.

* A 1° latitude by 1° longitude model of the World Ocean will be developed to explore the hypothesis about the Atlantic overturning "conveyor belt" circulation, which has already been tested in lower resolution models.

* The retrospective ocean climate calculations will be continued in higher resolution models.

PROJECT ACTIVITIES FY92

PROJECT PLANS FY93

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 Long Term Integration of a Coupled Model

K. Bryan | *S. Manabe*
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K. Dixon

ACTIVITIES FY92

During the past year, a coupled ocean-atmosphere model was time-integrated 1000 model years to study the role of the oceans in the natural variability of climate. This variability study is also important for the detection and prediction of climate change.

Analysis of the 1000-year integration has just begun. Fig. 1.1 (top) contains the standard deviations of the five-year annual mean surface air temperature and Fig. 1.1 (bottom) shows the one-period lagged correlations for the same variable. As shown in Fig 1.1 (top), the standard deviation of the surface air temperature is larger in high latitudes than low latitudes. Also, the standard deviations are larger over land and sea-ice-covered areas than over open ocean. The persistence of the annual mean surface air temperature (Fig. 1.1, bottom) indicates that over ocean areas the surface air

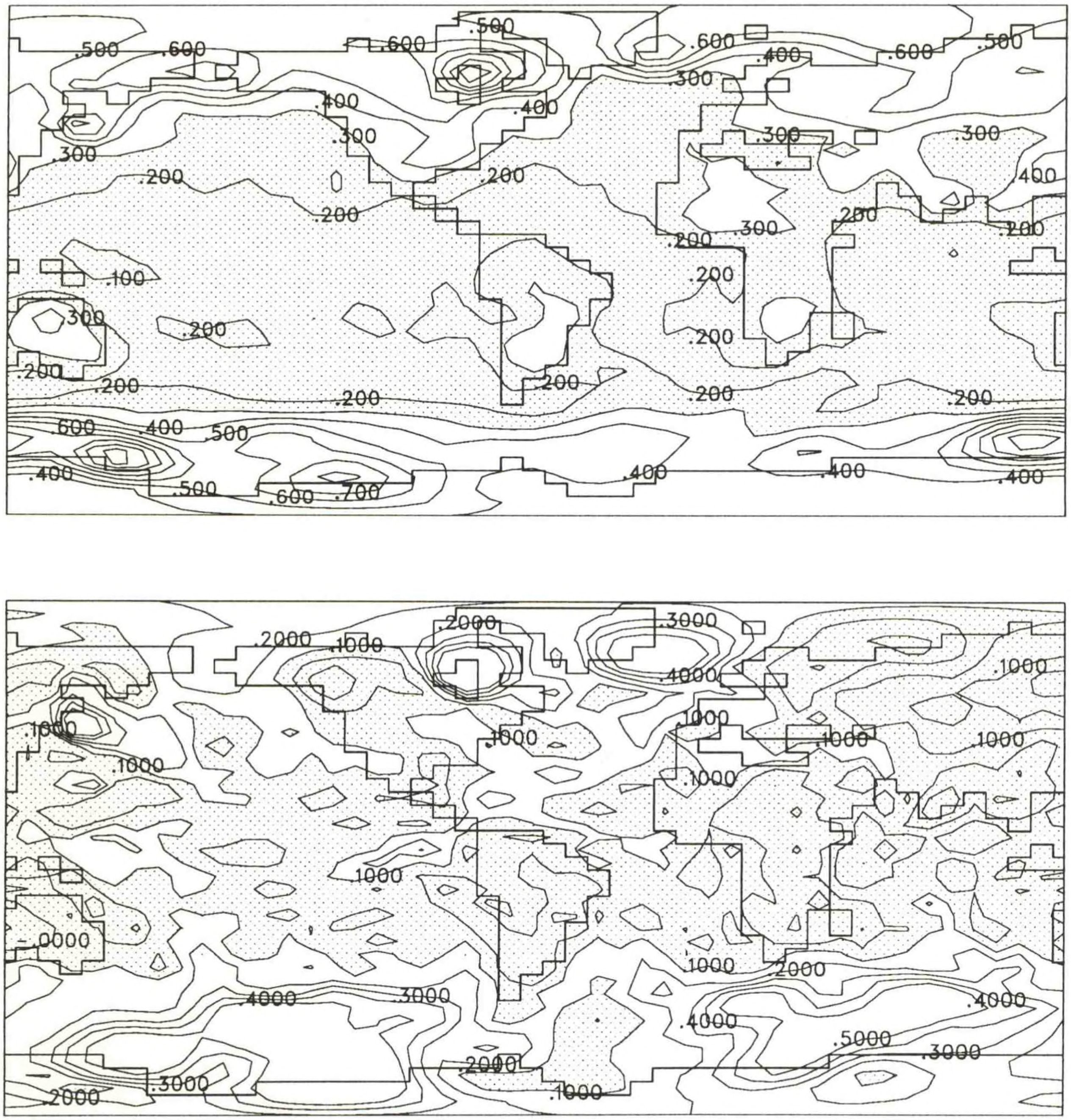

Fig. 1.1 *Top*: Standard deviations of 5-year mean surface temperature computed from a 1000-year integration of the coupled model. The units are °C. The shading indicates areas where the standard deviation is less than 0.3°C. *Bottom*: Lag-one-time-period correlation of the 5-year surface temperature time series. The shading indicates areas where the correlation is less than 0.1. The contour interval is 0.1.

temperature is more persistent than over land areas. Also, the maximum persistence tends to be in the neighborhood of intermediate or deep-water formation in the ocean, such as the northern North Atlantic Ocean, the northwestern end of the Pacific Ocean, and extensive areas in the Circumpolar Ocean of the Southern Hemisphere.

PLANS FY93

To elucidate the role of oceanic circulations in natural variability of climate, the 1000-year integration of the coupled model mentioned above will be compared with an integration of the atmospheric-mixed layer ocean model which does not include the effects of oceanic circulation.

1.1.2 Atlantic Variability

K. Bryan | *S. Manabe*
T. Delworth | *R. Stouffer*
K. Dixon

ACTIVITIES FY92

The principal objectives of the project are to characterize and study interdecadal variations in the intensity of the thermohaline circulation (THC) of the model North Atlantic Ocean, 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 atmosphere-ocean model used in this study has a global computational domain, realistic geography, seasonally varying insolation, and predicted cloudiness.

Analyses of a 1000-year integration have demonstrated that the THC in the model has considerable variability on interdecadal time scales. The characteristic pattern of sea surface temperature anomalies associated with variations in the intensity of the THC is shown in Fig. 1.2a. This can be contrasted to a pattern of observed interdecadal SST variations (Kushnir,1992)[1] shown in Fig. 1.2b. The observed pattern represents the differences in SST between the period 1950-1964 and 1970-1984, computed using the Comprehensive Ocean-Atmosphere Data Set (COADS). The similarity between the model and observed results is encouraging, suggesting that the model may be capable of simulating some aspects of interdecadal climate variability. There are also substantial anomalies of surface air temperature associated with the variations in the THC, particularly over the Arctic, northern North Atlantic, and northern Eurasia.

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1. Kushnir, Y., 1992: Interdecadal variations in North Atlantic sea surface temperature and associated conditions. Submitted to J. Climate.

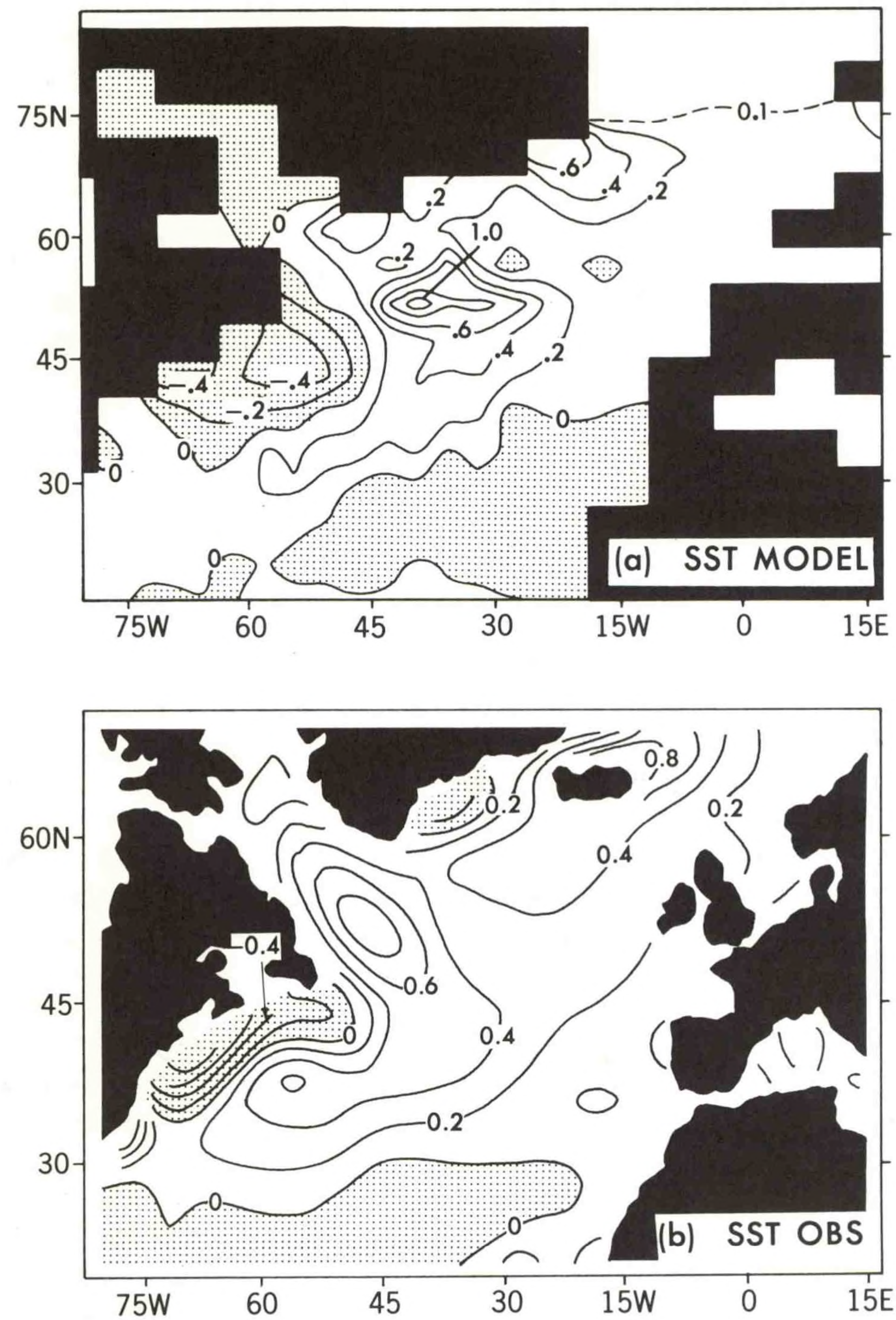

Fig. 1.2 (a) Differences in model sea surface temperature between four separate decades with a strong thermohaline circulation and four separate decades with a weak thermohaline circulation. Units are °C. (b) Pattern of observed interdecadal variation in sea surface temperature (Kushnir,1992) using the COADS data set. This field represents the difference in sea surface temperature between the "warm" period 1950-1964 and the "cold" period 1970-1984. Units are °C.

The variations in the intensity of the model THC are largely attributable to changes in the large-scale density structure in the model North Atlantic. The density anomaly of water between approximately 50°N and 75°N in the North Atlantic, combined with negative density anomalies at lower latitudes, is associated with an above normal intensity THC. The salt and heat anomalies, which determine the density anomaly, result largely from the anomalies in horizontal transports of heat and fresh water. Anomalies in surface fluxes of heat and fresh water are also associated with these variations in the THC.

PLANS FY93

The analysis of low-frequency variability in the coupled model of the atmosphere-ocean system will be continued. Particular emphasis will be placed on the variability of the thermohaline circulation of the North Atlantic on decadal and longer time scales and its impact on the variability of the atmosphere.

1.1.3 Two Stable Equilibria

K. Bryan *S. Manabe*
K. Dixon *R. Stouffer*

ACTIVITIES FY92

Two stable equilibria of the coupled ocean-atmosphere system have been described previously (896). One equilibrium (Exp. I) had a thermohaline circulation similar to the observed circulation in the Atlantic Ocean, and the other equilibrium (Exp. II) has no such circulation. The coupled model used for this study has annually averaged insolation without seasonal variation. It was questioned whether similar equilibria can exist when insolation was seasonally varying. During the last fiscal year, the study was repeated using the latest version of the coupled model which included the seasonal variation of insolation. It was found that this seasonal model also possesses two stable equilibria, similar to those described above.

Figure 1.3 shows the current vector differences between the two equilibria found in the seasonal model. The surface vector differences (Fig. 1.3, top) indicate that in the model the thermohaline circulation is evidenced by a northward flow along the east coasts of South and North America. There are also small vector differences in the surface flow in the Indian and Pacific Oceans. The southward return flow of the thermohaline circulation at depth in the Atlantic Ocean and its extension to the Indian Ocean are easily seen in Fig. 1.3 (bottom). In qualitative agreement with the

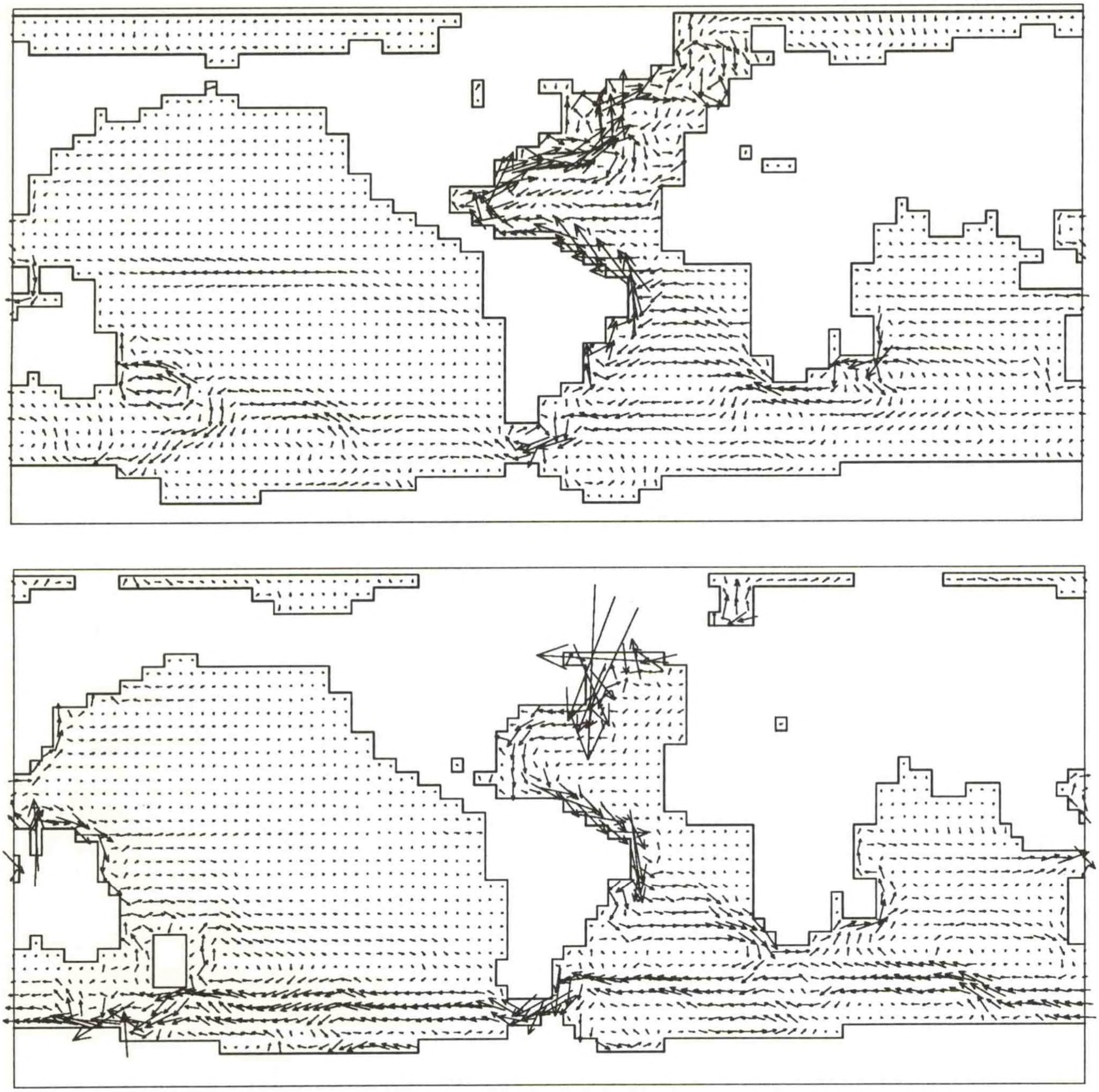

Fig. 1.3 Vectors indicating the difference in ocean currents between Exp. I and II (the experiments with and without the thermohaline circulation in the Atlantic Ocean). *Top*: Surface vector differences. *Bottom*: Vector differences at a depth of 1622 m.

observational study of A. Gordon (1986)[2], the so-called conveyor belt is not confined to the Atlantic Ocean, but extends to the Indian and Pacific Oceans.

1.1.4 Tropical Response to CO_2

T. Knutson *S. Manabe*

ACTIVITIES FY92

The impact of gradual changes in atmospheric CO_2 content on the mean climate and its variability in the tropics is being investigated. Two experiments with the GFDL coupled ocean-atmosphere GCM are being examined: a 180-year simulation with CO_2 increasing at 1%/yr compounded, and a 200-year integration with constant CO_2. The activities in FY92 have expanded on the preliminary results obtained for the tropical Pacific in FY91.

1.1.4.1 Changes in the Mean Climate

As the model climate warms with increased CO_2 at the rate of approximately 3°C per century, precipitation and evaporation both increase in the tropics by about 7% per century on average, as discussed in the FY91 Annual Report (A91/P92). In response to the increase in condensational heating in the troposphere, one might expect a substantial circulation response, such as an increase in the intensity of the Hadley circulation. However, the changes in the model's Hadley circulation and other tropical circulation responses were more modest than expected. In order to help explain this result, an analysis of the heat balance of the tropical troposphere is being conducted. The results to date indicate an important role for increased radiative cooling in the upper troposphere in balancing the increased latent heating occurring there. It is the net diabatic heating or cooling from the partially offsetting changes in radiative cooling and condensational heating that is balanced by dynamical terms in the temperature tendency equation (for example, changes in adiabatic cooling, subsidence warming, or advection). Investigation of these phenomena is continuing.

1.1.4.2 Changes in the Variability of Monthly Mean Fields

The impact of gradual changes in CO_2 on the variability of monthly mean fields in the tropics is also being analyzed. The model's response depends on the variable studied. Pronounced variability changes occur over both land and ocean for precipitation, evaporation, and total atmospheric water content. The area-averaged standard deviation of these variables over the tropics increases by about 10%, 8%,

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2. Gordon, A.L., 1986: Interocean exchange of thermohaline water. J. Geophys. Res., 91(C4), 5037-5046.

and 23% per century, respectively, for the CO_2 increase experiment. As a first approximation for these fields, the standard deviation changes by about the same fraction as the mean. Over tropical land, the variability of surface temperature and surface runoff also increases, by about 9% and 10% per century, respectively, while soil moisture and surface wind variability remain relatively constant. For moisture-related variables, the seasonal cycle variability changes by about the same fraction as the non-seasonal variability. ENSO-like fluctuations in the model's tropical Pacific are apparent throughout all the integrations, with the amplitude of model SST fluctuations being relatively insensitive to the CO_2-induced climate changes. In fact, there is little systematic trend in the area-averaged variability of monthly mean SST and surface winds over the entire tropical domain as CO_2 content changes. The statistical significance of variance changes has been assessed using a pooled permutation testing procedure.

PLANS FY93

The studies outlined above will continue in FY93. Remaining work includes completion of the heat-balance analysis and an analysis of the model's mean fields for statistically significant trends using a new, robust statistical technique developed by Craig Lindberg. Also planned for FY93 is the initiation of a new project with the general goal of providing better impacts-related climate-change information to scientists and/or policy makers working on the CO_2-climate problem. This new project may not be limited to the tropical domain.

1.1.5 Observed and Predicted Temperature Change

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

ACTIVITIES FY92

1.1.5.1 Geographic Distribution

The response of a coupled ocean-atmosphere model to a gradual increase of atmospheric CO_2 has been evaluated in comparison with the actual change of climate. Fig. 1.4 (top) illustrates the change of surface air temperature over the 60th to 80th year period, when the atmospheric concentration of carbon dioxide is doubled. It is compared with the recent change of observed surface air temperature shown in Fig. 1.4 (bottom). Since the observed distribution represents change over a relatively short time, *i.e.,* 20 years, and is likely to be overshadowed by the natural variability of the climate, one should not take this comparison too literally. Nevertheless, there is some qualitative similarity between the two distributions. For example, relatively large warming over the northern portions of North America and Eurasia is evident in both

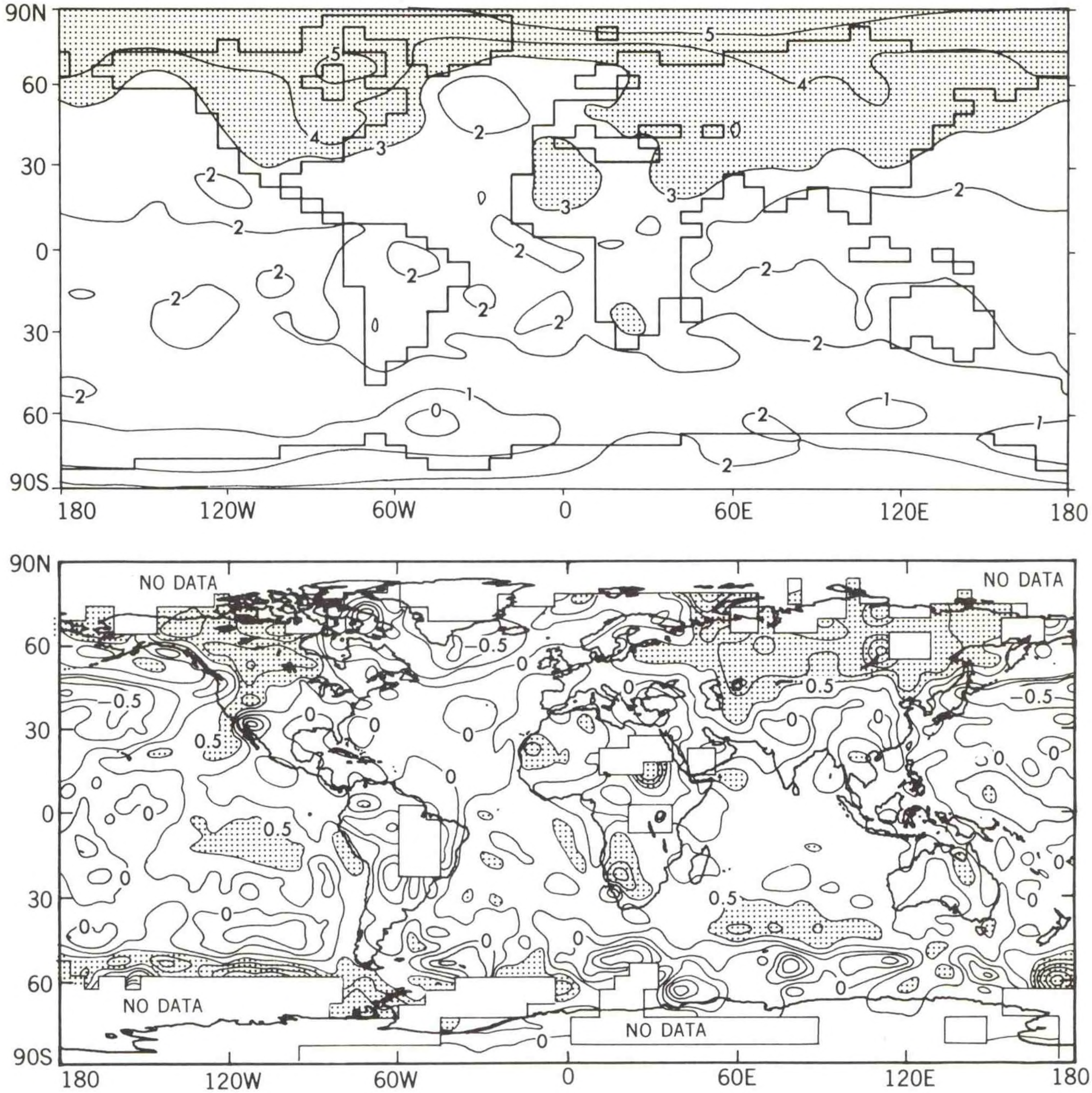

Fig. 1.4 *Top*: The transient response of surface air temperature of the ocean-atmosphere model to a 1%/year increase of atmospheric carbon dioxide. The response (°C) represents the average over the 60th to 80th years of the experiment when the atmospheric CO_2 is doubled. *Bottom*: Observed annual mean surface temperature anomaly averaged over 1981 to 1990, relative to the average over 1951 to 1980. Adapted from Figure C5(a) in *Climate Change* 1992, The Supplementary Report to the IPCC Scientific Assessment, J.T. Houghton et al., Ed., Cambridge University Press.

distributions. The region of slower warming over the North Atlantic of the model has the counterpart of a cooling in the observed anomalies.

1.1.5.2 Zonal-Mean Distribution

Polar and winter amplification of surface air temperature changes was first described in empirical studies (*e.g.*, Willett, 1950; Vinnikov and Groisman, 1979)[3,4]. Later it was found in the equilibrium response of a climate model to an external forcing. The aim of the current project is to determine whether such an amplification occurs in the time integration of a coupled ocean-atmosphere model without a greenhouse forcing.

A linear regression method was used to estimate the correspondence between the temporal variations of globally and zonally averaged surface air temperature. This method was applied to the long-term runs of a coupled ocean-atmosphere model and to the temporal variations of the actual climate system that were recorded during the period of instrumental meteorological measurements. The results were compared with the equilibrium response of an atmosphere-mixed layer ocean model to CO_2 doubling.

It was shown that polar amplification and other features of tropospheric temperature change appear both for global climate changes induced by greenhouse forcing and for natural global climate fluctuation in the coupled model without such a forcing. But in the middle stratosphere, the signs of mean annual temperature changes differ between the two cases (compare Fig. 1.5a and 1.5b).

Empirical estimates based on the GFDL free-atmosphere temperature data set show that during 1958-1989, changes in mean global annual surface air temperature were accompanied by changes of the same order and sign in the air temperature in the troposphere and of the opposite sign in the lower and middle stratosphere (see Fig. 1.5c). This suggests that the modern variations of the mean global temperature may be attributable to "greenhouse type" radiative forcing.

PLANS FY93

The analysis of both simulated and observed climate changes will continue.

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3. Willett, H.C., 1950: Temperature trends of the past century. Centenary Proc. Roy. Meteor. Soc., 195-206.
4. Vinnikov, K.Ya. and P.Ya. Groisman, 1979: Empirical model of modern climatic changes. Soviet Meteor. and Hydrol., 3, 18-27.

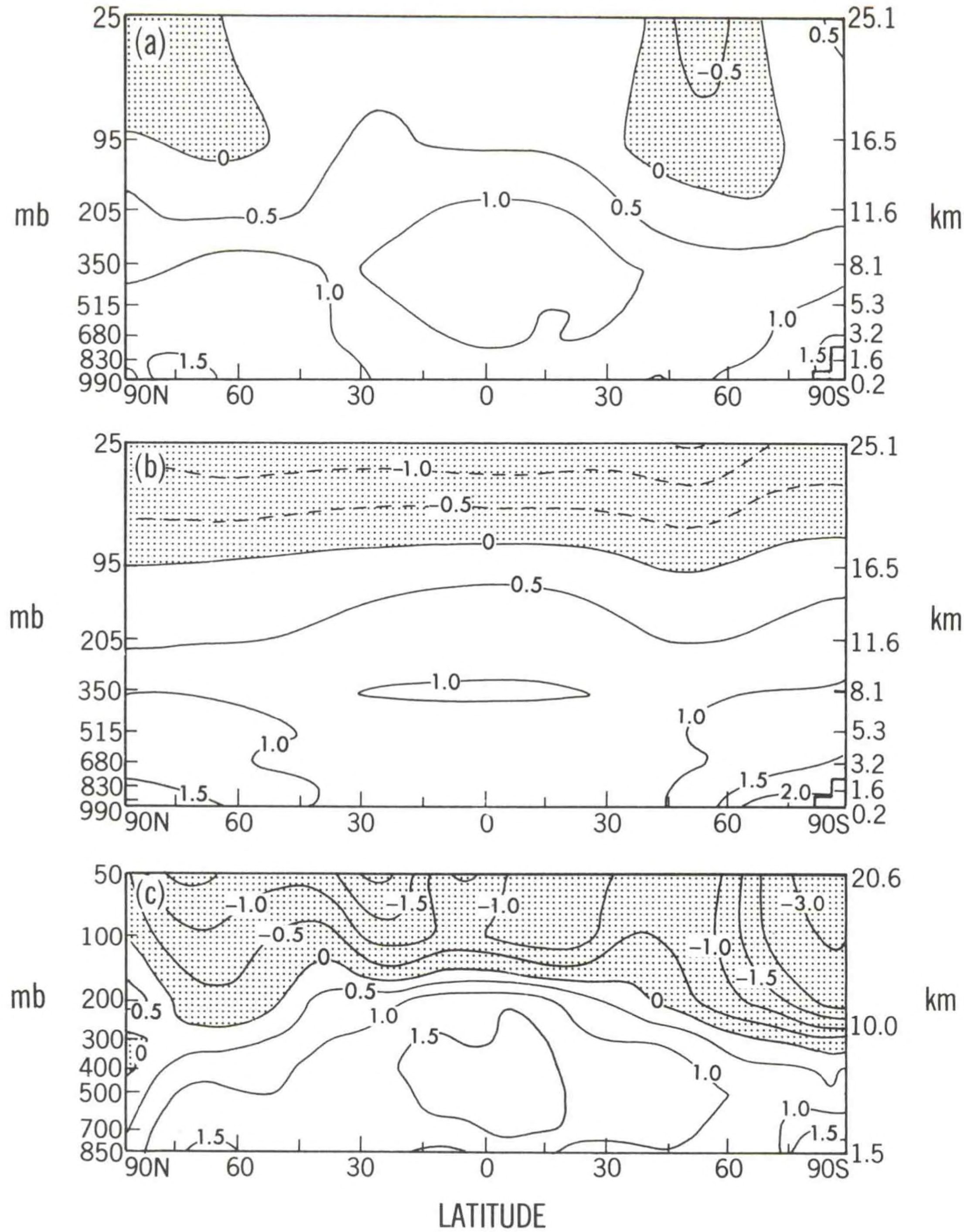

Fig. 1.5 (a) The linear regression between the globally averaged, annual mean surface air temperature and zonally averaged, annual mean surface air temperature obtained from the 200-year integration of the coupled ocean-atmosphere model. (b) Equilibrium response of the atmosphere-mixed layer ocean model to CO_2 doubling. Changes in zonally averaged annual mean temperature are normalized by changes of the globally averaged, annual mean surface air temperature. (c) Linear regression coefficient between observed global mean surface air temperature (Russian data) and zonal mean air temperature (GFDL free-atmosphere data).

1.2 LAND-SURFACE ATMOSPHERIC INTERACTION

1.2.1 Continental Hydrology and Climate

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

** U.S. Geological Survey*

ACTIVITIES FY92

The study of the sensitivity of climate to the hydrologic behavior of continental land surfaces was continued in FY92. The objectives of this work are to analyze and to improve the parameterization of land hydrology used in atmospheric GCMs and to study the role of continental hydrology in climate dynamics. This research is a cooperative effort between GFDL and the U. S. Geological Survey.

The sensitivity of climate to the magnitude of a globally constant soil water-holding capacity was investigated. Simulations were conducted using values of 4 cm and 60 cm, in conjunction with a GCM having prescribed ocean surface temperatures and clouds. The focus of the analysis was on the effects of this change on surface water and energy balances, atmospheric heating and circulation, and atmospheric transport of water vapor.

The direct result of an increase in soil water-holding capacity was to increase the role of soil-water storage in the surface water balance. Due to the increased magnitudes of the storage term, runoff was inhibited during periods of water excess, and evaporation was enhanced during periods of shortage. The direct effect on the surface energy balance was to cool the surface evaporatively, allowing reductions in sensible heat flux and radiative cooling, and lowering the surface temperature and the near-surface air temperature.

One fundamental problem studied was the question of where the water vapor from the additional evaporation returns to earth as precipitation. In the tropics, this redistribution of water vapor was driven mainly by the prevailing circulation and its induced changes. With more water cycling through the atmosphere, the Hadley circulation intensified and the monsoonal circulations were weakened. In the middle latitudes, the changes in water-vapor transport were associated instead with changes in the transient eddy fluxes of water, with a reduced onshore humidity gradient. At all latitudes, the effect of changes in transport was to export about half of the additional water vapor from the continents to the oceans.

The increase in evaporation due to an increase in soil-water-holding capacity provides an analog for the increase in evaporation that occurs due to large-scale irrigation of agricultural lands. Available estimates of the latter quantity can be used to scale the simulation results so as to obtain crude estimates of the equilibrium climatic effects of irrigation. Such an analysis suggests that current levels of irrigation may increase annual precipitation on the order of 1 cm and reduce temperature on the order of 0.1 K, both averaged over the continents of the globe. Due to the uneven distribution of global irrigation, regional effects are potentially larger. Consideration of cloud feedbacks could also modify these sensitivities significantly.

PLANS FY93

A more detailed analysis of the direct sensitivity of surface-water balance to soil water-holding capacity will be conducted. The study will be extended to include cloud feedbacks and a mixed-layer ocean.

1.2.2 Feedback Between Land Surface and Climate

B.M. Lofgren *S. Manabe*

ACTIVITIES FY92

A project was continued to assess the sensitivity of climate and soil moisture to changes in land-surface albedo. The heating of the overlying atmosphere is strongly influenced by the absorption of solar energy at the surface, and this can cause changes in the circulation and precipitation patterns. Also, the soil moisture can be directly influenced by the change in potential evaporation caused by a change in solar radiative energy absorbed. The net impact on soil moisture is thus due to a combination of the effects of altered potential evaporation and precipitation.

GCM results have shown that in the extratropics (latitudes higher than about 30°), precipitation is not very sensitive to land surface albedo, and the soil moisture change is primarily due to changes in potential evaporation. On the other hand, changes in albedo can cause significant changes in precipitation in tropical and subtropical areas, particularly areas of monsoonal rainfall. Increased albedo causes decreased precipitation and decreased soil moisture in these low-latitude areas. In general, the climate and soil moisture changes due to decreased land-surface albedo are of opposite sign and nearly equal amplitude to the changes due to increased land-surface albedo.

To represent explicitly a feedback among climate, vegetation cover, and land surface albedo, a simple parameterization has been developed to represent vegetation and land surface albedo as a function of annual mean precipitation and surface temperature, and model experiments have been run using this. In addition, soil-moisture field capacity and surface roughness are parameters which are linked to the vegetational cover and have the potential to influence the climate in ways which may enhance or diminish the effects of land-surface albedo. Therefore, similar parameterizations have been developed for these, and model experiments have been run using them.

The precipitation effects in the experiment with interactive surface albedo were found to be consistent with those in experiments in which surface albedo had prescribed perturbations; low albedo regions at low latitudes had greater precipitation, while high albedo regions had less, with little change in the extratropics. This constitutes a positive feedback; it tends to enhance the existing extremes of moisture and aridity at low latitudes through the vegetation and surface albedo. In the interactive surface-roughness experiment, there also appears to be a positive feedback in which the roughness of moist regions tends to enhance their precipitation, especially in coastal regions at low latitudes where there are low-level winds impinging on the coast. The effects of interactive field capacity appear to be smaller than those of interactive surface albedo or surface roughness.

PLANS FY93

Analysis will be completed on the experiments described above.

1.2.3 Mid-Continental Summer Dryness

S. Manabe *R.T. Wetherald*

ACTIVITIES FY92

Changes of surface hydrology induced by greenhouse warming have been the subject of extensive research both at GFDL and elsewhere. In particular, these studies have revealed, among other features, a tendency to produce drier summers in mid-latitude continental regions in response to an increase of atmospheric CO_2. One of the features responsible for this summer dryness is a systematic poleward shift of the middle-latitude rainbelt, or the region of maximum precipitation in middle latitudes. However, this poleward shift is difficult to determine and evaluate in models with realistic geography, due to the asymmetric distribution of continents and mountains. In order to identify more easily the mechanisms responsible for this poleward shift of the middle-latitude rainbelt, it was decided to conduct an R30 sensitivity experiment with flat topography and an idealized sector geography, in which both land and sea are bounded by meridians 120 degrees longitude apart. For this sensitivity study, the atmospheric CO_2 concentration was quadrupled in order to

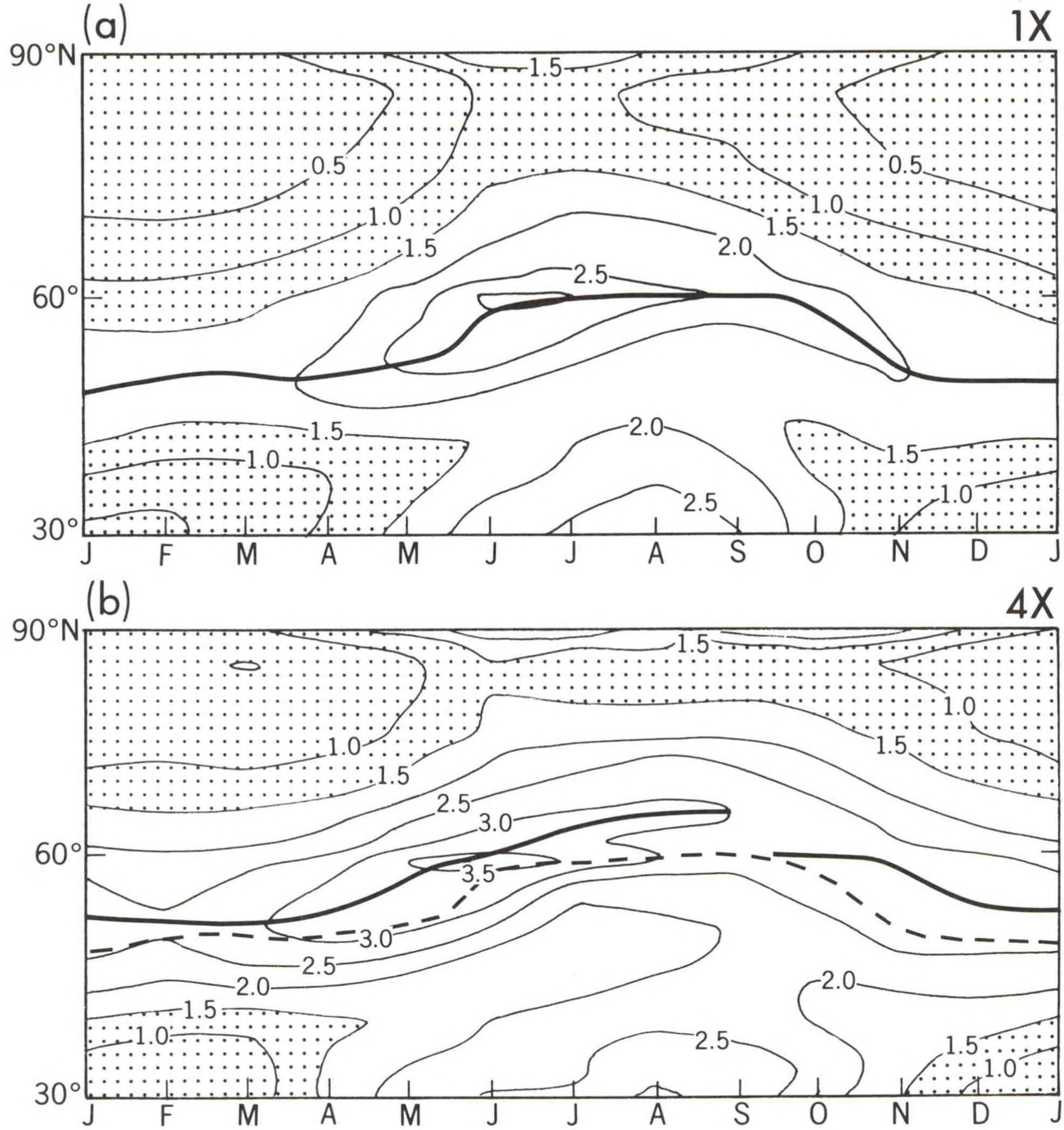

Fig. 1.6 Latitude-time distribution of zonal mean precipitation for: (a) the standard integration; and (b) the integration with quadrupled CO_2 concentration. Heavy solid lines denote the axis of the middle latitude rainbelt for each integration. For the sake of comparison, the axis of the rainbelt for the standard integration is added to (b) as a heavy dashed line. The two hemispheres have been averaged after shifting the phase by six months. Units are mm day^{-1}.

obtain a climate change large enough for easy identification. The poleward shift of the middle-latitude rainbelt obtained from this experiment is illustrated by Fig. 1.6.

PLANS FY93

To elucidate the mechanisms responsible for the poleward shift of the middle-latitude rainbelt, it is planned to analyze the change in zonal wind, storm tracks, and baroclinicity in the model atmosphere.

1.3 CONVECTION-RADIATION CLIMATE INTERACTIONS

1.3.1 Radiative-Convective Equilibria with Explicit Moist Convection

P. Baker *R. Hemler*
L. Donner *R. Martino*
I. Held *V. Ramaswamy*

ACTIVITIES FY92

A series of preliminary studies have been performed of the radiative-convective equilibrium obtained when a non-hydrostatic model of moist convection is coupled to a multiple-scattering radiative-transfer algorithm that is fully interactive with the predicted cloud and moisture fields. The convection model is two-dimensional. The domain is periodic in the horizontal coordinate and extends from the ground to 26 km. The lower boundary is a fixed-temperature water-saturated surface. The initial calculations were performed in a domain 600 km wide, with 5 km horizontal and 200 m vertical resolution. A number of integrations of several months duration have been completed. The temperature profiles obtained closely resemble those observed in the tropics, but the humidity profiles differ in having a maximum in relative humidity in the upper troposphere.

The model generates a QBO-like oscillation in the horizontally averaged winds, with an apparent period of approximately 60 days. This oscillation extends into the troposphere and influences the convective organization (see Fig. 1.7). In order to avoid the associated large vertical wind shears, calculations have also been performed in which the horizontally averaged winds are constrained to vanish. Surprisingly, the convection then evolves into a pattern in which the rain falls only within a small part of the domain. The moisture field appears to provide the memory that localizes the convection.

If the vertical shears are fixed at a modest non-zero value, this localization is avoided. This version of the model has been chosen for initial sensitivity studies. Comparing calculations with surface temperatures of 25° and 30°C, the planetary

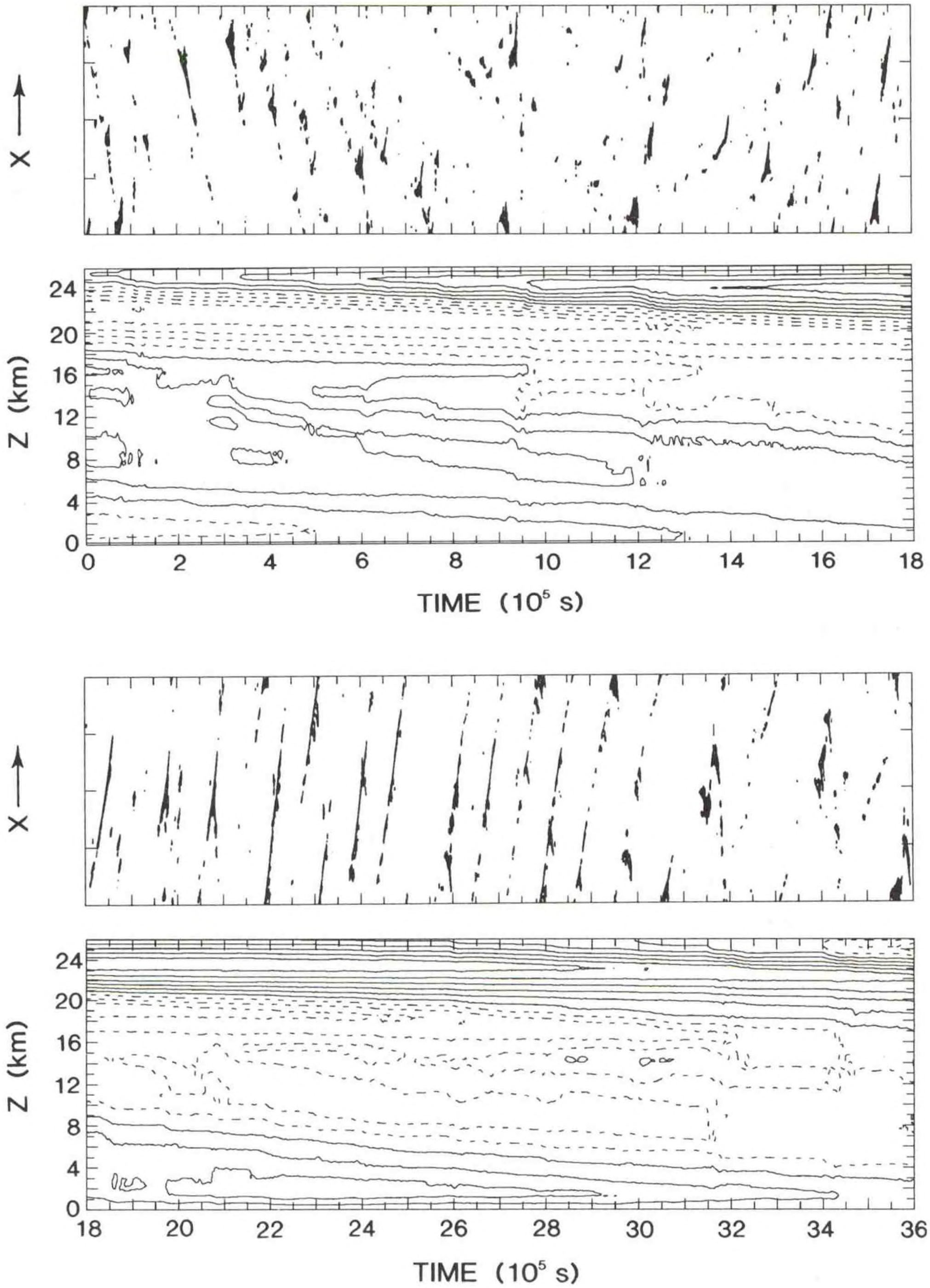

Fig. 1.7 Time evolution of precipitation at ground (as function of x) and domain-averaged zonal wind (as function of height). The contour interval for the wind is 5 ms^{-1}, with negative values stippled. A period of length 1.8×10^6s is shown in the upper two panels, and the following period of the same length in the lower two panels.

albedo is found to decrease with increasing temperature, primarily due to a reduction in low-level cloudiness. The changes in relative humidity are small and have a relatively minor effect on the model's sensitivity.

A new, more efficient radiative-transfer package has been prepared for this model, and the dynamical code is undergoing revision to improve its modularity and in preparation for 3-D calculations on parallel machines.

PLANS FY93

Code development will continue throughout the year, to provide a clean flexible tool for extensive studies with the 2-D model and exploratory calculations in 3-D. Sensitivity studies will be conducted with the 2-D model to explore the importance of the microphysical assumptions, horizontal and vertical resolution, domain size, and sub-grid scale diffusion. The model's "QBO" will be analyzed, with a particular focus on the mechanism for the descent through the troposphere.

1.3.2 Cumulus Parameterization

L. Donner

ACTIVITIES FY92

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 shortwave and longwave radiation. To address these problems in the context of GCMs, a parameterization for cumulus convection, which provides a physical basis for treating radiative interactions, has been developed (rr). 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 against forcing diagnosed in field programs and (2) the basic predicted against 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.

PLANS FY93

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

1.3.3 Cumulus Ensemble Models

L. Donner *R. Hemler*

ACTIVITIES FY92

The processes treated by the cumulus parameterization described in 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 GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment (GATE) and are examining the agreement between CEM integrations and field observations.

PLANS FY93

The emphasis of the CEM studies will shift to focus on testing the cumulus parameterization described in 1.3.2 in various synoptic contexts. Particular attention will be directed toward interactions involving radiative transfer.

1.3.4 Atmospheric Ice Clouds

L. Donner

ACTIVITIES FY92

To develop further understanding of the role in climate of atmospheric ice clouds, a parameterization for their ice content (Heymsfield and Donner, 1990)[5] has been incorporated in a GCM. This project represents an ongoing collaboration with the National Center for Atmospheric Research (NCAR), and the parameterization has

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5. 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.

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.

PLANS FY93

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.

1.3.5 Cloud Forcing

S. Manabe *R. Wetherald*

ACTIVITIES FY92

During FY91, extensive analyses were performed on the simulation of cloud forcing, as obtained from both an R15 and R30 GCM, and compared with Earth Radiation Budget Experiment (ERBE) observations. In FY92, this analysis was extended to re-evaluate this cloud forcing using a perturbation method developed by R. Cess. This method consists of computing the seasonal cloud forcing as a deviation from the annual mean cloud forcing and removing the effects of seasonal variation of solar radiation from the shortwave component. After this technique was applied to the GCM cloud forcings found previously, it was found that the deviation from the annual mean net cloud forcing in middle latitudes was approximately one and one-half to two times that derived from the ERBE data during July and January for both the R15 and R30 models. It was further determined that this difference occurred mainly in the shortwave component and was caused by the model's tendency to produce too much low cloud cover in the sub-tropics and middle latitudes in the winter hemisphere. Fig. 1.8 shows the results of this analysis for the month of July for the R15 model. This figure shows that while the annual mean net radiative flux at the top of the model atmosphere agrees reasonably well with that derived from the ERBE observations, the model tends to exaggerate the seasonal amplitude of the net cloud forcing as derived from this method.

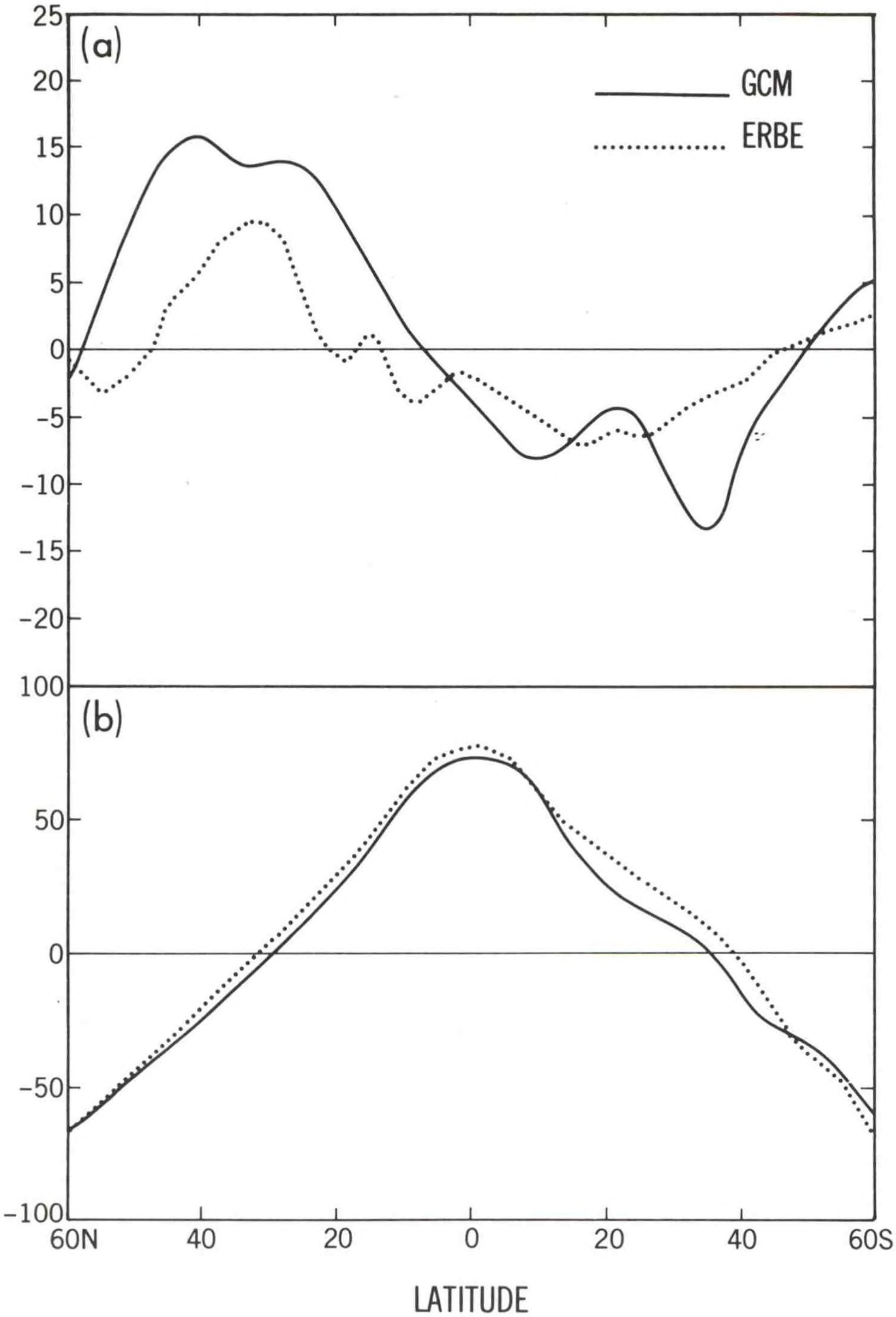

Fig. 1.8 (a) Net cloud forcing for the month of July defined as the deviation of the seasonal from the annual mean cloud forcing for the R15 model. The effects of seasonal variation of solar radiation have been removed from the solar component. (b) Annual mean net radiative flux at the top of the model atmosphere for the R15 model. Solid lines denote the GCM values whereas dotted lines denote the corresponding ERBE data. Units are Wm^{-2}.

PLANS FY93

Plans are for a more detailed analysis of seasonal cloud forcing, as computed from this perturbation method for both the R15 and R30 versions of the model, as part of an ongoing model intercomparison project sponsored by the Department of Energy.

1.4 PLANETARY WAVE DYNAMICS

1.4.1 Idealized Models of Storm-Track Dynamics, Rossby-Wave Propagation, and Wave-Mean Flow Interaction

F. Hansen *V. Pavan*
I. Held *J. Zhang*

ACTIVITIES FY92

1.4.1.1 Moist Baroclinic Instability in a Two Layer Model

Moisture transport and latent heating have been incorporated into a two-layer model of a baroclinically unstable jet, in order to isolate some of the effects of latent heat release on baroclinic eddies in the simplest possible dynamical context. The dependence of eddy kinetic energies, heat fluxes, and momentum fluxes on the strength of the latent heating and the evaporation are being analyzed. The model consistently predicts a reduction in the amplitudes of the horizontal flow as the latent heating in the atmosphere increases; however, the strength of the ageostrophic flow and vertical velocities typically increases. The eddy heat fluxes also decrease in amplitude as the latent heating increases, but surprisingly, the momentum fluxes increase in some cases. The model also produces a poleward shift of the storm track with increased latent heating. An understanding of this model should be of value in interpreting similar behavior seen in GCM responses to increasing greenhouse gases.

1.4.1.2 Two-Layer Model

Work is continuing on a systematic survey of the statistically steady states of an unstable baroclinic jet in the two-layer model. Phenomena of interest are subcritical instability and hysteresis (1029), baroclinic wave-packets (rk), and the formation of structures resembling vortex streets. Interest has also focused on the distinction between instabilities that mix upper-layer potential vorticity on both sides of the jet, while material contours at the center of the jet retain their integrity, and instabilities that mix fluid efficiently across all of the dynamically active potential-vorticity contours. The impression is that Southern Hemisphere storm tracks, particularly in summer, resemble the former, whereas the Northern Hemisphere storm tracks are in the latter camp.

1.4.1.3 A Multi-Layer Quasi-Geostrophic Model

A new multi-layer version of the quasi-geostrophic channel model has been constructed and is being used to study the dependence of the eddy fluxes on the strength of the meridional temperature gradient, contrasting these results with those obtained in a two-layer model. This model is also being used to study the relative importance of upper and lower tropospheric temperature gradients for the eddy amplitudes and fluxes, a problem that has some relevance to the greenhouse warming problem, as discussed in (pe).

1.4.1.4 Surface Quasi-Geostrophic Turbulence

Quasi-geostrophic flows with uniform potential vorticity, driven completely by surface-temperature dynamics, have many intriguing features. The resulting model is two-dimensional, but its dynamics differs considerably from standard 2-D turbulence. In fact, dimensional arguments suggest that the energy spectrum in the high wave number inertial range is proportional to $k^{-5/3}$, rather than k^{-3} as in 2-D turbulence. Numerical calculations have confirmed this distinction. Work is ongoing in collaboration with R. Pierrehumbert (U. of Chicago) to study various properties of this new kind of turbulence. The results may also be relevant to the observed differences in spectral shape near the surface and in the interior of the atmosphere.

1.4.1.5 Review Paper on Large-Scale Dynamics and Global Warming

A review of problems in large-scale dynamics, both in the atmosphere and in the oceans, that are of particular relevance to research on global warming, has been completed (rf).

PLANS FY93

Work will continue on problems related to baroclinic equilibration, storm-track dynamics, and geostrophic turbulence, using a variety of idealized models.

1.4.2 NOAA/University Collaboration on GCM Studies of the Maintenance of Regional Climates

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

ACTIVITIES FY92

A collaboration between GFDL, the Climate Monitoring and Diagnostics Laboratory (CMDL/NOAA), the Massachusetts Institute of Technology, the University of Washington, and the University of Chicago has been organized to create a critical mass of scientists using GCMs and other tools to study the interrelated problems of stationary waves, storm tracks, low-frequency variability, and the response of the atmosphere to perturbations in boundary forcing. The group has collaborated in designing experiments to be performed at GFDL. Large data sets are being passed on Exabyte cartridges to the various participants who, along with personnel at GFDL, analyze the results. Data sets generated within the past two years include 100 years of an R15 seasonal integration with observed SSTs, 40 years of a similar calculation with R30, two 40 year R15 integrations with observed COADS SSTs, 10,000-day perpetual January and July R15 controls for SST anomaly experiments, 2,000-day perpetual January and July R30 runs, several SST anomaly experiments with R15, and several R30 integrations with idealized boundary conditions. A special data set has been prepared using 30 days of the R30 seasonal model, in which the values of every variable at every time step have been stored. A variety of studies of the low-frequency variability, Lagrangian transport properties, and regional climates in these models are underway.

The results from GCM experiments with extratropical SST anomalies continue to be puzzling.The perpetual January R15 model has been perturbed with a simple monopolar SST anomaly in the North Atlantic. Four 6,000 day experiments have been conducted, with the strength of the anomaly equal to +1 K, -1 K, +4 K, and -4 K. The response for the 1 K experiments bears a qualitative resemblance to that expected, based on the observed structure in the decadal variability of surface pressure. But the 4 K experiments do not show the much larger responses anticipated. If anything, they are less well organized than the 1 K cases. Analysis of these perplexing results is in progress, in collaboration with Yochanan Kushnir (Columbia University).

Further discussion of results of this collaboration can be found in Section 5.4.

PLANS FY93

In light of the perplexing results obtained to date with extratropical SST anomalies in GCMs with realistic boundary conditions, a series of at least 20 calculations are planned with the low resolution R15 model using idealized boundary conditions and perpetual January insolation. The model will have a flat surface to simplify the analysis. A variety of zonally asymmetric control climates will be generated using different patterns in the prescribed lower-boundary temperature. These climates will then be perturbed by modifying this surface temperature distribution. The climatic responses will be analyzed with linear and nonlinear stationary wave models. The objective will be to understand more fully the role of transient eddies in determining the time-mean response and to determine whether or not equivalent barotropic resonances are relevant.

Perpetual integrations with the R30 model will be performed with insolation and SSTs set for several times between January and July to study the springtime transition of the stationary wave field and monsoon dynamics. One objective is to determine whether the system undergoes an abrupt transition given sufficient time to adjust to boundary conditions, or if the seasonal march is a stable continuous process.

1.4.3 Linear Stationary Wave Modeling of the Wintertime Response to Greenhouse Warming

I. Held *D. Stephenson*

ACTIVITIES FY92

The work on the changes in Northern winter stationary waves simulated in a GCM (1042,1067) as the climate warms is nearing completion. The change in stationary waves is marked by an equivalent barotropic low over western Canada and the U.S. and a high over eastern North America, resulting in southerly wind anomalies over the central continent that appear to play a significant role in enhancing the warming in this region. The decomposition of the stationary eddy field with a linear model suggests that a significant part of the response is forced from the tropics, due to a relatively small eastward displacement of the Indonesian heating. Changes in transient eddy fluxes play an important role as well, but no simple picture emerges that explains the total pattern.

PLANS FY93

The study of the changes in the stationary-wave field in the greenhouse warming model calculations will be extended to the summer season.

1.4.4 Intercomparison of GCM Dynamical Cores

I. Held *B. Wyman*
R. Hemler

ACTIVITIES FY92

GCM model intercomparisons performed to date suffer from the fact that the effects of different numerical schemes are mixed together in complex ways with the effects of different treatments of convection, boundary-layer fluxes, and radiation. In order to help in the careful evaluation of numerical schemes, work has started on the design of a set of standard experiments that can be performed with the dry dynamical core of any atmospheric GCM, in which convection, boundary-layer parameterizations, and radiation are replaced by very simple expressions for Newtonian cooling and Rayleigh friction. The focus will be on properties of the statistically steady states: the mean flow, transient energies and fluxes, spectra, etc. Preliminary calculations are being performed with an R30 model, with 20 and with 40 levels, to determine appropriate expressions for the forcing and dissipation.

PLANS FY93

Identical calculations with the dry dynamical cores of the spectral model and several grid-point models at GFDL (SKYHI and the E-grid eta-coordinate model) will be performed. Resolution studies will be initiated to determine the rate of convergence of the several models to high resolution solutions. Calculations will be conducted with a flat surface, initially, followed by calculations with isolated orography.

1.4.5 Tropical Intraseasonal Oscillations

D. Golder *Y. Hayashi*

ACTIVITIES FY92

To clarify differences between tropical 40-50 and 25-30 day oscillations and to examine the effects of geography and seasonal variation on these oscillations, space-time spectrum and filter analyses were performed on realistic and idealized R30 climate models (pl). The realistic R30 model results indicate that the 25-30 day oscillations exhibit a greater increase with height of their tropospheric amplitudes than the 40-50 day oscillations, resulting in different relative magnitudes at different levels. The time variances of the two oscillations have similar longitudinal distributions, implying that the two periods are not due to differences in local phase speeds. They appear to grow and decay independently, without any coherent phase relationship, implying that the two periods are not a result of the seasonal modulation of an intrinsic

30-40 day period. The ocean-surface perpetual-January R30 model indicates that not only the 25-30 day mode, but also the 40-50 day mode can be simulated in the absence of geographical and seasonal modulations. A comparison between the two R30 models suggests that sea-surface temperatures geographically modulate the intrinsically eastward-moving wave number one intraseasonal precipitation oscillations, resulting in their major (Pacific) and minor (Atlantic) local amplitudes. This in turn causes planetary-scale eastward-moving zonal-velocity oscillations and standing geopotential oscillations.

PLANS FY93

The study of tropical intraseasonal oscillations with the use of modified GCMs will continue.

1.5 PLANETARY ATMOSPHERES

G.P. Williams

ACTIVITIES FY92

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. This project requires a continuous restructuring of all programs to optimize use of the computer system for interactive prediction and animated graphics.

1.5.1 Coherent Structures

Long-lived vortices occur in Earth's oceans and in Jovian atmospheres. Studies are attempting to solve two problems: 1) to discover what atmospheric environments favor such highly predictable phenomena, and 2) to define what dynamical processes are involved in vortex production and maintenance.

The conditions under which planetary vortices form and persist have been found from solutions generated with a non-dissipative, 3-D primitive equation model. These solutions also suggest what vertical forms are favored by the temperature and wind fields on Jupiter, thereby guiding the development of global circulation models for unbounded atmospheres.

1.5.2 Global Circulations

The global circulations of unbounded atmospheres are being studied using GCMs to see if flows resembling those of the Jovian planets can be simulated. This requires experimenting with the atmospheric vertical structure to isolate the form that allows multiple mid-latitude jets, a super-rotating equatorial jet, and planetary vortices.

The GCM used was set up with a variety of high resolutions (R30-R120) to resolve the small eddies of large rapidly rotating planets and with a variety of heating forms to explore how circulations vary for various vertical structures. A heating and structural form was isolated that leads to multiple mid-latitude jets and an equatorial superrotation resembling Jupiter's at upper-cloud levels. The dynamics of these currents is being investigated further.

PLANS FY93

Further process calculations will be made to examine the influence of environment on the stability and genesis of 3-D planetary vortices. Methods for analyzing the dynamical processes will be developed.

The high resolution GCM will be used to improve the simulations of the Jovian circulation, to examine alternative states and to explore further the dynamics of bounded and unbounded atmospheres.

1.6 MODEL DEVELOPMENT

1.6.1 Computation of Solar Radiative Transfer

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V. Ramaswamy

ACTIVITIES FY92

1.6.1.1 Absorption by CO_2

Line-by-line (LBL) computations of the solar absorption in atmospheres containing carbon dioxide only, and carbon dioxide and water vapor, have been performed (ro). As illustrated by Fig. 1.9, the most significant feature due to CO_2 is the absorption in the stratosphere, particularly in the 1000-2500 cm^{-1} and in the 2500-4400 cm^{-1} spectral intervals. A parameterization (first introduced by Sasamori et al.) which has been employed in the laboratory's GCMs for several years was tested against the LBL computations and found to severely underestimate the heating due to CO_2, both in the stratosphere (errors > 30%) and in the troposphere (error ~20%). This formulation has been modified (termed as "modified Sasamori") such that the resulting atmospheric absorption is simulated more accurately (error < 3% between surface and 1 mb). The use of the new formulation implies an additional heat input in the GCM's stratosphere. The LBL studies also show that the overlap between CO_2

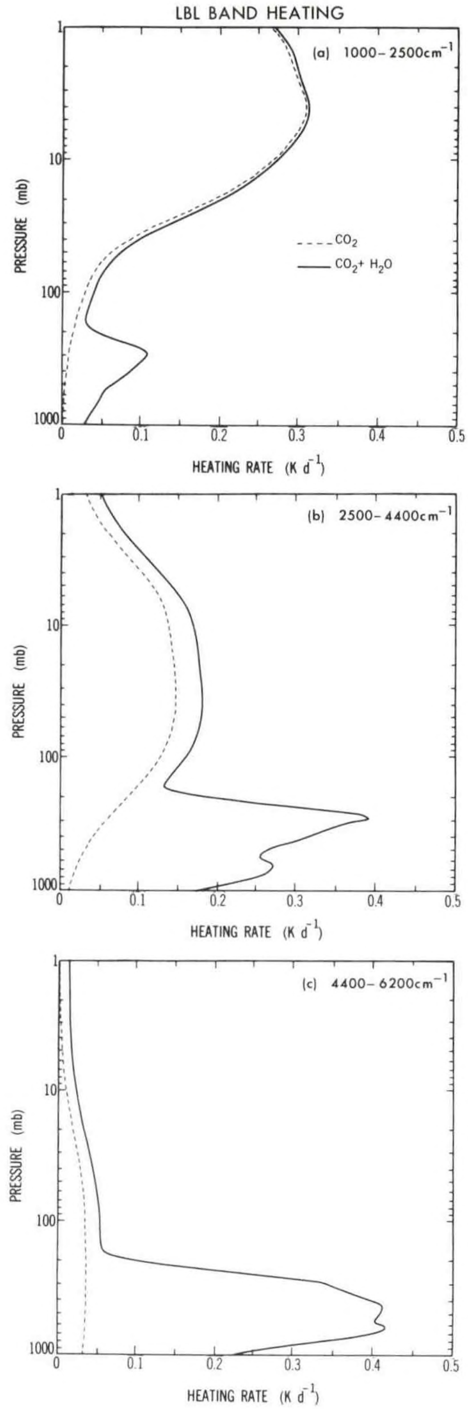

Fig. 1.9 Vertical profile of the atmospheric heating rate for CO_2 only and CO_2+H_2O in three different spectral regions: (a) 1000-2500 cm^{-1}; (b) 2500-4400 cm^{-1}; and (c) 4400-6200 cm^{-1}.

and H_2O acquires considerable significance in the lower stratosphere and the upper troposphere regions. The modified Sasamori has been combined with the modified Lacis-Hansen water-vapor parameterization developed earlier (A89/P90) to yield a combined parametric formulation for the solar absorption by CO_2 and H_2O. The errors in the heating rate due to the combined parameterization are less than 8%. Tests have been carried out for various model atmospheres (including CO_2 amounts up to 1200 ppm) and for various solar zenith angles.

1.6.1.2 Overcast Atmospheres - Benchmark Solutions

"Exact" computations of the near-infrared overcast sky (comprised of water vapor and liquid water) radiative transfer have been performed using a range of values for different parameters, such as drop-size distribution, optical depth, zenith angle, cloud location and thickness. In analyzing the various case studies, attention has been focused on the solar cloud absorption and the role of clouds in governing the surface and the atmosphere fluxes over nonreflecting surfaces. It is found that the solar flux absorbed in overcast atmospheres and the reflected flux at the top of the atmosphere exhibit different sensitivities in various spectral regions. An interesting feature seen in the calculations is that the surface flux is relatively insensitive to the location of the cloud; the same is not true of the absorbed flux in the atmosphere and the reflected flux at the top of the atmosphere.

1.6.1.3 Overcast Atmospheres - Parameterizations

Further work continued on analyzing the factors determining the broadband solar radiative transfer in overcast atmospheres (*e.g.,* drop-size distribution, cloud optical depth, location and thickness), and on parameterizing the effects due to such factors. Instead of single-layer clouds (reported in A91/P92), investigations of the transfer in the case of multiple cloud decks (*e.g.,* high, thin cloud overlying a low, thick cloud) were carried out. This particular situation represents an additional complexity in the development of broadband solar cloud-radiation parameterizations. The investigations concerning the single and multiple cloud decks have been reported (1095). As a general rule, it is found that current broadband parameterizations of cloud radiative effects need to be improved further in order to simulate more accurately the heating rates within clouds. Weather prediction and climate model simulations must recognize the potential error regimes associated with different solar radiation algorithms employed in these models.

A preliminary investigation has been conducted for representing the solar water vapor transmission as a sum of exponentials over distinct spectral intervals. This technique is in contrast to the broadband approaches that are currently employed in most GCMs. The representation of solar water-vapor transmission in terms of a multispectral formulation is desirable, particularly from the perspective of developing accurate overcast-sky transfer parameterizations. For water drops, too, broadband averages are inadequate for an accurate representation of the near-infrared interactions. It is expected that a multi-spectral approach will lead to improvements in the simulation of the overcast-sky radiative transfer, paving the way for a better understanding of cloud-climate interactions.

PLANS FY93

The analysis of the "exact" cases of the near-infrared transfer in overcast atmospheres (comprised of water vapor and liquid water) will continue, with the focus being on the absorbed solar flux, the reflected flux at the top, and the transmitted flux at the surface. The vertical disposition of the absorption in the atmosphere and the spectral signatures introduced by clouds will also be analyzed.

Further attempts will be undertaken to develop improved parameterizations for the simulation of the overcast-sky radiative transfer, both in the near-infrared and in the longwave spectra.

Computations of the "exact" total solar flux (including the near-infrared, visible, and ultra-violet spectra) for different conditions will be performed, taking into account water vapor, molecular scattering, ozone, and oxygen absorption.

1.6.2 Coupled Ocean-Atmosphere Model

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S. Manabe *R. Stouffer*

ACTIVITIES FY92

In FY92, a new project was begun to construct an ocean-atmosphere model having higher computational resolution. Recent studies of the climate response of the ocean-atmosphere model to changes of atmospheric carbon dioxide depend critically on the ability of the model to simulate the behavior of the actual ocean-atmosphere-land system. In this context, the model's grid resolution is a key factor. For example, the present model (R15 resolution) tends to overestimate the precipitation in high latitudes and is partly responsible for the relatively large correction of surface water flux that must be applied. It is possible that such a bias of the model results in overestimating the carbon dioxide-induced change of precipitation, along with the changes of near-surface salinity and thermohaline circulation. Furthermore, the computational resolution of the present ocean model is too coarse for resolving the bottom topography and ocean currents. Further improvements in the grid resolution of the oceanic and atmospheric components of the model are urgently needed.

In preparation for constructing the high resolution model, the new modular ocean model (MOM) code was incorporated into the coupled ocean-atmosphere model. The low resolution version of the new coupled model has been tested and is ready to be used for a wide variety of numerical experiments. Minor revisions were made to the code for several of the ocean model's physical processes, which will greatly facilitate the adaptation of the model to higher resolution and minimize the changes that are needed when the grid resolution is changed. As a result of this work, users of the coupled model will benefit from the increased clarity, ease of adapting new features, and faster integration time of the ocean model code.

PLANS FY93

The computational resolution of the new coupled model will be doubled. The performance of the high resolution model will be tested.

1.6.3 Effect of Vertical Resolution

A.J. Broccoli *S. Manabe*

ACTIVITIES FY92

The influence of vertical resolution on simulated climate has been explored in a series of climate-model integrations. Simulations were conducted at R15 horizontal resolution with 9, 14, 20, and 30 vertical levels. (These are identified as R15L9, R15L14, R15L20, and R15L30, respectively.) Preliminary results from these integrations suggest that increased vertical resolution is responsible for substantial improvements in the simulation of the wintertime Northern Hemisphere circulation.

One of the circulation characteristics improved by increasing vertical resolution is the stationary-wave distribution in the upper troposphere. Fig. 1.10 compares the observed distribution of 300-mb eddy geopotential height (departure from zonal mean) with those simulated by R15L9 and R15L30 versions of the climate model. While the positions of the Northern Hemisphere extrema are well-simulated by the R15L9 model, the ridge-trough couplet over North America is considerably weaker than observed. In contrast, the amplitude of this couplet is substantially higher and more realistic in the R15L30 simulation.

Improvement is also evident in simulation of the zonal mean zonal wind. In the R15L9 simulation, the upper-tropospheric winter jet stream in the Northern Hemisphere is not distinct from the polar-night westerly jet in the stratosphere. This failure to simulate closed isotachs at the location of the tropospheric jet has been a characteristic of climate-model integrations with low vertical resolution. The increased resolution of the R15L14, R15L20, and R15L30 simulations results in the simulation

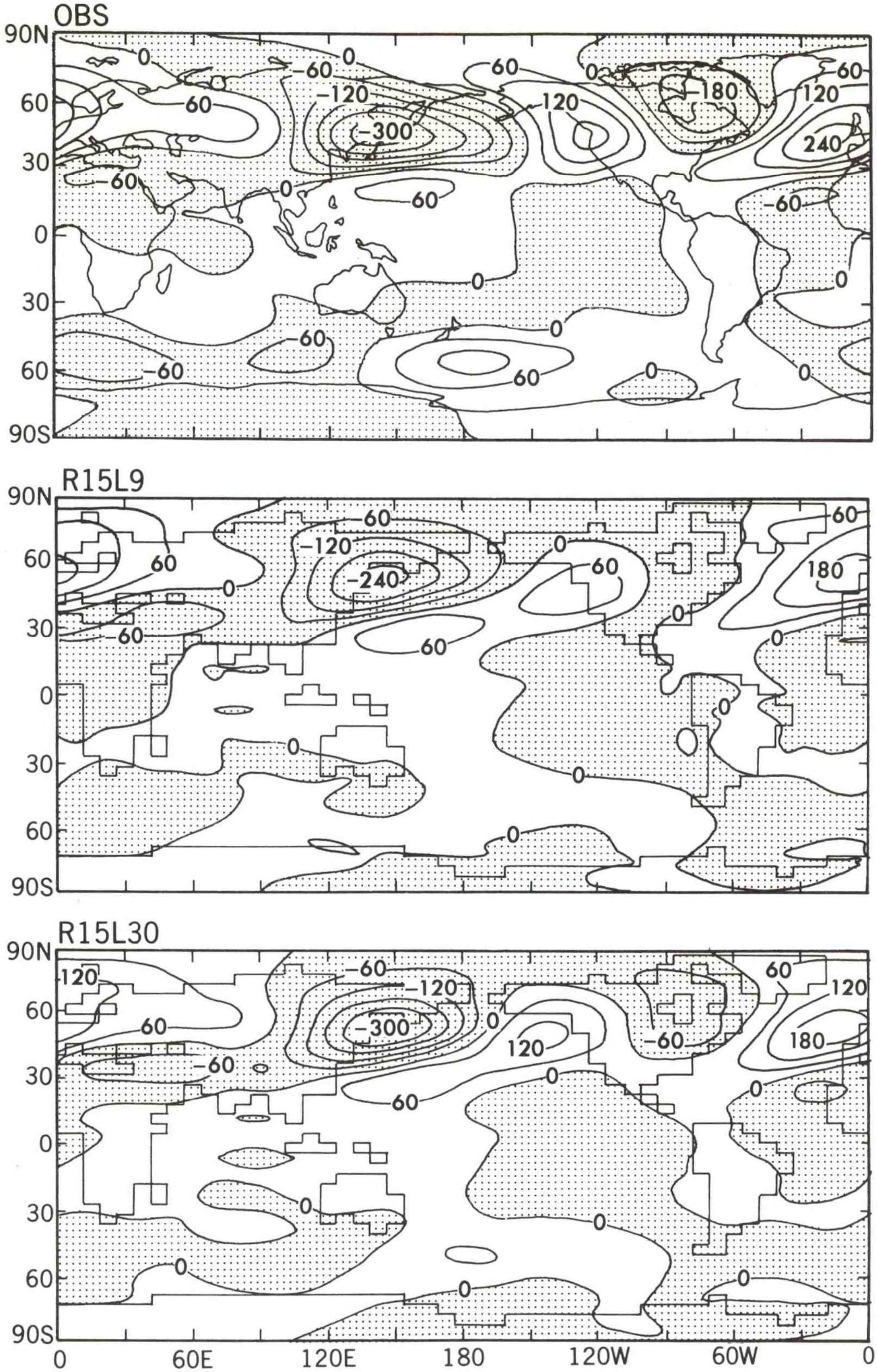

Fig. 1.10 Eddy geopotential height (m) at 300 mb level for boreal winter (December-January-February). *Top:* ECMWF analysis for the period 1980-1987. *Center:* R15L9 climate model. *Bottom:* R15L30 climate model. Contour interval is 60 m; negative values are stippled.

of a distinct upper tropospheric jet surrounded by closed isotachs. A similar improvement occurs in the simulation of the zonal mean zonal wind in the wintertime Southern Hemisphere.

PLANS FY93

Further evaluation of the R15 results will be undertaken, followed by an analogous series of climate simulations with horizontal resolution increased to R30. An attempt will be made to identify optimal vertical resolutions, based on both the fidelity of the climate simulation and computational requirements, for both the R15 and R30 versions of the model. This information will be used in the design of a wide range of future climate model-experiments.

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**	*W.J. Moxim*
*P.S. Kasibhatla**	*S. Oltmans****
H. Levy II	*P. Rayner*
*J.A. Logan***	*J.L. Richardson*****
J.D. Mahlman	*J.L. Sarmiento*

* *Georgia Institute of Technology*
** *Harvard University*
*** *Climate Monitoring and Diagnostics Laboratory/NOAA*
**** *NASA Langley Research Center*

ACTIVITIES FY92

2.1.1 Model Development

While there is a continuous effort to improve and expand the existing GCTM, work has now begun on the development of the next generation model. The tracer continuity equations will be integrated on-line in the SKYHI GCM, but the passive tracers will have no effect on the GCM meteorological fields. Computer code has been developed to incorporate physical tracer sources into the GCM, as well as to simulate the various physical (such as wet and dry removal) and chemical processes which determine global tracer distributions. The research is focussed on developing a set of tracer experiments that will provide insight into those meteorological features of the SKYHI GCM which affect global tracer distributions.

A collaboration to develop a more complete tropospheric chemical scheme for the GCTM's has begun with Dr. Sillman from the University of Michigan. The planned chemical module, with up to 10 transported species, will include both moderately and weakly reactive hydrocarbons, and should be able to simulate both the partitioning of reactive nitrogen compounds and the chemical production and destruction of ozone.

2.1.2 Tropospheric Reactive Nitrogen

The global distribution of the subcomponents of total reactive nitrogen compounds, NO_y, is the key to understanding the global biogeochemical cycle of nitrogen. Moreover, two of these compounds, NO and NO_2, control the chemical production and destruction of O_3, which indirectly controls the chemical reactivity of the atmosphere. Current work focuses on determining the relative contributions of the various sources of NO_y to the tropospheric NO_y budget and the global distribution of NO and NO_2.

The 11-level GFDL GCTM, through use of a version which explicitly treats NO_x, HNO_3, and PAN as transported species, has been used to assess the impact of fossil-fuel combustion emissions on the distribution of reactive nitrogen compounds (NO_y) in various regions of the troposphere. The validity of the wet removal parameterization used to simulate the scavenging of HNO_3 by precipitation is assessed by comparing modeled wet deposition fluxes with observed fluxes at locations known to be predominantly influenced by the fossil-fuel source.

From an analysis of the model simulations (see Fig. 2.1 for annual average surface mixing ratios), a number of new results have been achieved. (1) The model reproduces the observed spatial patterns of wet deposition near the major fossil-fuel combustion source regions. About 70-75% of the emissions are deposited in the source regions, with the remainder being exported mainly over the adjacent ocean basins. (2) The fossil-fuel source accounts for a large fraction of the observed surface concentrations and wet deposition fluxes of HNO_3 observed in the extra-tropical North Atlantic. (3) Significant fractions of the PAN and HNO_3 levels observed in the marine free troposphere during the National Aeronautics and Space Administration (NASA) Global Tropospheric Experiment (GTE) in the eastern North Pacific may be explained in terms of the fossil-fuel and stratospheric sources of NO_y. At the more remote Mauna Loa, Hawaii site only 20-40% of the observed NO_y during May 1988 appears to be due to distant fossil-fuel sources. In both regions, however, the fossil-fuel source accounts for only about 25% of the observed NO_x, suggesting either an important role for a local NO_x source or pointing to a bias in the model-calculated NO_x fraction due to some missing chemical reactions. (4) Even with the explicit treatment of PAN as a transported species, the fossil-fuel source has only a minor impact on NO_y levels in the remote tropics and in the Southern Hemisphere due to efficient scavenging of HNO_3 at the Inter-Tropical Convergence Zone (ITCZ). (5) Preliminary comparisons

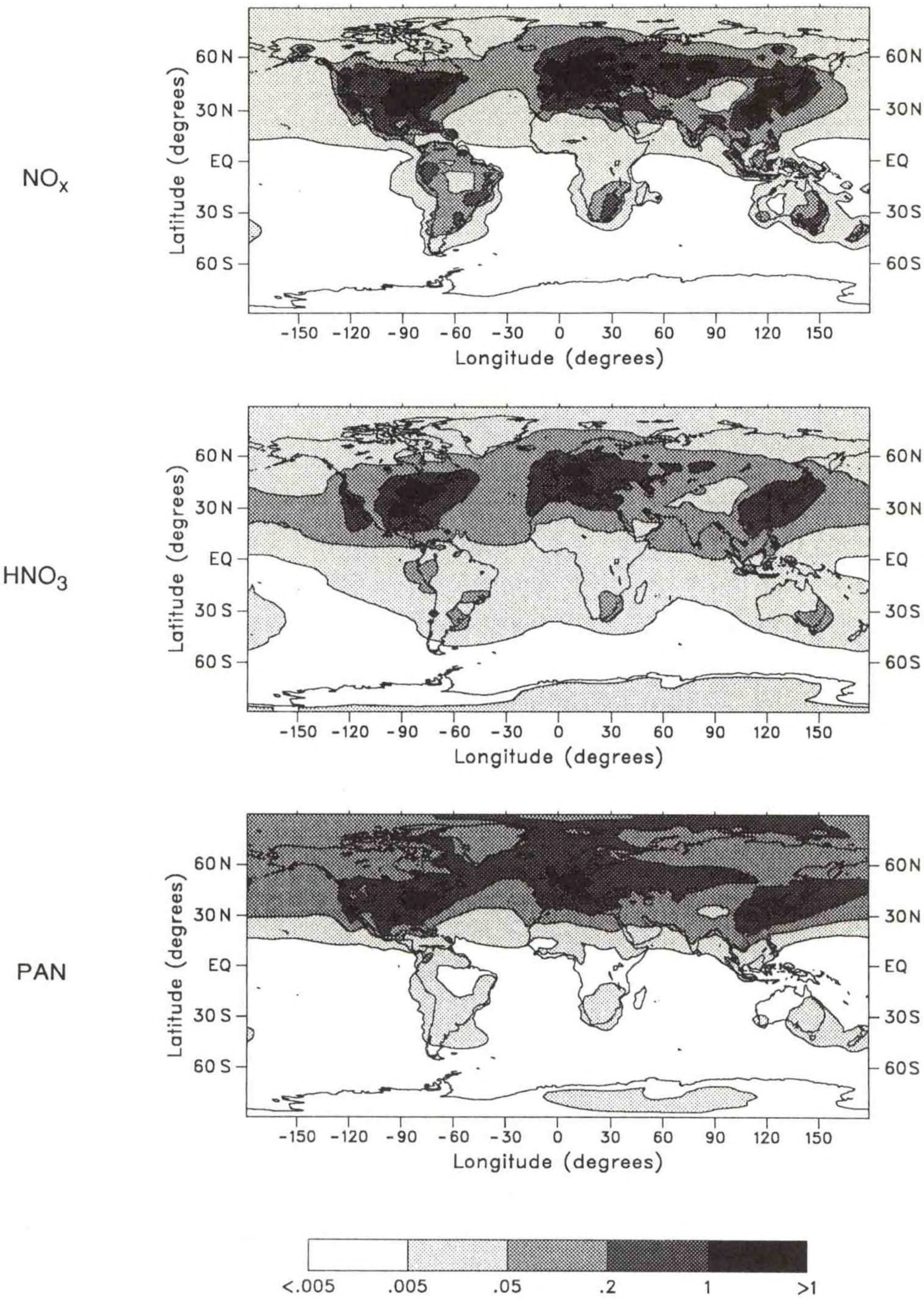

Fig. 2.1 Model-calculated annual-mean surface NO_x, HNO_3, and PAN mixing ratios with the fossil-fuel source alone. All values are in ppbv.

indicate that the relatively high levels of NOy, observed over western Alaska during the Atmospheric Boundary Layer Experiment (ABLE)-3A in July-August 1988, cannot be explained in terms of long-range transport of fossil-fuel combustion emissions from the Northern Hemisphere mid-latitude surface source regions. (6) Away from source regions, PAN is a major component of fossil-fuel NO_y, and is the dominant component poleward of 45°N. However, the impact of this sequestered PAN on regional springtime NO_x levels has not been established. While PAN is expected to decompose and form NO_x, the NO_x is rapidly converted to HNO_3.

Having first tested the sensitivity of the NO_x distribution to the height of NO_x emission by lightning, a height-dependent release function was constructed from the observations in South Africa of over 700 lightning flashes, both cloud-cloud and cloud-ground. Two separate studies were performed: in the first, the emissions from cloud-cloud and cloud-ground flashes were equal; in the second, emissions from cloud-ground flashes were 10 times the emissions from cloud-cloud lightning. While the mid- and upper-troposphere levels of NO and NO_2 were sensitive to both the height of release and the relative emission strengths, fundamental inconsistencies remain between the lightning NO_x emission levels needed to reproduce observed upper-troposphere NO_x levels [1-3 tgN globally] and those needed to reproduce the observed soluble nitrogen and nitrogen deposition in remote locations [10-20 tgN globally]. This conflict between observations and the model is still under study.

2.1.3 Tropospheric Ozone

Tropospheric ozone, which both controls the chemical reactivity of the lower atmosphere and is a significant greenhouse gas, is known 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 roles of the natural source of ozone, transport from the stratosphere, and the anthropogenic source, chemical production; (2) The relative contributions of natural and anthropogenic sources of ozone precursors to any chemical production of ozone in the troposphere.

An analysis of the first continuous measurements of ozone from Bermuda [32°N,65°W] and Barbados [13°N,60°W] has been completed (1102). Natural processes, rather than pollution, were shown to be generally in control over that region. Although springtime daily-averages at Bermuda exceeded 70 parts per billion by volume (ppbv) every year and hourly values exceeded the Canadian Air Quality limit of 80 ppbv in 1989, these high levels of ozone were transported from the clean upper-troposphere more than 5 km over the northern U.S. and Canada. During summer months, when pollution-driven photochemical production generates surface ozone levels of 70ppb or higher over the eastern U.S., typical mixing ratios at Bermuda were between 15-25 ppbv, values normally found over the Tropical Atlantic.

Meanwhile, at Barbados both the seasonal and diurnal ozone variations were nearly identical to those observed at Samoa, an island in the tropical South Pacific noted for its isolation from anthropogenic sources, where NO_x levels are very low and natural processes appear to control ozone.

An update to an earlier study of the impact of stratospheric ozone on the troposphere was run with the current GCTM. The 10 mb ozone mixing ratios were set to the monthly-average zonal-mean Solar Backscatter Ultraviolet (SBUV) observations, and the only ozone loss processes were chemical destruction in the atmospheric boundary layer and dry deposition at the surface. While the agreement between this simulation and available observations is very good for the remote/maritime surface layer, the simulated monthly mean values at 500 mb are generally much less than observed and the seasonal cycles are different. It is planned to continue this study with the new SKYHI model.

Until the mid1980s, the limited observations of tropospheric O_3 showed lowest concentrations in tropical regions, and less O_3 in the Southern Hemisphere (SH) than in the Northern Hemisphere (NH). However, recent analyses of satellite data, as well as ozonesonde data, indicate O_3 levels appearing off the west coast of Africa during the SH burning season that are comparable to those over industrialized countries. Current work focuses on determining the actual impact of emissions from biomass burning. Both an inert tracer and a tracer with a height-dependent lifetime similar to O_3 were emitted throughout the lower troposphere from regions of biomass burning. Observed profiles of water vapor from sites in the SH tropics were used to calculate a lifetime for O_3 based on the reaction of odd oxygen with water vapor. Some characteristics of the observed ozone distribution were reproduced from these simulations, such as the annual amplitude of the total tropospheric O_3 amount over the southern Indian Ocean. However, a number of characteristics, for reasons not yet understood, were not reproduced: 1) The Atlantic maximum indicated by the satellite data appears as far as 1500 mi west of the African Continent; 2) There appears to be 30 to 40% less ozone in the NH than in the SH during the respective austral springs although the amount of burning in each appears to be comparable; 3) Ozonesonde data from sites in the SH tropics show up to 90-100 ppb of O_3 in the mid and upper troposphere during January-March.

2.1.4 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.

It has been shown that fossil fuel combustion is the major source of tropospheric NO_y in the Northern Hemisphere mid and high latitudes. Recent scientific literature has discussed the possibility of winter storage of PAN due to its long lifetime in cold temperatures (< 0°C). The subsequent springtime release of NOx from PAN in the N. Atlantic, as storms sweep the PAN downward to warmer surface temperatures, could lead to a possible chemical source of ozone.

An examination of the current three specie (NO_x,HNO_3,PAN) combustion nitrogen experiment confirmed that PAN is sequestered in winter with values > 500ppt north of 55°N between 500 and 685 mb. To determine the responsible transport mechanism, a time sequence of isentropic analyses was examined. This clearly shows that cold fronts moving eastward across the eastern U.S. combustion source region sweep air rich in PAN northward and upward, depositing it near Greenland at heights of 3.5 - 5.5 km.

Monthly averaged, model surface NO_x maps over the N. Atlantic during the Spring showed large values of NO_x, but there was no straightforward way to discern what is NOx derived from PAN, NO_x stored aloft, and combustion NO_x from nearby sources. Further model analysis showed that the maximum loading of PAN north of 40°N between 315 and 835 mb occurs around April 1. As a first attempt to examine the release of NO_x from PAN during the spring warming, an experiment was devised where PAN is initialized to its global values on April 1 with NO_x and HNO_3 reset to their background values of 1 ppt. The combustion source was then turned off and the chemistry allowed to proceed as usual, so that all the resulting NO_x originated from PAN decomposition. An examination of an NO_x 990 mb time series in the N. Atlantic (55°N,15°W), showed that NO_x gradually grows to a maximum value of 105ppt on April 7 as a model North Atlantic cyclone sweeps by. The mixing ratio then decayed away as the NO_x was converted to HNO_3.

This initial experiment indicates that the model can produce significant local NOx values due to PAN decomposition. However, it provides only a brief snapshot of the processes, since in order to capture the PAN --> NO_x chemistry, the combustion source must be deactivated. The next step will be to devise an experiment that allows quantification of the PAN/NO_x interrelationship resulting from a continuous combustion source.

2.1.5 Carbon Budget Studies

To determine the distribution of sources and sinks for carbon dioxide, an inversion study has been performed using the GCTM and the observed latitudinal distribution of carbon dioxide. The GFDL GCTM has higher horizontal and vertical resolution than those used in previous work on this problem. The observed source-sink distribution, in keeping with other similar studies, suggests that the Northern

Hemisphere must be a large sink for carbon dioxide produced in that hemisphere. The results for the tropics and southern hemisphere are markedly different, showing comparatively little transport of CO_2 away from the tropics to the south and a correspondingly small southern hemisphere sink. This work is being extended to study the sensitivity of the inferred source-sink distribution to the observed tracer distribution and model formulation.

PLANS FY93

Three specie reactive nitrogen simulations will be carried out with all the nitrogen sources and regionally dependent distributions of PAN-forming hydrocarbons. Both the global fields of NO_y and the chemically important subset, NO_x, will be generated.

The development of an in situ chemistry for the GCTM will continue and preliminary simulations of the ozone/nitrogen/hydrocarbon system in the GCTM will be started.

SKYHI transport studies will be performed with a suite of tracers: CFC-11 to characterize the interhemispheric transport in the GCM; 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.

Modeling studies of the impact of biomass burning on the observed O_3 distribution will continue. The photochemistry of emissions and O_3 over the tropical ocean will be examined in conjunction with the regional scale transport.

To unravel the interdependencies of the PAN to NO_x chemical decomposition, a five specie experiment will be run with NO_x separated into three components: NO_x generated directly from fossil fuel combustion; NO_x formed from PAN in the local combustion source region; and NO_x formed from PAN after the PAN is transported away from the source region.

2.2 MODELS OF THE TROPOSPHERE-STRATOSPHERE-MESOSPHERE

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ACTIVITIES FY92

2.2.1 SKYHI Model Development

The entire SKYHI model code has been rewritten in a new flexible and modular form. This effort has produced a much more user-friendly code with substantial improvements in scientific flexibility. It is designed to serve as a candidate framework for a wide range of finite-difference modeling options for the embryonic GFDL atmospheric modeling consortium.

Special features added to this modular SKYHI code include an arbitrary number of latitude rows included within the model's I/O scheme. This allows exploration, for the first time, of three-dimensionally consistent higher-order advection schemes, one of which (pseudo 4th order) is currently being tested. This code also allows inclusion of a modularly separable and arbitrary number of trace species included for chemical and climatic experiments.

The code has been completely written in a new configuration that is specifically designed to work on a variety of massively parallel processor (MPP) systems. The code, including radiation and other physics routines, is currently being prepared for testing on the CM-5 MPP system in Los Alamos, NM.

Incorporating parameterizations of the radiative effects of CH_4, N_2O, CFC-11 and CFC-12 into SKYHI has begun. While incorporating CFC effects is straightforward, more care is required for CH_4 and N_2O, because of a significant overlap of their spectral absorption features with those of water vapor.

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 grid-spacing versions of the SKYHI model were continued. The 1° model integration now extends for 21 months, while the control run with the 3° model has proceeded for 26 years. Progress has been made in characterizing the model climatology from these integrations and from the nearly 3 year integration with a 2° x 2.4° version completed earlier (A91/P92). The simulated seasonal zonal mean winds and temperatures have been compared to observations from the GFDL radiosonde climatology (599) (up to 50 mb) and to the Congress for Space Research (COSPAR) reference atmosphere (from 50 mb to 0.0096 mb). The results for the zonal wind field show good overall agreement between model and observations, at least up to about 10 mb. Above 10 mb, the polar night jet in the model is found to be displaced poleward of that observed, and the simulated winter polar temperatures are unrealistically cold. These problems are much more severe in the SH winter than in the NH winter. The simulated 1 mb South Pole temperatures are ~65°C colder than observed in the 3° model, but this bias improves to ~45°C in the 2° model and to ~30°C in the 1° model.

An impressive aspect of the simulation of the NH winter stratospheric circulation is the degree of day-to-day and interannual variability which is found. This is illustrated dramatically by Fig. 2.2, which shows daily time series of 30 mb North Pole temperature for 10 consecutive winters in observations and in the 3° SKYHI integration.

Zonally averaged eddy statistics and three-dimensional monthly mean fields in SKYHI have been compared with observations pieced together from 8 years of ECMWF analyses (up to 10 mb) and four years of National Meteorological Center (NMC) upper atmosphere analyses (100 mb to 0.4 mb). The near surface flow in the model was found to become more intense with increasing horizontal resolution. This means that the Southern Hemisphere lower tropospheric circulation becomes realistically strong at 1° resolution, while in the Northern Hemisphere the surface westerlies are too strong in the 1° model. This is similar to the behavior seen in spectral GCMs, which do not include parameterized gravity wave drag. Unlike the experience with spectral models, however, in SKYHI the intensification of the zonal flow with increasing resolution is not a significant problem in the upper troposphere.

Detailed comparisons were also made of the precipitation climatology in the SKYHI runs with one based on rain gauge observations. The SKYHI results were found to be comparable to or better than those obtained by other currently available GCMs. Some significant discrepancies between model and observations remain, however. The model underestimates precipitation in northern India and has a single equatorial rainfall maximum in the tropical western Pacific (rather than the two off-equatorial maxima seen in observations). These problems are similar at all three horizontal resolutions.

2.2.3 Diurnal and Other High Frequency Waves in SKYHI

Analysis is continuing on multiyear 3° SKYHI integrations with 2 hourly data archiving. These runs enable the model diurnal cycle to be characterized. In addition,

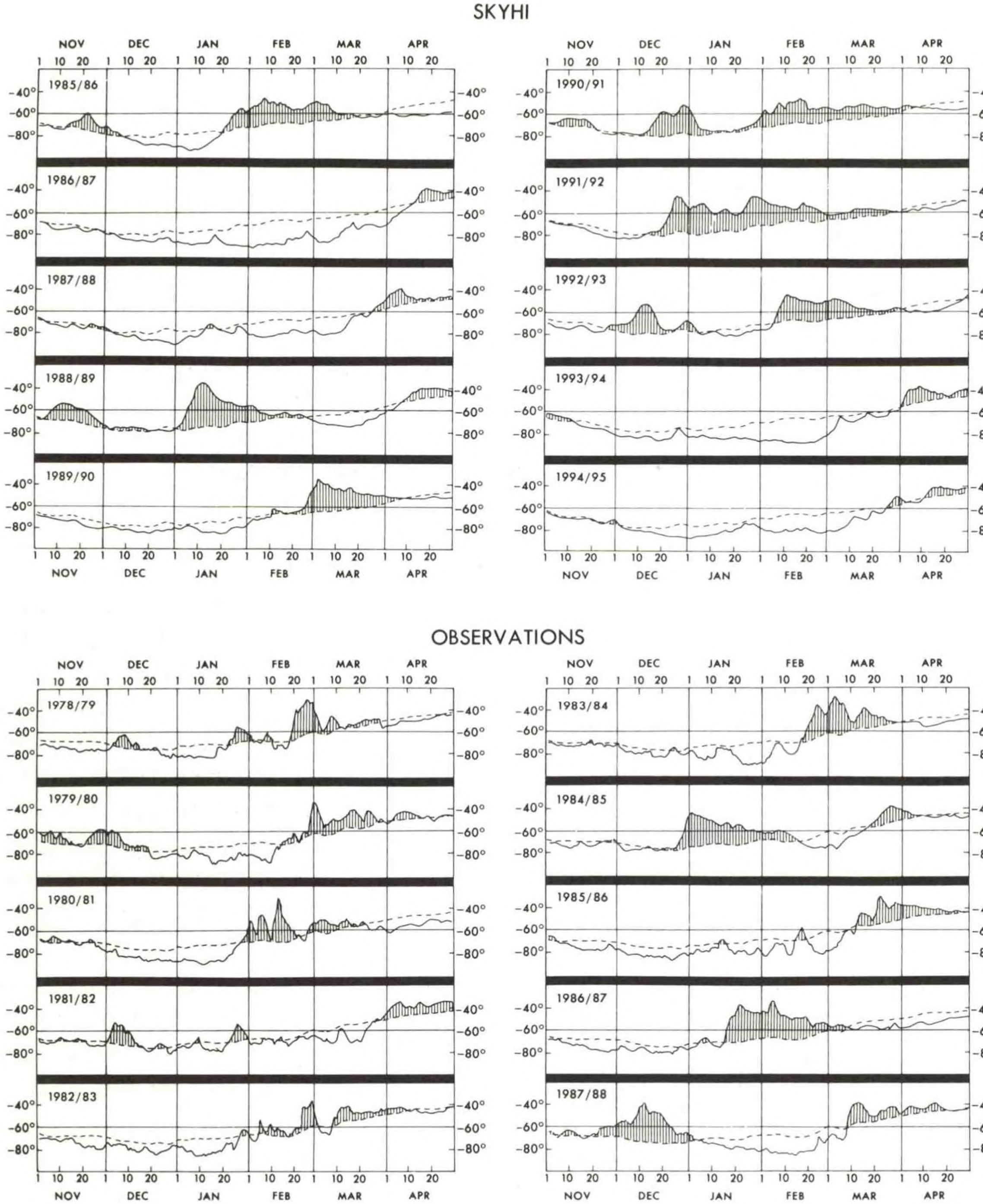

Fig. 2.2 Time series of daily 30 mb North Pole Temperatures for November-March periods of ten consecutive years. Results for the 3° latitude SKYHI control integration *(top)* and for observations provided by the Institute of Meteorology of the Free University of Berlin *(bottom)*. The dashed lines give the long term mean values for each calendar day. Anomalously warm periods are shaded.

some evidence has been found for an oscillation in the model similar to the observed "two day wave".

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

As is the case for all current GCMs, SKYHI does not produce a realistic QBO in the tropical stratosphere. In order to study the possible extratropical effects of the QBO, a number of 3° SKYHI model integrations with imposed tropical wind and temperature perturbations were conducted. A total of twenty August-February integrations with a westerly zonal mean zonal momentum source imposed in the tropical stratosphere have been performed. A series of ten similar integrations with an easterly momentum source is almost complete. Analysis of these results is in its preliminary stages, but it is encouraging that the rather arbitrary specification of the momentum source has produced tropical and subtropical wind fields that closely resemble the observed extremes of the QBO.

2.2.5 Sudden Warmings in SKYHI

A climatology of the occurrence and nature of midwinter stratospheric sudden warmings in the control integration with the 3° model is being constructed. It appears that major warmings occur in somewhat over half the winters, in agreement with observations. The warmings that are seen in the simulation display an impressive variety in terms of both timing and morphology. Warmings are seen in December, January, and February in various years of the simulation. Some model warmings involve growth of zonal wave number one disturbances, while others are dominated by zonal wave two. An example of the development of the stratospheric flow during a very strong model wave-two warming is given in Fig. 2.3.

These encouraging results suggest that the 3° SKYHI model can be a useful tool in understanding the dynamics of stratospheric sudden warmings. As a first step in this direction, an extensive series of 40 day integrations designed to characterize the predictability of the stratospheric flow has been completed. In each of these integrations, the global tropospheric temperature field was perturbed with small scale noise at some date before a sudden warming was known to occur in the control run. It was found that if the perturbation was made after a rather well defined threshold (about a month before the warming peaks in the stratosphere), the model still obtained a quite good simulation of the evolution of the stratospheric flow during the warming. However, when perturbations were imposed before this threshold, no stratospheric warming occurred in the subsequent 40 day integration.

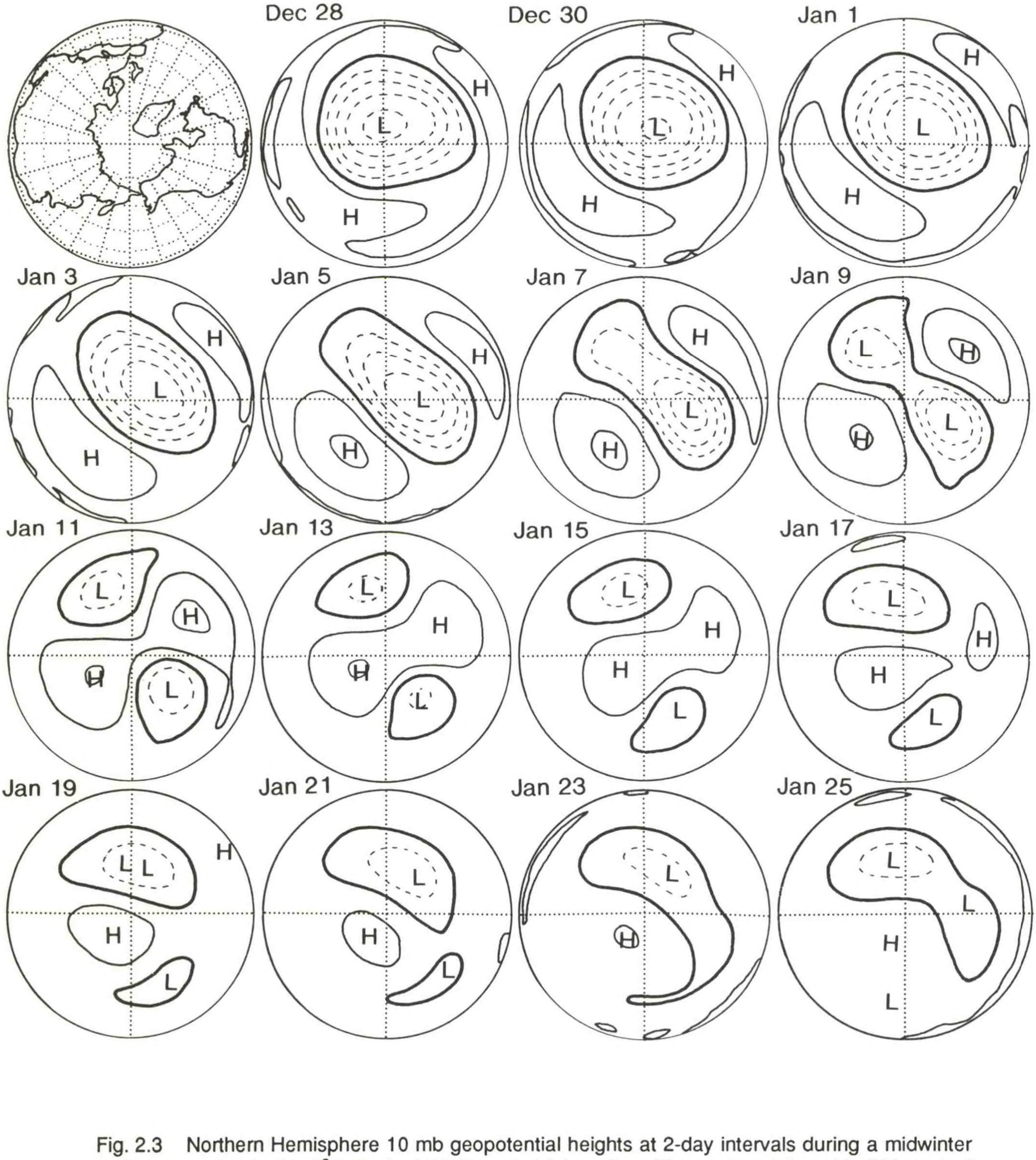

Fig. 2.3 Northern Hemisphere 10 mb geopotential heights at 2-day intervals during a midwinter sudden warming in the 3° latitude SKYHI control integration. The contour interval is 500 m, and dashed contours are used for values below 30000 m.

2.2.6 Sea Surface Temperature Perturbations in SKYHI

As described in A91/P92, this project is an examination of the effects of the Southern Oscillation on the stratosphere. Twenty August-February integrations of the 3° SKYHI model have now been completed. Ten of these runs had warm SST anomalies imposed in the equatorial Pacific and ten had cold anomalies imposed. Preliminary analysis shows that the SST anomalies have only very small effects on the extratropical stratospheric circulation. The effects on the zonal mean circulation in the tropical stratosphere are also quite small. Work is now underway to characterize the stratospheric penetration of the SST-induced perturbations of the Walker circulation.

2.2.7 Experiments on Tropical Wind Variations in a Spectral Model

Some final calculations related to the experiments with instantaneous perturbation of the tropical stratospheric winds in a 30-level spectral GCM were completed. The basic results reported in A91/P92 were found to be unchanged when a more complete analysis of the transformed-Eulerian zonal mean momentum budget was performed. The final results are consistent with the view that the absence of a QBO in this GCM is caused by a deficiency in large-scale, low-frequency components of the spectrum of vertically propagating waves generated in the tropical troposphere.

Analysis of the extratropical stratospheric effects of the tropical mean wind perturbations was rather inconclusive. This issue is now being addressed much more thoroughly in the set of SKYHI experiments described in 2.2.4 above.

2.2.8 Models of Vertically-Propagating Waves Forced by Convective Heating

The calculations with the simple linear analogue of the full SKYHI model reported in A91/P92 were completed. This linear model was forced with a time series of hourly mean convective heating taken from an integration of the 3° version of SKYHI. The comparison of results of the linear simulation with that in the full model allowed a rather direct and unambiguous demonstration of the importance of convective heating in forcing the vertically propagating waves in SKYHI (1062, rq).

2.2.9 Simulation of the Mesoscale Velocity Variance Regime

The study of the mesoscale velocity spectrum has been continued through the application of an f-plane primitive equation shallow water spectral model. The flow field in this model can be analyzed into vortical modes (*i.e.,* balanced motions which include all the potential vorticity of the flow) and gravitational modes (unbalanced motions which should behave rather like linear inertia-gravity waves). Experiments have been performed in which all the forcing is confined to large scale vortical modes. The results show that this large scale forcing produces a k^{-3} vortical mode spectrum and a much shallower gravity wave spectrum. Precisely comparable quasi-geostrophic integrations produce virtually identical results for the vortical mode spectrum. The origin of the gravity wave component in the primitive equation model is being studied through detailed analysis of the spectral energetics.

2.2.10 Statistics of Stratospheric Inertia-Gravity Waves from Rocket Observations and Comparison with SKYHI Simulation

The analysis of the characteristics of the inertia-gravity wave field in the 29-58 km height range based using rocketsonde observations reported in A90/P91 and A91/P92 was applied to column data from SKYHI model simulations. Thus far the analysis has been applied only to summer hemisphere data from the 3° model control integration. The results show very impressive agreement between the model and observations at mid-latitude sites. For locations poleward of about 60° latitude, the wind and temperature fluctuations associated with the SKYHI gravity wave field are somewhat weaker than observed (1056).

2.2.11 Tracer Transport in the SKYHI Model

The spatial and temporal evolution of tracers (N_2O and potential vorticity) are analyzed on isentropic surfaces in the stratosphere during selected periods of the high-resolution (1° latitude) run of the SKYHI GCM. The analysis has revealed that the model's winter polar vortex consists of a relatively cold, quiescent core and a "surf zone" that surrounds the core, where the tracer fields are largely homogenized by quasi-adiabatic, horizontal mixing. The boundaries of these regions are marked by sharp gradients, or edges, in the tracer concentration. In the Northern Hemisphere winter, the core is under continuous deformation due to planetary-wave breaking events, leading to significant core-to-surf-zone exchange. In the Southern Hemisphere spring, on the contrary, the core maintains remarkable coherence and isolation until a final warming occurs in early December.

The size of the core, defined by the average area closed by the inner edge, diminishes with decreasing height, and the definition of the core becomes obscure around 450 K. At lower levels, strong gradients re-appear in the vicinity of the tropopause; the variability there is characterized by repeated folding events, arising from finite-amplitude baroclinic eddies. Unlike the core aloft, the region poleward of the tropopause in the lowest few isentropic surfaces appears to be dominated by two-dimensional turbulence.

Kinematics of the potential vorticity and N_2O is similar in the surf zone, where large-scale strain dominates the motion. In the core, however, the chemical tracer responds much more sensitively to the seasonal variation of the radiation than does the potential vorticity. The different forms of the source term in the equations for the two tracers appear to be responsible for this difference.

The unprecedented realism of the 1° latitude SKYHI simulation, as revealed by the analysis, encourages an extensive use of this data set to explore fundamental issues of transport processes, such as Lagrangian trajectories and parameterization of large-scale mixing.

2.2.12 Diagnosis of Polar Stratosphere and Tracer Structure

Polar aircraft expeditions exploring the "ozone hole" phenomena have generated a wealth of data on the chemical and dynamical structure of the late winter/ early spring polar stratosphere. Tracer data from these expeditions, analyzed in isentropic coordinates, have been compared with 1° latitude resolution SKYHI tracer data from one Antarctic and two Arctic winters. SKYHI has been shown to do a realistic job of simulating winds, temperatures, position and variability of the vortex, and tracer fields in both the Arctic and Antarctic. Temperatures inside the Antarctic vortex are unrealistically cold (by ~7-10 K at 50 mb).

Power spectra of the conservative tracer N_2O have been used as a measure of atmospheric variability and as a diagnostic of wave activity in stratospheric observations and SKYHI. Comparing spectra of the 1° SKYHI to that of the observations has shown that the SKYHI Arctic winter lower stratosphere is dynamically active enough to generate tracer variability comparable to the real atmosphere. The agreement of spectral slopes suggests that the subgrid scale parameterized diffusion damps the cascade of variance to smaller scales at about the right rate. The comparison between observations and the SKYHI Antarctic winter is not nearly as favorable. SKYHI shows inadequate power at scales of 220-3000 km, indicating too little variability in the model Antarctic stratosphere. This likely results from the same dynamical cause as the low 50 mb polar temperatures.

A new analysis has been performed that coarsely separates the power spectra into contributions from breaking planetary waves, causing slowly-varying atmospheric features, and breaking gravity waves, or other rapidly-varying sources of atmospheric variability. In the wavelength range of the comparison (220-1200 km) and at both poles, the observations and SKYHI indicate significant contributions to variability from planetary wave breaking and stretching processes. However, the SKYHI Antarctic shows some inadequacy when compared to the observations.

Comparison of tracer fields provides additional insight into the polar stratospheric circulation. The remarkable similarity between N_2O gradients at the vortex edge in the second SKYHI Arctic winter and the observations suggests that SKYHI has a realistic diabatic meridional circulation. However, the SKYHI Antarctic

N_2O field shows evidence of a too-weak southern diabatic circulation. Model N_2O mixing ratios are too high and vortex edge gradients are less steep than the observations. Because strong wave forcing sharpens the edge gradient, the relatively flat edge gradients and the inadequate spectral power suggest that the wave-forced diabatic descent is too weak.

Lower stratospheric aircraft N_2O data available from 72°S to 90°N provide another test of SKYHI's diabatic meridional circulation. Because of the nearly complete decoupling of N_2O chemistry from dynamics in the lower stratosphere, separate diagnoses for SKYHI's chemistry and dynamics are possible. In the Northern Hemisphere, SKYHI's meridional gradient of N_2O is in excellent agreement with the observed gradient, indicating a reasonable diabatic meridional circulation. SKYHI mixing ratios are generally 40 ppb too high, suggesting that today's parameterized N_2O destruction coefficients are too small. In the Southern Hemisphere, the model equator to pole gradient is significantly too flat, providing further evidence for a weak diabatic meridional circulation there. What may be required to improve SKYHI tracer fields (*i.e.,* model circulation and transport) could be a combination of faster N_2O destruction chemistry and a strengthening of the Southern Hemisphere diabatic circulation through increased upward flux of tropospheric wave activity.

PLANS FY93

Further development of the modular version of SKYHI will continue, with emphasis on generalizing it for climate studies and for computational testing on massively parallel systems.

The current control integrations of the SKYHI model will be continued. New control integrations with improved distributions of clouds and ozone, as well as updated radiative transfer algorithms, will be started.

The work describing the basic SKYHI climatology and its comparison with observations will be completed.

The work on comparing small-scale variations in the wind and temperature fields from the GCM integrations with observations from rockets and lidars will be continued.

Analysis of the interannual variability of the simulated Northern Hemisphere winter stratospheric circulation in SKYHI will be conducted using the control integrations, as well as the results of SST and tropical wind perturbation experiments.

2.3 PHYSICAL PROCESSES IN THE MIDDLE ATMOSPHERE

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ACTIVITIES FY92

2.3.1 Ice Phase Effects in the Atmosphere

Simulations with the one-dimensional radiative-microphysical model (A89/P90) demonstrate that the determination of the radiative properties of ice clouds requires a binning of the size distribution spectrum into at least two categories. While the larger size portion of the spectrum (equivalent spherical radius > 50 microns) represents the dominant contribution to the mass, the smaller size portion (radius < 20 microns) makes an important contribution to the albedo field. Observations suggest that both ends of the size spectrum may be present in cirrus clouds, although the number concentrations at the smaller end have yet to be quantified by observations. The present analysis suggests that, in explicit radiative-microphysical simulations of the ice phase, neither component can be ignored.

2.3.2 Ozone Photochemistry

The GFDL/Aeronomy Laboratory ozone photochemistry code has been extensively tested in its one-dimensional version. Extensive revision of the code has been undertaken to fit in with the modular version of SKYHI (2.2.1) and its flexible options that allow for a wide range of SKYHI photochemical experiments throughout the atmosphere.

2.3.3 Study of the Ozone QBO Using TOMS Satellite Data

The study of the QBO, as revealed in zonal-mean values of the total ozone measurements reported in A91/P92, has been completed.

PLANS FY93

Incorporation of more accurate radiative transfer modules to the SKYHI code will continue.

SKYHI experiments with various levels of ozone chemistry will be underway. These experiments will establish a baseline for an extended research effort in tropospheric chemistry and ozone-climate interactions in the lower stratosphere.

A radiative transfer model that can compute the radiation field, based on inputs of ice-water path and size, will be incorporated in a version of the SKYHI GCM. Investigations into the factors governing the prognostic simulation of ice water paths in the GCM will commence.

2.4 EFFECTS OF CHANGES IN ATMOSPHERIC COMPOSITION

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ACTIVITIES FY92

2.4.1 Antarctic Ozone Depletion

As described in GFDL A91/P92, the 3° latitude resolution SKYHI model has been used to investigate the global chemical-radiative-transport-dynamical response to an Antarctic "ozone hole" chemistry. The nearly 5 years of ozone hole integration is being compared to 6 years of SKYHI control climatology. The analyses of this set of experiments is now completed.

Further analysis of this experiment has shown that the Antarctic ozone depletion acts to reduce SKYHI lower stratosphere Southern Hemisphere mean temperature by about 1.5°C, an amount similar to that already seen in the observational record (pt). Also, the polar vortex becomes tighter and longer lived in Antarctic spring due to the reduced ozone. This effect, coupled with the induced additional high latitude diabatic sinking motion (as reported in A91/P92), acts to steepen the meridional slopes of all quasi-conservative constituent isolines. Thus, the entire radiative-dynamical-transport character of the Southern Hemisphere stratosphere is altered by the presence of the Antarctic ozone hole phenomenon.

2.4.2 Stratospheric Aerosols and Their Climatic Effects

ACTIVITIES FY92

The climate-forcing effect of stratospheric aerosols over a 10-year period (corresponding to 1978-1988) was investigated using the 1-D radiative-convective model (A90/P91). The seasonally-varying global stratospheric aerosol optical depth was reconstructed from a combination of the lidar profiles at NASA/Langley (representative of mid-latitudes), Mauna Loa (representative of tropics), and the Stratospheric Aerosol Measurement System (SAMS) extinction measurements. Climate sensitivities to both small and large particle mode assumptions were examined. Also, the temperature response in the case of a "swamp" as well as a "mixed layer" (depth = 50m) were studied. Temperature changes at the surface and in the stratosphere due to the stratospheric aerosols were contrasted with the results obtained due to considerations of only the trace gas increases over the 1978-1988 period.

The stratospheric aerosol radiative forcing over the period is characterized by a rise to large values (peak > 2 W/m^2) between 1982-1985, followed by a decay to substantially lower values (< 0.2 W/m^2) by 1988. In contrast, the increase in the trace gas forcing due to CO_2, CH_4, N_2O, and CFCs is about 0.5 W/m^2 during the decade. The peak surface cooling induced by the aerosols in the "swamp" model experiment is -1.8 K while the peak cooling in the "mixed layer" experiment is -0.35 K. In both simulations, there is a recovery from the aerosol-induced perturbation by the end of the 10-year period. However, surface temperatures at the end of the simulation are still less warm than those due to the effects of the "greenhouse" gases alone. There is also a warming of the stratosphere as a result of solar and longwave absorption by aerosols. This warming is sensitive to the particle mode assumed. The evolution of the stratospheric warming, especially in the lower stratosphere, is synchronous with the pattern of the forcing. During the peak forcing years, the aerosol-induced warming overwhelms the cooling induced by the trace gas increases. Even at the end of the period, the simulations with the stratospheric aerosol exhibit a less cool stratosphere than that due to trace gas increases alone.

An additional experiment was performed in which global stratospheric ozone losses were also introduced for the 10-year period (estimated from Hohenpeissenberg and Stratospheric Aerosol and Gases Experiment (SAGE) profiles). The ozone losses tend to cool the lower stratosphere during the 10-year period. Also, the peak stratosphere warming induced by the aerosols is reduced.

2.4.3 Radiative Effects Due to Greenhouse Gases

The experiments with the narrow-band 1D radiative-convective model (A90/P91) were examined for the influences due to the various gases in the stratosphere over the period 1958-1988. These simulations include the effects due to CO_2 alone, CO_2 and all the other well-mixed greenhouse gases; both these cases were performed using a "swamp" (zero heat capacity) or a "mixed layer" (water depth = 50 m) surface. At 10 mb, the cooling obtained over the 30 year period is about -1 K, with relatively little influence due to gases other than CO_2. At 50 mb, the total cooling due to all gases is about -0.15 K for a "swamp" surface and -0.17 K for the mixed layer case.

Considerations of CO_2 increases alone yield an additional cooling of 0.08 K at 50 mb. Clearly, there is less cooling in the lower stratosphere when the presence of the non-CO_2, longer-lived trace gases is considered.

2.4.4 Stratospheric Effects Due to Increased Carbon Dioxide

The long-term SKYHI run with doubled CO_2 is continuing. About 3 years of the simulations have been completed thus far.

2.4.5 Climate Implications of Observed 1979-1990 Ozone Changes

Observations from satellite (Total Ozone Mapping Spectrometer (TOMS), SAGE) and ground-based stations indicate that between 1979 and 1990, there have been statistically significant losses of ozone in the lower stratosphere of the middle to high latitudes in both hemispheres. The radiative forcing of the surface-troposphere system due to this change has been determined by employing the total ozone losses observed by TOMS in the GFDL fixed-dynamical heating (FDH) model (Fig. 2.4). (This figure also illustrates the results obtained by K. Shine with the University of Reading (UK) model.) It is assumed, based on the SAGE and ground-based results, that the ozone losses occur in a layer extending from the local tropopause to 7 km above it. The resulting forcing is compared with that resulting from the increase in the well-mixed greenhouse gases (CO_2, CH_4, N_2O and CFCs) over the same time period (1071). The ozone losses lead to a negative forcing that is opposite to that due to the greenhouse gases at all latitudes and during all seasons. This constitutes a new element in considerations of the decadal climate forcing inasmuch as the meridional and vertical structure of the radiative effects is different from that expected due to greenhouse gas increases alone. In the middle to high latitudes, the magnitude of the forcing due to the lower stratospheric ozone losses is comparable to or even exceeds the magnitude due to CFCs alone, and is also comparable to the total effect due to all the greenhouse gases. As the anthropogenic emissions of CFCs and other halocarbons are thought to be largely responsible for the observed ozone depletions, the net decadal contributions due to the CFCs, by virtue of their indirect chemical effect, is less than what their direct "greenhouse" effect alone would indicate (1071).

The changes introduced by the stratospheric ozone losses depend crucially on the altitude profile of the loss. FDH computations have been performed to investigate the sensitivity of the ozone radiative forcing to the assumed altitude profile of ozone depletion at 4.5°N and 40°N. In the mid-latitudes, the magnitude of the negative ozone forcing decreases as the altitude of losses increases away from the tropopause. This decrease at 40°N can be as much as 50%, depending on the assumed profile below 17 km. The use of SAGE profiles at 4.5°N suggests that, in contrast to the results obtained using the TOMS values (Fig. 2.4), there exists a significant negative forcing due to the stratospheric ozone losses in the tropics as well

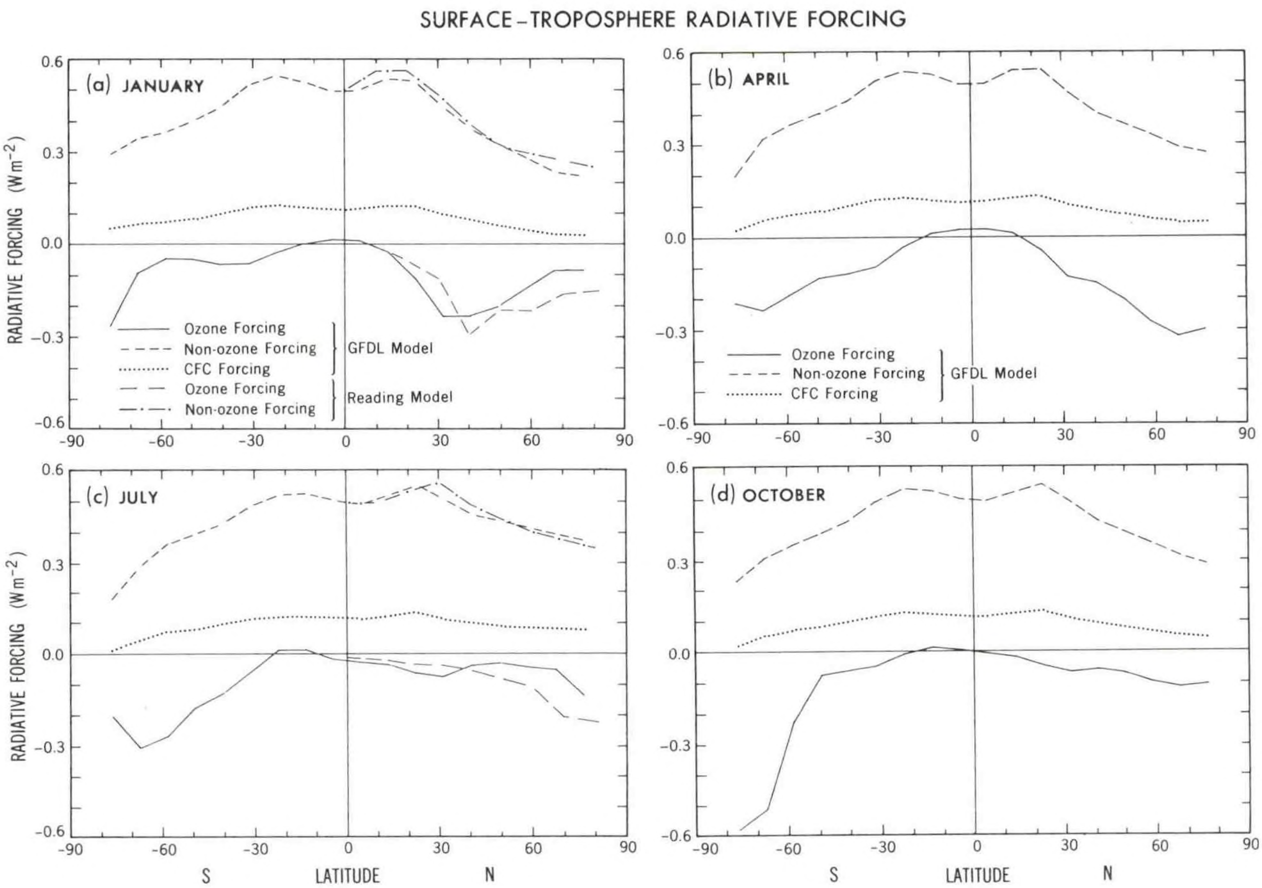

Fig. 2.4 Latitudinal dependence of the surface-troposphere radiative forcing obtained by FDH models due to the 1979-1990 increases in: i) CFCs alone, ii) all the non-ozone gases (CO_2, CH_4, N_2O and CFCs), and that due to lower stratospheric losses of ozone. Results from the Reading model are for perturbations in January and July only, while the GFDL results are for each of the four midseason months.

(see also 2.4.1). At both latitudes and for the range of observed depletions, there is a linear relationship between ozone loss and the ensuing radiative forcing.

In addition to the stratospheric ozone losses, there are suggestions of an increase in tropospheric ozone at a few locations in the Northern Hemisphere. The radiative forcing of the surface-troposphere system due to tropospheric ozone increases are opposite to that induced by the stratospheric ozone losses. FDH model computations indicate that the forcing due to stratospheric ozone may be thereby reduced. In fact, the trends at the Hohenpeissenberg station (~17%/decade) suggest that the forcing there due to tropospheric ozone changes over the past decade may be comparable in magnitude to that due to the stratospheric losses.

The overall implications for radiative forcing can be summarized as follows: a) considering the separate chemical effects that lead to stratospheric O_3 losses and tropospheric increases, the former yields an indirect radiative effect attributable to CFCs, while the latter implies a direct "greenhouse" contribution attributable to the tropospheric ozone precursors; b) in the context of total ozone changes, tropospheric ozone increases tend to offset the effects due to the stratospheric ozone losses, with a vertical redistribution of the positive and the negative components of the forcing. Reports of the above investigations appear in Chapter 7 of the World Meteorological Organization (WMO) Scientific Assessment of Ozone Depletion: 1991 (1992) and in Chapter 2 of the IPCC 1992 Scientific Assessment of Climate Change.

The effects due to the observed ozone losses (using the TOMS observations) are now under investigation using the three-dimensional SKYHI 3° latitude resolution GCM. The ozone losses imposed in the GCM's lower stratosphere (tropopause + 7 km above it) of each latitude belt are the annual averages of the observed ozone losses. These values are held invariant throughout the year as the model marches through the annual cycle. Six years of the perturbation experiment have been performed and the results of the last 3 years have been compared with that from the long-term "Control" run (2.2.2). Preliminary analyses indicate that there is a substantial cooling of the lower stratosphere at all latitudes due to the decadal ozone losses. The cooling pattern extends into the upper troposphere of the model, well below the location of the imposed ozone losses. The simulated features are strikingly similar to the pattern emerging in the GFDL Antarctic Ozone Hole experiment (2.4.1). Corresponding to the GCM experiment, FDH runs also have been made in order to diagnose the relative roles of radiative and dynamical processes in the thermal response.

PLANS FY93

A modified version of the radiation algorithm used in the one-dimensional radiative-convective model experiments will be prepared for use in stratospheric aerosol perturbation experiments with the SKYHI GCM.

Further analysis of the temperature evolution in the high-resolution radiative-convective model experiments with a full suite of greenhouse gases will continue.

The doubled CO_2 experiments will be run for further years and the diagnostic analysis will begin.

The analyses of the GCM and FDH experiments on the climatic implications of stratospheric ozone loss will continue, including a more complete assessment of the sensitivity to the vertical profile. Whenever possible, comparisons will be made with observed temperature trends.

3. EXPERIMENTAL PREDICTION

GOALS

To develop more accurate and efficient atmospheric GCMs for monthly forecasting and to explore useful approaches to ensemble prediction.

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

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

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

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

3.1 MODEL IMPROVEMENT

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

ACTIVITIES FY92

3.1.1 Spectral Model

The simulated distributions of precipitation, clouds and soil moisture have been dramatically improved by using the filtering techniques of Lanczos[1] to reduce the Gibbs phenomena, associated with the spectral representation of model orography. This work was motivated by attempts at simulating the ENSO phenomena (see 3.2.3).

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1. Canuto et al., 1988: Spectral methods in fluid dynamics. Springer-Verlag.

The annual SST cycle in the eastern equatorial Pacific has been seriously biased due to errors in the simulated surface winds. It was hypothesized that the Gibbs phenomena, associated with the steep Andes mountains, plays a role in causing the erroneous winds. Now the global orography has been filtered two-dimensionally by the Lanczos filter, so that the Gibbs phenomena are largely removed.

Figure 3.1 presents the precipitation distributions produced by the Gibbs reduced model, compared with the conventional model. The ripples in the latter model (*e.g.* the rainfall over the Sahel) have been produced dominantly by the Andes and the Antarctic mountains.

A similar filter is applied to the cumulus parameterization in the transform process from grid to spectral space. Negative values of moisture in spectral models, which have plagued spectral models in the past, have been mostly eliminated by this method.

The lid on the shallow convection parameterization was lowered from 750 hPa to 800 hPa in an attempt to alleviate some deficiencies in the rainfall distribution (3.2.1).

A T63L18 resolution model was tested, but the computer resource requirements do not make it a practical model for extended integration on the YMP computer.

3.1.2 Global Cloud Prediction Studies

Low cloud amount as well as total cloud amount are contaminated by a standing wave pattern of "noise" in the spectral model integration. This effect has been reduced by preventing convective cloud amount from altering the values of relative humidity input into the cloud prediction scheme. This simple modification may be beneficial even when techniques to filter Gibbs phenomena (3.1.1) are applied.

The clear sky portion of the radiation code is now functioning properly.

Cloud amount and cloud radiative properties, derived from the ISCCP C2 data for the period from July 1983 to December 1990 are being prepared for insertion into the atmospheric GCM. The intent is to constrain the model's cloud-radiation forcing to agree closely with observations

3.1.3 Global Eta-Model

As was described in A91/P92, the global Eta-model was developed and has been investigated extensively. This is a grid point model on the E-grid system in this

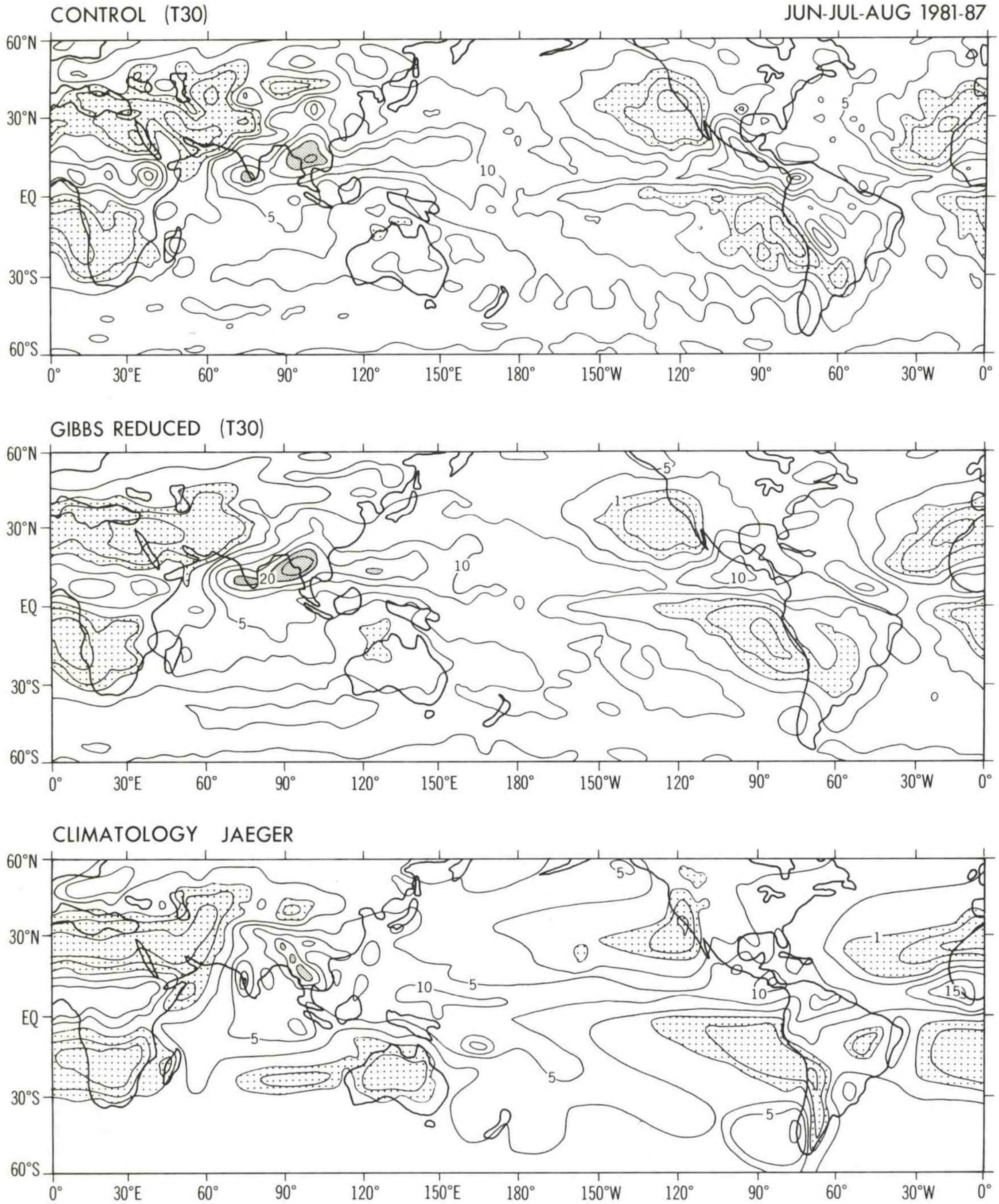

Fig. 3.1 The distribution of simulated precipitation by two models of T30L18 resolution for the summer season of June-July-August from 1981 to 1987. The conventional model *(top),* the Gibbs reduced model *(middle),* and the JJA climatology by Jaeger (1976) *(bottom).* The contours are at .1, .5, 1, 2.5, 5, 10, 15, 20, 25, and 30 mm/ day. The domains of < 1 mm/day are lightly shaded, and those of > 20 mm/day are densely shaded.

particular case, and it can be equally applied to the C-grid system. The model uses either sigma or eta as the vertical coordinate. The latter is characterized as the step-mountain pressure coordinate. Model comparisons have been performed in two steps, keeping the same physical parameterizations. The first step is to compare sigma coordinate versions of the grid model *versus* the spectral model, and the second step is to compare the eta-coordinate *versus* the sigma-coordinate version of the grid model. This investigation, based on a 3 year integration, has revealed that the eta-coordinate model behaves satisfactorily, compared with the sigma-coordinate model, and that the distributions of simulated rainfall are clearly different in the two models.

3.1.4 Study of Subgrid-Scale Parameterization

Three versions of the atmospheric parameterization packages have been incorporated in the T42L18 spectral model, and the impact of physics on the GCM is being tested by making a 3 year run for each version. The three versions are *Experiment I*, which is the control run, based on a previous study, E-physics (987), *Experiment II,* which includes the effect of molecular viscosity and free convection on the surface exchange coefficients and a modified mixing length scale in turbulence closure scheme, and *Experiment III*, which replaces the cumulus parameterization of "convective adjustment" by the Arakawa-Schubert scheme, modified to improve the simulation of the Madden-Julian Oscillation.

3.1.5 Upper Ocean Model

An option to solve reformulated barotropic equations for the surface-pressure field rather than the volume transport stream function has been included in the modular ocean model (MOM). The new method has several advantages over the stream function formulation: 1) any number of islands may be included at no extra cost.; 2) the model can handle steep gradients in bottom topography; 3) the efficiency for parallel processors is increased; and 4) the free surface height is a prognostic variable which simplifies the assimilation of altimeter data (3.3.3). The MOM has been coupled with the atmospheric spectral model, and a number of 6 ~ 20 year runs have been performed successfully (3.2.3).

3.1.6 Meso-Scale Eta-Model

A meso-scale model with bulk cloud-physics is being developed from a limited area version of the NMC eta-model. Prognostic equations for cloud liquid water, cloud ice, liquid and solid precipitation have been formulated and are now being coded. The random cloud model concept of Mellor (261) and Sommeria and Deardorff[2] is used to

2. Sommeria, G. and J.W. Deardorff (1977): Subgrid-scale condensation in models of nonprecipitating clouds. J. Atmos. Sci., 34, 344-355.

make the partial cloudiness more consistent with the cloud water content. This model will be applied first to the First ISCCP Regional Experiment (FIRE) II and later to Coupled Ocean-Atmosphere Response Experiment (TOGA-COARE).

PLANS FY93

The investigation of the Gibbs reduced scheme for cumulus convection will be continued. Three year simulations of the subgrid-scale experiments on atmospheric parameterization, *i.e., Experiments* I, II and III, will be summarized. The bucket versus the SiB model test was not pursued in FY92, but it will be resumed.

The inclusion of an implicit free surface version of the MOM will be implemented. A lateral boundary condition to the elliptic equation for the surface pressure will be added to the MOM. This condition includes a viscous slip for the shore-parallel component of ocean current.

The $1^\circ \times 1^\circ$ ocean model will be tested for the air-sea coupled model (3.2.3).

The total and clear sky radiation budgets and cloud-radiation forcing budget will be computed, based upon the less noisy cloud prediction scheme. A long term integration with specified ISCCP clouds will be carried out. The working version of the meso-scale eta-model with cloud physics and the random cloud component will be further developed and implemented.

A C-grid option will be added to the grid model, and comparisons will be made between the C-grid and the E-grid versions.

3.2 SIMULATION AND DIAGNOSTIC STUDIES

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

ACTIVITIES FY92

3.2.1 Ten-Year Integrations of Atmospheric GCM

Two kinds of 10 year integrations have been reported. One is multiple runs with the same model, and the other is a single run under the Atmospheric Model Intercomparison Project (AMIP).

Nine runs using the T30L18 model have been completed, and now another set of nine runs using the T42L18 model is underway. All these integrations are performed with the same observed SSTs prescribed. One of the objectives of these runs is to assess the model's climatology, compared with observation. Some variables have been analyzed based on the available integrations and compared with observed climatologies (c.l. rainfall, Jaeger, 1976[3], and the ECMWF statistics, Schubert et al., 1990[4]). Many climatological features are reasonably represented by the model. The higher resolution model (T42) produces a better simulation of the subtropical westerlies.

The AMIP ten-year run with T42L18 model (3.1.1) has been completed. In order to comply with the AMIP specification, the GCM has been modified with respect to cloud-radiation interaction diagnostics, along with specification of SSTs, carbon-dioxide and the solar constant.

3.2.2 Sensitivity Study with the Air-Sea Model

Sensitivity studies are being performed in order to investigate the annual variability of the SST in the coupled air-sea model. Tests are underway involving atmospheric parameters which may affect the SST variability, such as the surface winds, sensible and latent heat fluxes, incoming shortwave radiation, precipitation, and the atmospheric GCM's resolution. It is known that the surface wind stress in the eastern tropical Pacific is most influential for the annual cycle and interannual variability of SST. A partial cause for the deficiency in the simulation of the SST variability is the bias in the south-easterly trades in the eastern tropical Pacific. This speculation has been confirmed by an experimental run, using the observed climatological wind data through a surface-wind-correction method. This coupled model run has been extended for 20 years, in which the interannual variabilities appear, but the SST anomaly amplitude is only about 15% of that observed. It is hypothesized that this bias is caused by the spectral Gibbs phenomena, associated with the steep Andes orography. Another drawback is the strong easterly bias in the western and the central equatorial Pacific. This systematic error affects the SST of the equatorial Pacific in connection with cumulus convection, and hence crucially influences the ENSO process.

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3. Jaeger, L., 1976: Monatskarten des Neiderschlags für die gauze Erde. Ber. Dtsch. Witterdienstes, 18, No. 139, Offenbach, Germany.
4. Schubert, S.D., C.-K. Park, W. Higgins, S. Moorthi, and M. Suarez, 1990: An atlas of ECMWF analyses (1980-87). Part I - First moment quantities. NASA, Tech. Memorandum 100747.

3.2.3 Systematic Biases in the Air-Sea Coupled Model

As mentioned in A91/P92, the current air-sea coupled model generates large systematic errors. The errors are characterized by zonalization of the SST pattern, lack of variability in the annual cycle (3.2.2), and extratropical deficiencies.

The impact of the horizontal resolution of the atmospheric GCM was studied using the R21L9 and the T42L18 atmospheric models. Fig. 3.2 shows the SST error distributions (calculated using the NMC SST analysis for 7 Februaries from 1982 to 1988). A cold bias prevails over a large portion of the oceans. Large negative SST errors exists along the equator. A warm bias can be seen over the Southern Ocean, some portions of the Gulf Stream and Kuroshio, and also the eastern sides of the ocean basins. The equatorial cold bias is decreased appreciably in the T42L18 model, compared with that in the R21L9 model. This is more evident in the diagrams of zonal mean SST error at the right hand side of Fig. 3.2. The cold bias at the equator has been reduced by a factor of 1.7 from the lower to the higher resolution.

However, increased resolution alone does not remove all types of biases. The annual cycle in the eastern equatorial Pacific is partly related to the southerly trades along the Andes (3.2.2). A test is underway, coupling the Gibbs reduced model of the atmosphere (T30L18) with the ocean model. Yet the tendency toward zonalization still continues to exist in such a way that the South Pacific Convergence Zone (SPCZ) is erroneously distributed, *i.e.*, parallel to the equator. For this reason, a homogeneous grid ocean model (1° (*longitude*) x 1° (*latitude*) without the equatorial refinement) is being coupled (3.1.5), though the 1° resolution is somewhat disadvantageous for the ENSO simulation.

PLANS FY93

The nine runs using the atmospheric T42L18 GCM will be completed, and the results will be analyzed and compared with observations. Related to the sensitivity study with the air-sea model, the model with a *local* *surface-wind-correction* *method* (T42L18) will be tested. A coupled system with the Gibbs reduced model (T30L18) will be developed. The new coupled model, in which the 1° x 1° ocean model is employed, will be integrated for 7 years.

SST ERRORS FEBRUARY MEANS

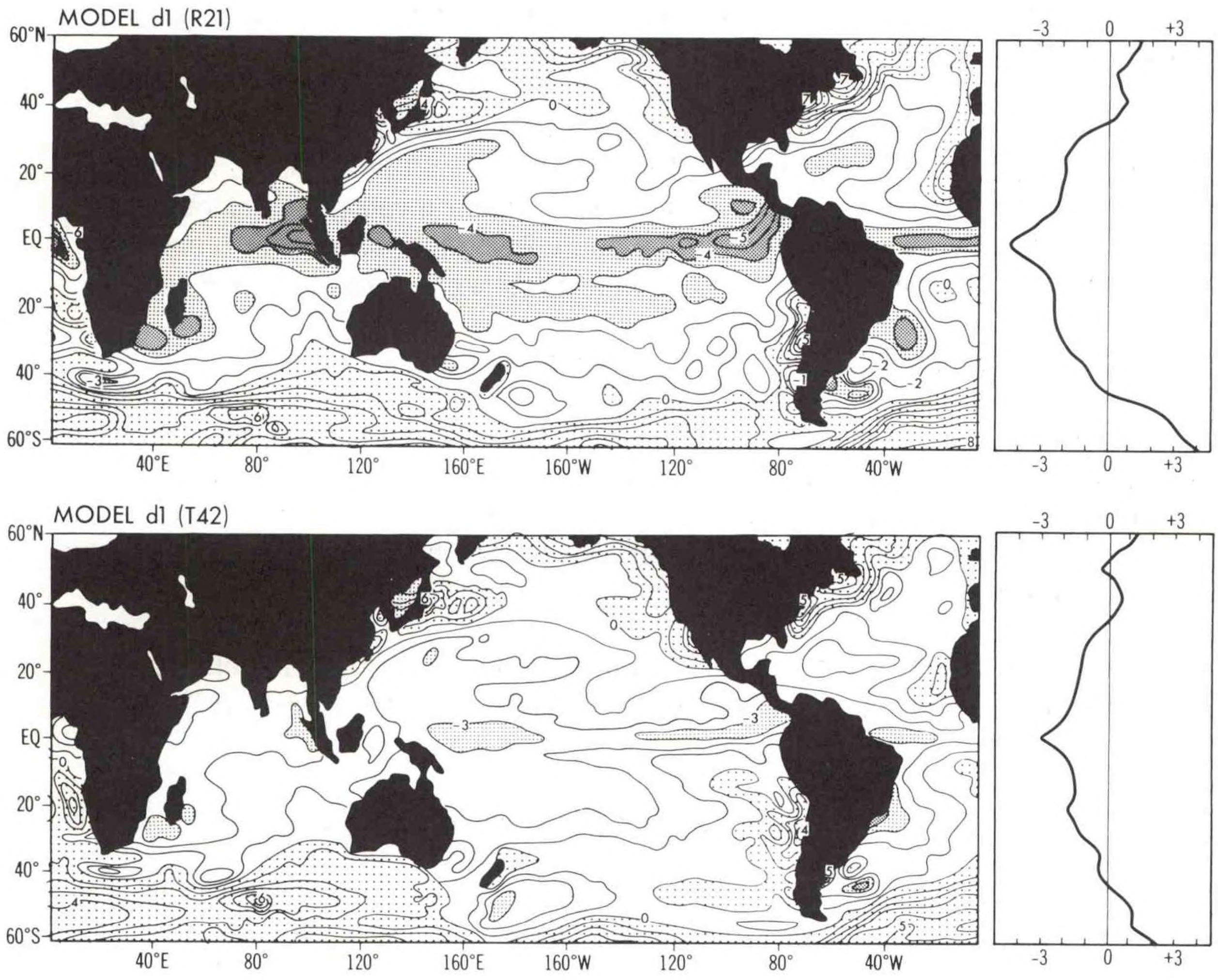

Fig. 3.2 Seven year average of SST errors for February in the R21L9 model *(upper)* and T42L18 model *(lower)*. The contour interval is 1°C. The zonal mean errors are shown at the right hand side.

3.3 DATA ASSIMILATION

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

ACTIVITIES FY92

3.3.1 Atmospheric Data Assimilation

The triangularly truncated spectral model has been applied to the atmospheric data assimilation on the Cray computer without any problem.

In connection with the 30-day ensemble prediction (3.4.1), attention has been focused on the analysis "uncertainty". The uncertainty can be obtained in principle through the data assimilation system. Therefore, a careful investigation of the existing data assimilation system has been carried out, utilizing the *identical twin* approach. As a result, several errors in the scheme as well as code errors have been uncovered.

3.3.2 Ten-Year Series of Ocean Data Assimilation

XBT and MBT data for 1984 to 1988 obtained from the National Oceanographic Data Center (NODC/NOAA) together with COADS data has been applied to the global data assimilation system. However, the combined data set still contains much less data than the Master Oceanographic Observations Data Set (MOODS), which covered the preceding years, *i.e.,* 1979-1984.

Fortunately additional XBT and moored buoy data was obtained from the world TOGA data center at Brest, France, though this data is limited to the TOGA region only.

Using the merged data set, another ten-year series of data assimilation is being performed.

3.3.3 Data Assimilation of Altimeter Measurements

The altimeter data from the geodetic satellite (GEOSAT) were obtained from two sources, *i.e.,* one from Geophysical Data Records (Dr. Cheney) and the other from the Jet Propulsion Laboratory (Dr. Zlotnicki). These data for January 1987-December 1988 are being processed, and the anomaly components of sea surface height are being calculated. So far the data has been processed on a 5° x 5° grid for the domain of 60°S to 60°N. Meanwhile, work is underway to explore a method to assimilate the altimeter measurements into the ocean analysis system. The MOM code (3.1.5) is tested on ocean surface pressure, which is closely related to the surface height obtained from the altimeter data.

PLANS FY93

The method to estimate the uncertainty in the atmospheric analysis will be continued. The compatibility of the MOM's surface pressure with that derived from the altimeter data will be investigated. An algorithm to assimilate the altimeter data will be developed. The ocean data assimilation will be repeated with the TOGA data combined.

3.4 LONG-RANGE FORECAST EXPERIMENTS

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A. Navarra	*R. Smith*
J. Ploshay	*W. Stern*

ACTIVITIES FY92

3.4.1 30-Day Ensemble Forecast

A test is being conducted on the sensitivity of prediction to an ensemble of perturbations about the initial conditions, which lie within the range of analysis uncertainty. A preliminary investigation is underway, utilizing the *identical twin* approach, in which the true solution and the analysis error are perfectly known. It will be determined whether bifurcations exist in the ensemble forecast, and whether the density of the distribution yields a measure of predictability.

Using an initial condition taken from the data assimilation as a base, a set of ensemble forecasts is prepared based on the knowledge of analysis uncertainty. The perturbed initial conditions are arranged to form a Gaussian distribution around the base initial condition through the Monte Carlo method. The vertical structures of the perturbation are determined by a technique of statistical three-dimensional correlations. These perturbations are next initialized. Two methods are tested for their capability in dynamical and thermodynamical balancing; one is the nudging method and the other is the full-fledged data assimilation scheme. The latter is the GFDL data assimilation system. Originally it was thought that the nudging method would be sufficient for the purpose of Monte Carlo initialization, but it turned out to be inadequate. The GFDL assimilation system gave better initialization.

3.4.2 Occasional Attractors in Seasonal Forecasts

In determining a measure of predictability for seasonal predictions, a different approach is needed than that used for the 30 day forecasts. The tracing of bifurcation characteristics for each of the multiple members in the seasonal forecasts would be very difficult, if not impossible, because of the length of the forecast time. Therefore, an index of reproducibility is chosen as a measure of the predictability; the reproducibility is assessed by calculating the spread of selected variables among members of the ensemble (nine in our case). This measure differs from the "potential predictability" or the "signal-to-noise ratio" (Madden, 1976[5]; Zwiers, 1987[6]). Reproducibility appears to be more appropriate and practical than the signal-to-noise ratio. The investigation involving nine decadal runs indicates that outside the tropics, there is no period during the decade in which the signal clearly dominates the noise. However, it is also true that high reproducibility is not found all the time, but only occasionally, implying that seasonal forecasts might be feasible only during these periods, if an accurate ocean temperature were known. In fact, the 1988 U.S. drought appears to correspond to one of these occasions.

A crucial question, however, is whether the occasions of high reproducibility are statistically valid and robust. In other words, are nine members sufficient to assess the reproducibility? Do these occasions in the T30L18 model agree with those in the T42L18 model, for example? In order to investigate the latter point, nine decadal runs are being repeated under the same oceanic forcing with the T42L18 GCM. So far, 4 runs have been completed.

PLANS FY93

Ensemble forecasts will be performed, using a set of about 100 perturbed initial conditions. Two states of atmospheric circulation, predominately *zonal flow* and *blocking* patterns, will be investigated as reasonable ways of stratifying the ensemble.

The nine decadal runs with the higher resolution T42L18 model will be completed, and the reproducibility of selected variables will be studied. A comparison of the model's drought index with the observations over the U.S. will be carried out. A 40 year SST data set is being supplied by U.K. Met. Office (Mr. C. Folland). Using this data, a 40 year simulation will be started.

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5. Madden, R.A., 1976: Estimate of the natural variability of time averaged sea level pressure. Mon. Wea. Rev., 104, 942-952.
6. Zwiers, F.W., 1987: A potential predictability study conducted with an atmospheric general circulation model. Mon. Wea. Rev., 113, 54-64.

Seasonal forecasts using the coupled model will be made to explore model sensitivity to various initial conditions. Initial conditions will be generated using both the nudging method as well as the full-fledged data assimilation scheme. Observed SSTs and observed surface winds will both be utilized in creating the initial conditions.

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

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L. Goddard	*S.G.H. Philander*
N.-C. Lau	*S.-P. Xie*
J. Li	

ACTIVITIES FY92

Numerous low frequency phenomena associated with climate variability are neither strictly oceanic nor strictly atmospheric, but involve interactions between these two media. To gain an understanding of these phenomena and to develop models capable of simulating them realistically and predicting them accurately, a number of studies that involve a variety of models have been undertaken. The focus is on the Southern Oscillation /El Niño and the seasonal cycle.

4.1.1 Energetics and Predictability of El Niño

Although there are coupled ocean-atmosphere models capable of predicting El Niño, the reasons for their success are unclear. Sometimes the predictions from slightly different initial conditions are all consistent, in which case the forecast is likely to be accurate. At other times the predictions diverge. The criteria that determine when there is, and when there is not, predictability are not known. The atmosphere responds rapidly to changes in sea surface temperatures, within weeks, but the oceans take months to years to adjust to changes in the winds. It is therefore assumed that long-term predictability depends on the memory of the ocean. However, whatever the ocean does is in response to the winds. To address the questions related to predictability, an investigation is being made of the energetics of the ocean, the work that the wind does on the ocean, and the creation of potential energy (thermocline displacements) in the ocean. To obtain the necessary data, a realistic oceanic GCM is forced with observed winds for the period 1956 onwards. Preliminary results indicate that the wind does work on the ocean and creates available potential energy, primarily during the cold La Niña phase of the Southern Oscillation. Unusually intense easterly winds during that period appear to be a reliable precursor of an unusually intense El Niño a year later. These results, while confirming that the "delayed oscillator" mechanism is relevant to the Southern Oscillation, indicate that Prof. Wyrtki's earlier ideas concerning intense easterlies as precursors of El Niño are applicable.

4.1.2 The Seasonal Cycle

The Earth's response to seasonal variations in solar radiation involves coupled ocean-atmosphere modes of oscillation, especially in the eastern equatorial Atlantic and Pacific Oceans. These modes have a structure different from the delayed oscillator modes, involved in interannual fluctuations. The seasonal oscillations depend on phase lags (in space and time) between the zonal winds and sea surface temperatures, and are associated with westward phase propagation. To study the excitation of such modes by the seasonally varying solar radiation (which has both annual and semiannual harmonics) and its interaction with the interannual oscillations, a simple coupled ocean-atmosphere model has been constructed. (Its oceanic component is a 2-layer model driven with winds and heat fluxes; its atmospheric component is a 1-layer model that responds to heat sources related to sea surface temperatures.) The coupled model is being forced with periodically varying solar radiation - the period changes from experiment to experiment. Preliminary results indicate that semiannual forcing is too rapid to excite a natural mode of oscillation of the coupled system, but the annual cycle does excite such modes, primarily in the eastern sides of equatorial basins where the thermocline is shallow.

4.1.3 North-South Movements of the ITCZ

The meridional movements of the ITCZ are, from a meteorological point of view, in part attributable to sea surface temperature changes: the ITCZ is furthest north when SST at and south of the equator is low, and moves southward when the surface waters near the equator warm up. From an oceanic point of view, the sea surface temperature changes are attributable to the wind changes associated with the ITCZ movements. Simple coupled ocean-atmosphere models have been developed to investigate the implied air-sea interactions. In these models, the atmospheric component is a one-layer model that is driven by anomalous heat sources related to sea surface temperatures. The oceanic component is designed to focus in turn on (a) entrainment into the mixed surface layer, (b) variations in heat flux across the surface, and (c) the dynamical response of the ocean to changes in the winds. Surprisingly, each of these oceanic processes results in feedbacks that tend to maintain the ITCZ in a northerly position, if it is there initially. Entrainment, which is most intense where the winds are strong, is minimal beneath the ITCZ, where the winds are weak, so that sea surface temperatures are at a maximum there. The strong winds far from the ITCZ not only enhance entrainment, but also enhance evaporation. The low stratus cloud cover also increases over regions of low sea surface temperature in the eastern equatorial Pacific, thus reducing the heat flux. In other words, there is a tendency for heat flux into the eastern equatorial Pacific to be low in regions of low sea surface temperatures, thus keeping these temperatures low. Finally, the dynamical response to southerly winds includes upwelling at and south of the equator, so that the southerly winds associated with an ITCZ in a northerly position maintain cold surface waters near the equator.

These results indicate that in the development of more sophisticated coupled GCMs, several different processes, dynamical and thermodynamical, must be simulated to reproduce a realistic tropical seasonal cycle.

4.1.4 Coupled General Circulation Models of the Ocean and Atmosphere

Previously (1077), the variability was described in a coupled atmosphere ocean system, consisting of a spectral R15 atmosphere and a regional Pacific Ocean model, under annual mean solar forcing and zonally averaged annual mean cloudiness. Interannual variability on a time scale of three to five years was demonstrated with a maximum SST difference of approximately 4°C between warm and cold events.

Subsequent to these experiments, the oceanic component of the coupled model was modified to cover the entire globe between 50°N and S. The more realistic continental geometry in the western Pacific now permits the Indian and Pacific Oceans to exchange surface waters. In a repetition of the earlier coupled experiments, the model again simulated interannual variability in response to annual mean solar radiation, but the amplitude was smaller than in the earlier experiments. (A possible explanation is poorer reflection of equatorial waves off the western coast of the Pacific.)

One of the main flaws in the R15 model is that the amplitude of the trade winds is only 60% of realistic values. In an attempt to rectify this and better resolve the ITCZ, the atmospheric R15 model was replaced by an R30 resolution. The coupled system was integrated for 10 years. The results are shown in Fig. 4.1. Although interannual variability was again present, the amplitude was small and the mean SST was unrealistically low, especially in the equatorial upwelling zone.

Up to this stage, the forcing in all the experiments was annual mean solar radiation. Seasonal variations were next taken into account by forcing with solar radiation that varies daily as observed. A further change involved the cloud cover: rather than being specified and fixed, as in earlier experiments, a parameterization that permits the model to calculate the appropriate cloud cover as the integration proceeds was incorporated. In the integrations, a pronounced climate drift immediately became apparent. The ocean cooled considerably, because heat fluxes into the ocean were too low by approximately 30 watts/m^2. The integrations were halted after 2 years because the simulation grew steadily worse.

The cloud parameterization seems to be a serious problem because further experiments, in which the clouds were specified and fixed, showed a reversal of the cooling trend: a warming drift started.

PLANS FY93

Although coupled models forced with annual mean solar radiation are capable of reproducing realistic interannual fluctuations, the inclusion of seasonal forcing is creating serious problems. From studies with simple coupled models, it is clear that heat fluxes across the ocean, and the thermodynamics of the ocean, are far more important seasonally than interannually. Studies with simple models will continue in order to gain a better understanding of the seasonal cycle, including meridional movements of the ITCZ. In the case of the coupled GCMs, need for improved cloud parameterization is clear. In the meantime, the climate drift problem will be coped with by including flux corrections. At first it will be included in the ocean to ensure realistic annual mean sea surface temperatures. Hopefully the seasonal cycle will be accurate once the time-mean conditions are realistic.

4.2 OCEANIC RESPONSE STUDIES

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C. Koeberle	*S.G.H. Philander*
Z. Liu	*C. Ravelo*

ACTIVITIES FY92

Seasonal and interannual sea surface temperature variations in the tropical Pacific and Atlantic are remarkably similar: a cold equatorial tongue in the east and cold surface waters to the south of the tongue are prominent features of the cold

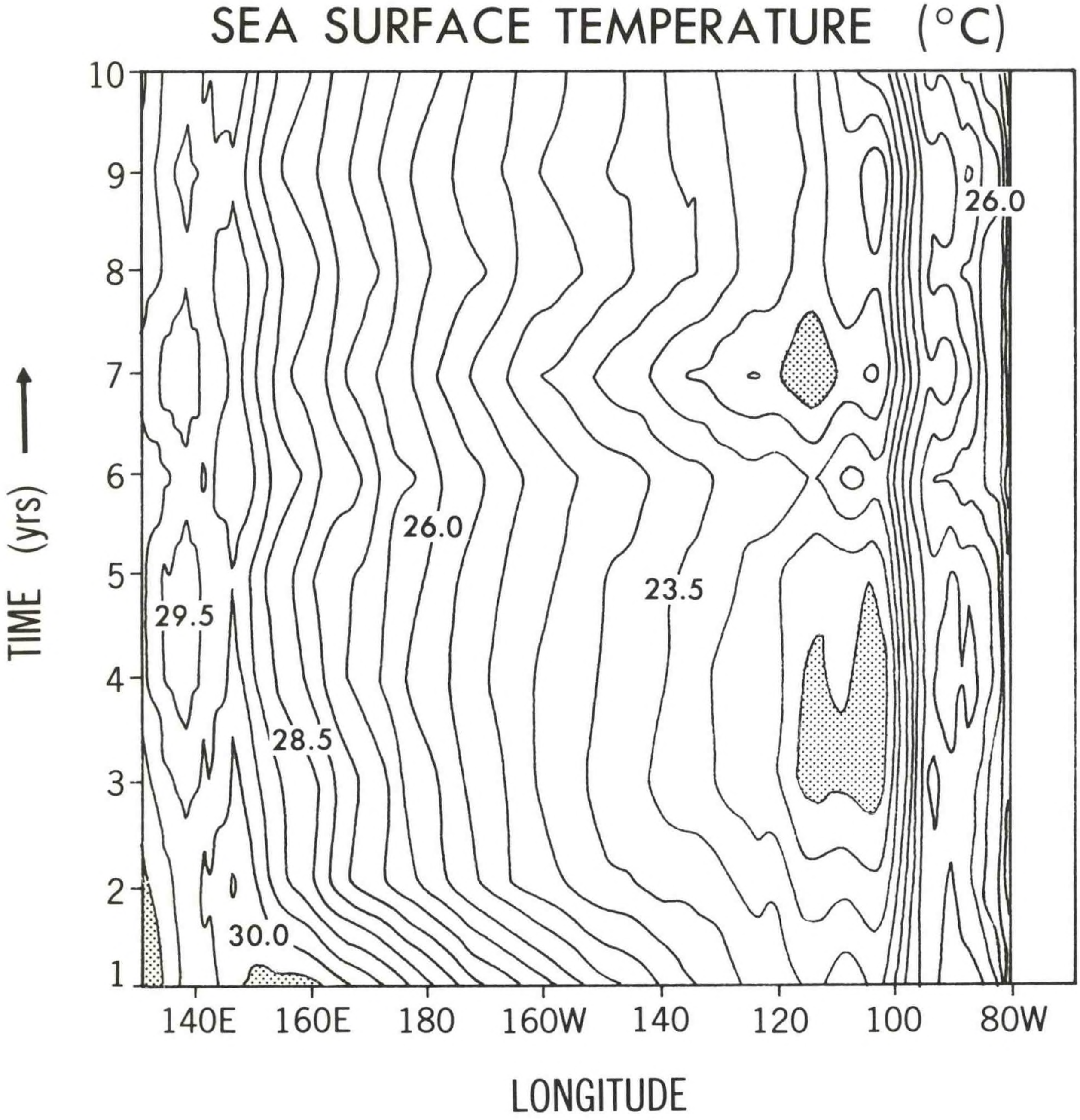

Fig. 4.1 Results from the coupled global ocean model and high resolution R-30 atmospheric model without seasons and with clouds specified from climatology. Model prediction of SST is shown for the equatorial Pacific as a function of longitude and time. Note the exceptional lack of model drift, and the evidence for variability on El Niño time scales.

phase; these features are far less prominent during the warm phase. The oceanic processes responsible for these changes are strikingly different on seasonal and interannual time scales. Interannually, a horizontal redistribution of upper ocean waters across the entire tropical Pacific basin is primarily responsible for the SST changes. Studies with a realistic oceanic GCM forced with climatological winds indicate that seasonal SST changes are controlled primarily by local processes: variations in upwelling and in the heat flux across the ocean surface. Of critical importance are the time-mean winds and heat fluxes. The fluctuating winds and heat fluxes have supplementary roles: both induce lower SSTs during the northern summer, higher SSTs late in the northern winter. The implication for coupled GCMs is that the demands on the atmospheric component are different on seasonal and interannual time scales. Interannually, the atmospheric models need only reproduce realistic winds; seasonally, both the winds and heat fluxes need to be accurate.

Paleoclimatic studies of the last interglacial period, some 9000 years ago, indicate that enhanced monsoons were associated with much stronger surface winds over the tropical Atlantic and Indian Oceans. Modeling studies up to now assumed that sea surface temperatures were unchanged, so that the wind changes could be calculated with an atmospheric model. The problem, in reality, is a coupled ocean-atmosphere one in which SST changes affect the winds and vice versa. Before attempting studies with a coupled model, an oceanic GCM is being forced with the winds from one of the atmospheric models used to simulate conditions 9000 years ago - data provided by Prof. Kutzbach. The goal is to determine the extent to which tropical SSTs would have changed in response to such winds.

In these oceanic response studies, the basic thermal structure of the ocean is specified and is assumed to be the same today as in the past. What determines that structure? It is unlikely that the mean state in the tropics is determined locally; it probably depends on conditions in high latitudes. The relation between the tropics and extratropics is being explored. To this end, an oceanic GCM for a sector ocean that extends from 60°N to 60°S is being forced in a variety of ways, with the forcing sometimes confined to high latitudes, sometimes to low latitudes.

PLANS FY93

Studies of the relation between tropical and extratropical conditions will continue, as will an investigation of oceanic conditions in the tropical Atlantic 9000 years ago. In addition, the oceanic structure of El Niño type events in the Atlantic will be studied. In the Pacific, such events are symmetrical about the equator (as far as thermocline displacements are concerned), but in the much smaller Atlantic, the continents are important and the equator is no longer a special line. The horizontal redistribution of warm surface water is far more complex than in the Pacific and needs to be documented.

4.3 WORLD OCEAN STUDIES

4.3.1 Water Masses and Carbon Cycle

B. Samuels *J.R. Toggweiler*

Activities FY92

Oceanographers generally assume that the ocean overturns because the input of buoyancy (warming) in low latitudes and the removal of buoyancy (cooling and salinification) in high latitudes allows dense high latitude water to sink and flow equatorward along the bottom. Mixing or stirring processes are thought to diffuse heat downward in low latitudes, warming the cold deep water in the interior and making it less dense. The idea that the ocean works this way is strongly ingrained in oceanographic thinking, but there are major problems with this point of view. In particular, the amount of diffusion needed to warm the ocean's deep water seems excessive. Recent work at GFDL suggests that the ocean's large-scale overturning might best be viewed in a different way. The large-scale overturning may actually be in large part a wind-driven circulation forced by the strong westerlies in the circumpolar belt of the Southern Hemisphere (qh, qt).

This idea rests on the constraint that north-south geostrophic flows in the latitude band containing Drake Passage must be deeper than the tops of the deep submarine ridges which span this latitude band. This constraint applies in a region where strong westerly winds drive a northward surface drift of some 20×10^6 m^3 s^{-1}. There must be a poleward flow somewhere below the surface to balance the wind drift. The Gill and Bryan constraint requires that the poleward flow is below 1000-2000 m. Thus, the circumpolar winds, in forcing circumpolar surface waters northward, essentially "pull" mid depth water poleward from the rest of the ocean. In this view, virtually all the upwelling of deep water occurs around Antarctica, where the upwelling is clearly wind-driven.

Conventional thinking attributes the production and outflow of North Atlantic Deep Water (NADW) in the Atlantic Ocean entirely to cooling and salinification in the high latitudes of the North Atlantic. While these processes certainly make it possible for NADW to form, they may not, by themselves, cause large quantities of NADW to flow out of the Atlantic basin. Model simulations (qh) show (see Fig. 4.2) that there is a tendency for the outflow of NADW to scale with the wind stress in the circumpolar belt. Thus the formation of dense water in the North Atlantic, instead of being the critical process in a purely thermohaline circulation, may actually be part of a quasi-mechanical closure linking the wind drift and deep poleward flow in the circumpolar belt. If this is true, many important climate problems related to the formation of NADW,

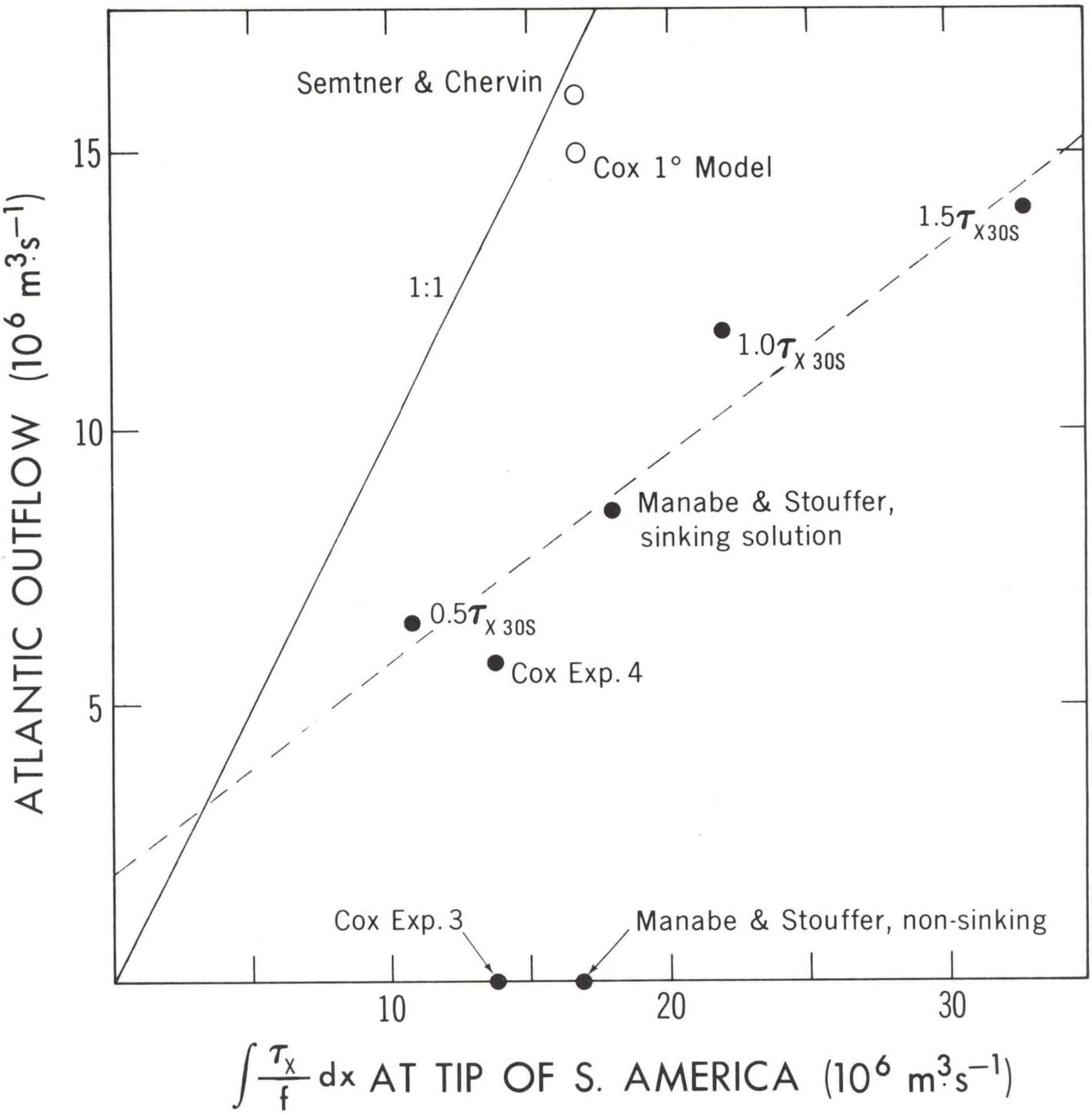

Fig. 4.2 The outflow of deep water from the Atlantic basin as a function of the zonally integrated wind drift at the latitude of the tip of South America. Boundary conditions in each model provide for similar amounts of cooling and salinification in the North Atlantic, yet the magnitude of Atlantic outflow is most strongly correlated with the strength of the circumpolar wind stress. An extrapolation to zero winds suggests that the Atlantic outflow would be nearly zero without the wind effect. The solid dots represent results from low-resolution ocean models. The open circles represent results from two high-resolution models. A given amount of wind forcing appears to produce a stronger outflow in higher resolution models.

such as the synchroneity of ice age climate changes in both hemispheres, may have to be looked at in a whole new light.

PLANS FY93

The hypothetical relationship between circumpolar wind stress and the outflow of deep water from the Atlantic, Indian, and Pacific basins needs to be explored in a higher resolution model where the bottom topography is better resolved and the level of friction in the circumpolar current is substantially reduced. A series of sensitivity experiments are planned for the ocean group's 2° World Ocean model. A new 1° model will also be set up to carry these tests one step further.

4.3.2 CFC Studies

K. Bryan *K. Dixon*

ACTIVITIES FY92

Multidecadal simulations of the global ocean circulation using coarse resolution versions of the GFDL Modular Ocean Model were run and analyzed during FY92. These models have approximately 4° resolution in the latitudinal and longitudinal directions and twelve vertical levels. Standard water mass analyses were augmented by simulations of oceanic tracers: chlorofluorocarbons (CFCs), carbon tetrachloride, and idealized age tracers. Collaborations with researchers at the Pacific Marine Environmental Laboratory (PMEL) and the University of Washington continued, providing additional observed tracer data sets for comparison with model results.

Tracer analyses suggest that the coarse resolution ocean models tend to form North Atlantic Deep Water that is not as dense and moves southward more slowly than observed. Observationalists often use a water parcel's CFC-11/CFC-12 ratio as an indicator of a water parcel's "age", or the time that has elapsed since being ventilated at the sea surface. Estimating a water parcel's "age" using the CFC ratio method can be biased by mixing of water parcels having different CFC ratios. The relatively large amount of numerical diffusion required for numerical stability in the coarse resolution ocean model simulations cause CFC ratio ages to significantly differ from the idealized age to the tracer age. This bias should be reduced in higher resolution models characterized by smaller numerical diffusion and stronger currents.

PLANS FY93

A global ocean model having ~2° horizontal resolution and approximately 20 vertical levels will be developed and tested. This model configuration will be used for both ocean-only and coupled atmosphere-ocean climate simulations. During the development process, questions concerning the roles of mixing parameterizations, the Mediterranean Sea, and sea-ice will be addressed. Collaborations with PMEL/NOAA and the University of Washington will continue.

4.3.3 Retrospective Calculations and Water Mass Properties and Sea Level Rise

K. Bryan *K. Dixon*

Activities FY92

Sea surface temperature data sets extend over a century. To seek some understanding of the relationship of sea surface temperature changes and subsurface temperature change, calculations have been carried out with the GFDL global model. The historical sea surface temperature data have been applied at the upper surface of the model and anomalies allowed to penetrate the ocean by advection and diffusion. The ocean circulation varies with season but otherwise is constrained to remain in a nearly steady state. Generally rising temperatures at the ocean surface over most of the early part of the century cause a net warming of the entire volume of the ocean of 0.1°C.

Repeat hydrographic sections have been made in the North Atlantic that allow a verification of the model predictions with data. Fig. 4.3 shows the change predicted at 24°N between 1960 and 1980. Both the retrospective model and observations show cooling in the upper ocean associated with the cooling of the entire Northern Hemisphere in the 1960's and 1970's. On the other hand, warming is indicated at deeper levels, reflecting the longer term rise in Northern Hemisphere temperatures since the beginning of the century.

PLANS FY93

The retrospective calculations using historical SST will be extended using high resolution models and analyzed in more detail to establish relationships between local heat input to the ocean and global sea level rise.

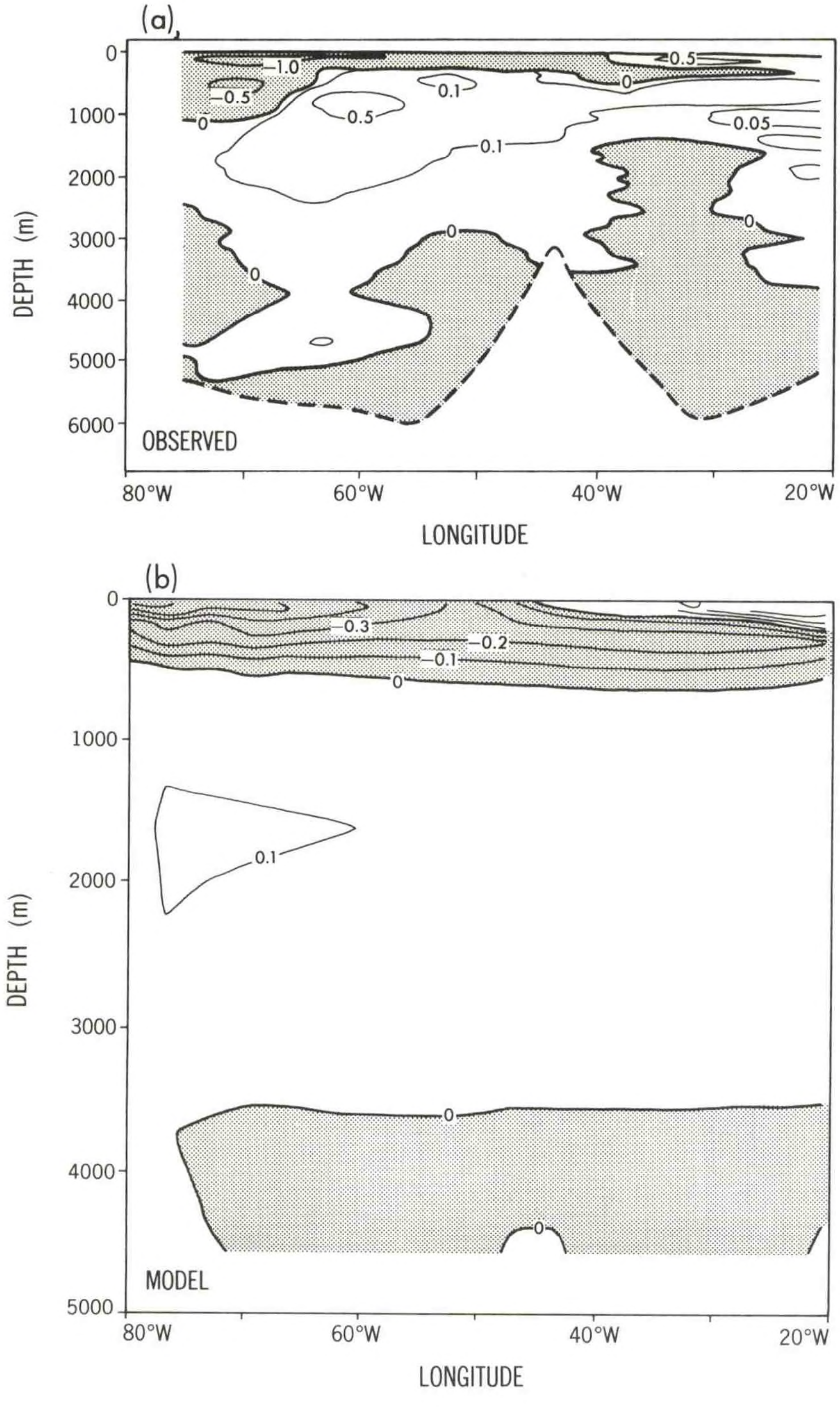

Fig. 4.3 Results from a retrospective study of the World Ocean using historical SST data. Predicted temperature changes from 1960 to 1980 in a vertical section at 24°N in the North Atlantic. (a) Observed by Roemmich and Wunsch (Nature, 307, 447-450, 1984). (b) Predicted by the GFDL ocean climate model.

4.3.4 Model Development

K. Bryan *A. Rosati*
W. Hurlin *D. Stephenson*
R. Pacanowski

ACTIVITIES FY92

Collaboration with the CHAMMP program at Los Alamos has led to an alternative method for solving the barotropic equations in the ocean model. Instead of solving an elliptic equation for the stream function, an elliptic equation is solved for the surface pressure. One motivation is to provide more efficient means of solution on massively parallel computers. The surface pressure method has two additional advantages over the stream function method: an unlimited number of islands can be handled without added computational cost and the convergence properties are unaffected by steep bottom topographic gradients. An energetically consistent free surface configuration is also being tested. Apart from offering more efficient solutions, these methods will facilitate assimilation of satellite surface elevation information into the ocean model. It is hoped, although as of yet unknown, that the speed advantage of these new methods will be retained on serial and vector computer architectures.

A study of the electro-magnetic field generated by the ocean circulation has been completed (rg).

PLANS FY93

A new model will be set up to study the coupling between the Arctic Ocean and the North Atlantic which can be extended to high resolution. Close collaboration with Los Alamos will continue.

4.4 GULF STREAM MODELING AND DATA ASSIMILATION

T. Ezer *G.L. Mellor*
R.K. McCarthy

ACTIVITIES FY92

The Princeton Ocean Model is a 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. During FY92, the model has been used in several studies of the Gulf Stream system as part of the Data Assimilation and Model Evaluation Experiments (DAMEE), a project supported and organized by the Institute for Naval Oceanography. Work on data assimilation, begun in FY91 (1092), has continued with the development of data assimilation schemes to combine satellite derived altimetry and SST data in a nowcast/forecast system (1093). The Princeton model shows a forecast skill (better than persistence) for at least a 2-week period (sa) using the U.S. Navy's analysis fields for initialization and comparison. Another study evaluated the usefulness of GEOSAT altimetry and SST data for assimilation in the Gulf Stream region by comparing the sea surface height fields derived from the two data sources (sb). Other studies focused on improvement of the model climatology and variability compared to observations and the understanding of scientific problems such as the effect of atmospheric forcing on Gulf Stream separation (sa), the effect of the Gulf Stream on the flow over the continental shelf (rz), and the interaction of the Gulf Stream with the New England Seamounts Chain (sc).

A study of Lagrangian particle trajectories is in progress and should be completed in FY92. The simulated trajectories will be compared with drifters released at the 106 mile dump site located off the New Jersey coast.

PLANS FY93

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. The feasibility of extending the data assimilation scheme to the entire North Atlantic Ocean and of modeling coastal sea level variability associated with ocean circulation and climatic changes will be evaluated.

4.5 CARBON SYSTEM

4.5.1 Anthropogenic CO_2 Budget

J. Olszewski *J.L. Sarmiento*
J. Orr *U. Siegenthaler**
P. Rayner *E. Sundquist***

* *University of Bern, Bern, Switzerland*
***U.S. Geological Survey, Woods Hole*

ACTIVITIES FY92

The extent of future global warming will largely be determined by the increase in atmospheric CO_2 content. The ocean's capacity to take up anthropogenic CO_2 has been estimated with a 3-D ocean general circulation model (1084). The uptake estimate for the 1980 to 1989 decade (1.9 GtC/yr) is in excellent agreement with other models, but significantly larger than the Tans et al. (1990)[1] estimate of 0.3 to 0.8 GtC/yr, based on observations and an atmospheric model. The discrepancy has been explained as arising primarily from the fact that Tans et al. ignored the substantial net flux of carbon into the ocean by rivers (1086). The major processes affecting the anthropogenic CO_2 budget and the sources of uncertainty in this budget were summarized in two published articles (1085, 1088).

An important by-product of atmospheric models, such as that used by Tans et al., is that they provide specific constraints on the spatial distribution of the air-sea CO_2 flux. An inversion study has been performed using a three-dimensional tracer transport model developed by the Middle Atmosphere Dynamics and Chemistry group. Preliminary results show substantially less transport of CO_2 out of the tropical ocean and into the Southern Hemisphere ocean than predicted by previous models.

PLANS FY93

The atmospheric CO_2 inversion study will be completed.

A set of simulations of oceanic anthropogenic CO_2 uptake will be carried out using a new ocean carbon system model that is being developed with a more realistic representation of the biological and solubility pumps than used for previous studies (see 4.5.2).

A project will be initiated in collaboration with the Climate Dynamics group to calculate oceanic uptake of anthropogenic CO_2 in coupled air-sea models of the climate response to increased atmospheric CO_2.

4.5.2 Perturbation Models

J. Orr *J.L. Sarmiento*

ACTIVITIES FY92

The study of the potential response of atmospheric CO_2 to perturbations in the ocean carbon cycle, such as those that might result from enhancing new production by iron fertilization of the high latitude Southern Ocean, was completed (1048, 1087). The iron fertilization scenario could potentially have a significant impact on atmospheric CO_2, but the extreme conditions required to achieve a large impact would be difficult, if not impossible, to satisfy. The same model was used to show that the potential of growth of marine macroalgae as a sink for CO_2 is minor (1090).

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1. Tans, P.P., I.Y. Fung, and T. Takahashi, 1990: Observational constraints on the global atmospheric CO_2 budget. Science, 247, 1431-1438.

PLANS FY93

The implications of the iron fertilization scenario for the reduction of CO_2 during the last ice age will be examined.

4.5.3 Models of Photosynthesis

R. Armstrong	*J.L. Sarmiento*
S. Carson	*R. Slater*
*M. Fasham**	*J.R. Toggweiler*

**Institute of Ocean Sciences, Wormley, UK*

ACTIVITIES FY92

Photosynthesis uptake plays a major role in determining the distribution of carbon in the ocean. Work is being done on the development of models that would enable the prediction of how photosynthesis uptake might respond to changes in ocean circulation and climate, including shorter term fluctuations such as El Niño. An analysis of the ecosystem model of nitrogen cycling in the North Atlantic has recently been completed (rw, rx). This model can predict many of the observed features of the nutrient and chlorophyll distributions. Further work is being done on the biological model, with the aim of changing it to meet more directly and understandably the requirements of global carbon cycle modeling. Achieving this goal will require both that the structure of the model be simplified and that its predictive power be increased. Work is being done towards this goal (1) by identifying critical processes and parameters and eliminating those that are not necessary, and (2) by adding structures that will enable geographical variability in critical parameters to be generated automatically through biologically sound mechanisms. A first version of a carbon-nitrogen ecosystem model has been developed and also run in the North Atlantic.

The ecosystem nitrogen cycling model has also been run in a global equatorial ocean circulation model.

PLANS FY93

Results of the tropical Pacific portion of the global equatorial ecosystem model will be analyzed and the impact of El Niño will be simulated.

The nitrogen ecosystem model will be put into a 2.5 level mixed-layer circulation model of the Indian Ocean, developed by Jay McCreary of Nova University.

A slightly modified version of the carbon-nitrogen model will be put in a global circulation model and used to examine the role of the biology in the CO_2 budget.

Efforts to improve the ecosystem model will continue.

A new effort is being undertaken to examine the feasibility of assimilating satellite ocean color observations into the ecosystem model as a technique for using such data to obtain information on carbon fluxes in the ocean.

4.5.4 Models of Remineralization

L. Anderson	*J.L. Sarmiento*
R.M. Key	*J.R. Toggweiler*
R. Murnane	*T. Tromp*

ACTIVITIES FY92

Previous work showed that most of the carbon removed by photosynthesis in the surface ocean is remineralized in the deep ocean or sediments (1069, 1089, ru). A one-dimensional coupled atmosphere-ocean-sediment model was used to investigate the interaction effects of the carbon system. A new set of simulations of the biological and chemical cycling of carbon throughout the water column were initiated with a model of carbon's solubility pump. The solubility pump is one of three "pumps" that transfer carbon from the surface to deep ocean. The solubility pump is driven by the increase in the solubility of CO_2 in cold water. The other two pumps are the biological pump, which is driven by organic carbon cycling, and the carbonate pump, which is driven by calcium carbonate cycling. Their combined effects result in dissolved carbon concentrations increasing with depth in the ocean. This work should provide data on the relative importance of these three processes in the ocean. The model of the solubility pump explicitly includes total carbon and the ^{13}C isotope, gas exchange, the carbonate species H_2CO_3, HCO_3-, and CO_3=, as well as the contributions to total alkalinity of dissolved silica, phosphate, water, and borate species. An analysis of these results is underway.

The utility of using inverse techniques to estimate particle cycling rate constant has been demonstrated with data sets from the North Pacific and Northwest Atlantic. A reanalysis of thorium data from Station P in the North Pacific provided realistic estimates of the concentration of sinking particles and of the magnitude of particle cycling rate constants (re). A compilation of the thorium and particle data from the Nares Abyssal Plain in the Northwest Atlantic was used to determine particle cycling rate constants throughout the water column (rv). Estimated particle cycling rates are similar at the two locations, however there is a large uncertainty associated with the estimates. The analyses suggest that precise estimates of particle cycling rates require measurements of the time-dependent changes in the activity of different thorium isotopes and in the concentration of particulate matter.

PLANS FY93

Simulations that incorporate the oceanic cycling of organic carbon and calcium carbonate will be completed. In addition, the effects of silica-secreting organisms should be included. These results should provide an estimate of surface ocean pCO_2, which can be used as an initial condition for simulations of anthropogenic CO_2 uptake.

An inversion of ^{234}Th, ^{228}Th, nitrogen, and carbon data from the Joint Global Ocean Flux Study (JGOFS) North Atlantic Bloom Experiment (NABE) will be attempted. This data set provides estimates of the change with time of the activity of thorium isotopes and concentration of nitrogen and carbon. This data should help to provide more precise estimates of carbon and particle cycling rate constants.

The ongoing reanalysis of oceanic nutrient observations, in order to obtain new estimates of Redfield ratios, will be completed.

4.5.5 Measurements

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

ACTIVITIES FY92

A new carbon system measurement program was established this year to support the World Ocean Circulation Experiment/Hydrographic Program (WOCE/HP) by providing high precision carbon system measurements on their cruises. The marine carbon system is still not completely understood today. These measurements will help to evaluate the marine carbon cycle and will be used to constrain the ocean carbon models which have been developed over the past several years. Recent results of this modeling research have clearly convinced us of the importance and value of ocean measurements in constraining the oceanic sink for anthropogenic CO_2. Equipment has been purchased to make continuous at-sea measurements of mixed layer and atmospheric boundary layer pCO_2 values. This instrument is expected to be running in time for our first WOCE/HP cruise to the southern Pacific Ocean in October of this year.

PLANS FY93

Instruments will be constructed to measure total CO_2 and titration alkalinity. Two cruises are planned for the far western and northeastern Pacific.

4.6 NITROUS OXIDE

J. Orr *P. Suntharalingam*
J.L. Sarmiento

ACTIVITIES FY92

Nitrous oxide is an important greenhouse gas whose concentration has been increasing with time. The ocean appears to be a major source to the atmosphere. It has been shown that the impact of the Southern Ocean iron fertilization scenario on atmospheric nitrous oxide levels is potentially quite large, increasing the flux by an order of 2.6 (0.1 to 15.4) TgN yr^{-1}, compared to the present flux of 1.4 to 2.6 TgN yr^{-1}.

PLANS FY93

A new project to develop models of the present oceanic nitrous oxide cycle is being undertaken.

4.7 OCEAN CIRCULATION TRACERS

H. Figueroa *J.L. Sarmiento*
R.M. Key *J.R. Toggweiler*
G. MacDonald *T. Tromp*
J. Orr *V. Webb*
R. Rotter *L. Yuan*

ACTIVITIES FY92

4.7.1 Thermohaline Ventilation

The physical processes responsible for the subduction of thermocline waters in the North Atlantic are being investigated. This effort combines the use of numerical modeling of passive tracers with very different delivery patterns, with observations of radium-228 collected by Princeton's Ocean Tracers Laboratory (OTL), as well as other tracers collected as part of the North and Tropical Atlantic Transient Tracers in the Oceans (TTO) experiment and South Atlantic Ventilation Experiment (SAVE).

4.7.2 ^{228}Ra

Final processing of ^{228}Ra samples collected by the Ocean Tracers Laboratory during the North Atlantic TTO is nearly complete. A data report for the Western Boundary Exchange experiment carried out in the same region was completed and distributed. Initial processing of the few remaining samples collected during SAVE will be completed this summer. It is expected that all of the remaining Atlantic samples will have been completed by the end of 1993. Interpretation of these results is now underway, including both classical methods as well as the numerical model mentioned previously.

4.7.3 ^{14}C

At the present time, the Ocean Tracers Laboratory is the primary laboratory for collection and interpretation of ^{14}C in the U.S. Pacific World Ocean Circulation Experiment. During FY92, members of the laboratory participated in 7 sampling cruises, mostly in mid-latitude eastern Pacific waters. Both large volume beta counting and small volume accelerator mass spectrometry are being used to analyze the samples. Modeling and interpretation of existing data sets continues with the use of the GFDL 2° resolution global model. Work has been aimed at better understanding the formation of Circumpolar Deep Water. A combination of ^{14}C and salinity as tracers appears to be more useful than salinity and temperature in deciphering the formation mode for this water mass. At this point, the interpretation is still hampered by the very sparse data set.

PLANS FY93

The North Atlantic thermocline ventilation studies will be continued with the possibility of extending the analysis of the South Atlantic, particularly to the region of the Agulhas retroflection and southwestern Atlantic.

The Ocean Tracers Laboratory will continue to participate in the WOCE program. Approximately 300 days of sea time are currently scheduled for FY93. These cruises will sample the southeastern quadrant of the Pacific, the far northeast Pacific, and the far western Pacific. Very little or no ^{14}C data currently exists in these areas. Plans are currently underway to extend the WOCE program into the Indian Ocean. OTL is participating in these planning sessions. If current plans hold up, OTL will be responsible for ^{14}C and ^{228}Ra in the Indian Ocean program. 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. Lanzante *A. Raval*
C. Lindberg *M. Rosenstein*
A.H. Oort

ACTIVITIES FY92

5.1.1 Processing of Upper-Air Data

A major effort was devoted to writing, testing and performing production runs using a new program which decodes "raw rawinsonde" observations in the NMC format. About 110 magnetic tapes were decoded creating a data set (U, V, T, Q and Z) of about 10 GB which spans approximately the last 20 years.

As a preliminary step in deriving new climatological data limits (used in quality checking of the radiosonde data) a pilot study involving January and July specific humidity data from 64 selected stations was conducted. Goodness of fit of the Normal and Gamma distributions was tested. It was found that the Gamma distribution was better than the Normal for many locations/levels; interesting bi-modal behavior was found in some regions.

The feasibility of keypunching a unique, early period (~1920-1950's) pilot balloon data set available from the National Climate Data Center (NCDC) on microfilm was investigated. A scheme was devised and tested on several years of data for a single station. This process proved to be very time consuming and tedious. In addition, efforts aimed at automatic entry (optical scanning) also proved impractical given the current technology. As a result, pursuit of this project was suspended indefinitely.

The TD54 data set which was created by the U.S. Air Force and includes early (~ mid 1940's-early 1960's) radiosonde observations was acquired on magnetic tape from NCAR. This data set is being examined to extend the global atmospheric circulation statistics analyses (599) back to the late 1940's in order to generate a 45-year homogeneous set of analyses. For the first 10 years the analyses will have to be limited to the Northern Hemisphere because of the scarcity of Southern Hemisphere soundings before about 1958. The daily data will also be prepared in a collaborative effort with Roy Jenne for possible use in the NMC/NCAR re-analysis project. A look at a preliminary inventory indicates that TD54 may be able to fill in gaps in the existing NCAR archive for data sparse regions prior to 1958. A program to interpret the "over punches" which exist in this data set and to perform the first step of re-organization/checking has been written and is starting to be applied.

5.1.2 Data Requests

Requests for subsets of monthly Global Atmospheric Circulation Statistics and ocean surface statistics based on COADS for the 1958-1988 period continue to come in and are, if feasible, fulfilled at the rate of one to two requests a month. The basic monthly grid point fields were all analyzed in the Observational Studies Project at GFDL during the last 10 to 20 years.

5.1.3 Data and Software for Public Use

The World WeatherDisc, a compact disc with about 600 MB of meteorological and climatological data was acquired for users at GFDL. For convenience, the data set was copied to the Cray. Software to perform cluster analysis, a statistical technique aimed at objectively grouping similar structures, was also acquired and copied for public access. Memos and documentation announcing and detailing these acquisitions were prepared and distributed.

PLANS FY93

Revision of the code for processing and analyzing radiosonde data will continue. The recent (~ last 20 years) radiosonde data will be re-organized and used to derive new climatological limits for quality checking. The TD54 data for the 1946-1963 period will be re-organized and decoded, and quality checking/data assessment will begin. These data, in addition to the regular NCAR archived station data, will be used to extend the upper air analyses back to the late 1940's.

5.2 CLIMATE OF THE ATMOSPHERE

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

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

ACTIVITIES FY92

5.2.1 Atmospheric Temperature and Humidity Variations

The GFDL temperature analyses for the 1958-1989 period (pt) have been adopted as the basic reference data for the observed tropospheric and lower stratospheric temperature trends in the "Climate Change 1992" Supplementary Report to the IPCC Scientific Assessment.

A significant diurnal variation in the hemispheric mean atmospheric temperature below 850 mb was discovered. The 1000 mb temperatures at 12 GMT, when the Eurasian continent is the warmest, were found to be about 0.7°C warmer than at 00 GMT in the Northern Hemisphere and 0.2°C in the Southern Hemisphere. These differences tend to become small between 850 and 200 mb. However, large differences on the order of 0.3°C in the Northern and 0.8°C in the Southern Hemisphere were found in the lower stratosphere at 100 and 50 mb, but they are probably not real and due to instrumental problems (pt).

Preliminary estimates of the specific humidity trends from the 1958-1989 statistics tend to show a global mean increase at and below 700 mb and a slow decrease at 500 and 300 mb. The strongest increases are found in the tropics in agreement with a recently published work by W.P. Elliott and J.D. Gaffen[1] at the Atmospheric Research Laboratory (ARL). The just completed analyses of relative humidity (only available from 1973 on) tend to show little or no global change below 700 mb, but substantial decreases at and above 700 mb. Since very little information on relative humidity can be found in the existing literature, an extensive joint study of both the climatological distribution of relative humidity and its temporal and spatial variability is underway with Prof. José P. Peixoto of the University of Lisbon.

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1. Elliot, W.P, and J.D. Gaffen, 1991: On the utility of radiosonde humidity archives for climate studies. Bull. Am. Meteorol. Soc., 72, 1507-1520.

Techniques for detecting volcanic and inhomogeneity effects in temperature records are being developed in cooperation with Reena Freedman of Bryn Mawr. A better understanding of these effects will allow temperature data to be corrected, and to be of more use in global change studies.

5.2.2 Trends in Atmospheric Variability

In cooperation with Dr. J. Angell of ARL, a joint study is underway to describe and better understand the apparent increase in spatial variability of temperature and geopotential height during the last 31 years. Such an increase was noted earlier by Dr. Angell in his 63 station analyses and has been confirmed in the GFDL "~700 station" analyses.

5.2.3 Model Simulation of the Climatological March of the Asian Summer Monsoon

In association with the collaborative model diagnosis effort between GFDL and various NOAA and university research groups (see also Section 3.1), a 40-year integration of a rhomboidal 30-wave number, 9-level GCM has been completed. A comprehensive study on various climatological features associated with the Asian summer monsoon appearing in this model run has been conducted in a joint study with A.-K. Lau. It is demonstrated that the simulated monsoon circulation typically evolves through several distinct stages. Particularly noteworthy in the early phase of the monsoon season (May to early June) are the rather abrupt northward displacement of the westerly jet stream over the Tibetan Plateau, the formation of the "Mei-Yu" (or Plum Rain) rainband over the East China Sea and Sea of Japan, the arrival of copious rains over the Bay of Bengal and the Indo-Chinese Peninsula, and the subsequent onset of the wet season over the Indian Subcontinent. As the summer monsoon enters the mature phase during June and July, the subtropical high pressure zone over the western Pacific migrates steadily northward, an extensive area of low-level flow convergence and convective precipitation appears over the near-equatorial western Pacific, and the upper level circulation over South Asia is dominated by the anticyclone over the Tibetan Plateau. Analysis of heat and moisture budgets over the Asian monsoon region indicates that the summertime heating is dominated by the latent heat release associated with moist convection in the model atmosphere.

Some of the above model features have been compared with those appearing in the real atmosphere, as documented in earlier studies (1005, 1008, 1019, qq). The simulated monsoon features tend to occur earlier in the calendar year than their observed counterparts, thereby prolonging the monsoon season in the model atmosphere by about one month. The simulated monsoon westerlies over the Bay of Bengal are too strong. The conditions over India in the model atmosphere are too dry, partly as a result of the inadequate resolution of the local orography, and partly due to the lack of westward traveling monsoon depressions over the Bay of Bengal. The excessive precipitation over Tibet may be related to difficulties in applying the moist convective adjustment procedure in regions of steep terrain, especially within the present spectral model framework.

5.2.4 Differences Between Model Climatologies for the Spring and Autumn Seasons

Various springtime and autumntime climatological features appearing in the 40-year integration of the GCM described in Section 5.2.3 have been documented in detail. Special emphasis was placed on those phenomena which exhibit notable differences during these two transition seasons. Of particular interest are the near-surface circulation and precipitation patterns in the vicinity of the upwelling regions in the tropical eastern Pacific and Atlantic Oceans, as well as the planetary-scale circulation at various tropospheric levels in the extratropical Northern Hemisphere. It is demonstrated that the cross-equatorial surface flow and the intertropical convergence zone over the tropical oceans during the boreal autumn are much more developed than the corresponding features during spring. This spring-autumn asymmetry is apparently associated with the appearance of a distinct "cold tongue" of ocean water in the equatorial Pacific and Atlantic during the northern autumn. The differences between the Northern Hemisphere extratropical geopotential height field for the two transition seasons are characterized by strong ocean-continent contrasts in the lower troposphere, and by a pattern with a considerable degree of zonal symmetry in the upper levels. The jet streams in spring tend to reside at lower latitudes than in autumn. The above model results are in broad agreement with those reported in the observational literature. These findings suggest that the spring-autumn differences detected in the middle and higher latitudes may be linked to differences in the latent heating in the deep tropics during these two seasons. Linear modeling techniques (778, 863, 904, 985, 1018) with different combinations of forcing terms might be helpful in testing the latter hypothesis.

5.2.5 Greenhouse Effect

The cooperative work with Prof. David Karoly, Monash University, on the detection of the CO_2 signal in the upper air data is continuing; it shows some agreement with model simulations (se). The influence of water vapor is also being investigated in joint work with Dr. James Hansen of NASA, and Prof. Peixoto.

Using radiosonde measurements and records of atmospheric carbon dioxide, the relationships between variations of atmospheric temperature, water vapor and CO_2 as functions of geographic location and temporal scale have been investigated. Estimates of coherence, feedback parameters and phase relationships were made. It was found that as much as 96% of the variance in temperature at some time scales can be accounted for by a simple linear combination of CO_2 and water vapor signals.

Upper tropospheric and stratospheric temperatures are closely related to ozone densities by both dynamical and radiative processes. With Rebecca Orris, a student at Princeton University, ozone measurements and their relationship to atmospheric temperatures are being investigated. The high frequency broadband variance of the ozone is concentrated in a suite of bands centered on half-integral multiples of the annual frequency. The signal in each of these bands is well described by a single rapidly-varying oscillation amplitude-modulating a sinusoidal variation. This modulation is sufficiently rapid that conventional filters are inadequate to resolve it, but a novel family of filters is being developed to study this effect. Analysis of Kp, a global index of magnetic activity, suggests that this modulation is at least partly due to the flux of solar protons and relativistic electrons in the solar wind. Preliminary analysis of ozone records show that the ozone concentration has an interesting nonstationary behavior.

5.2.6 Publication of Book on Physics of Climate

The book *Physics of Climate*, a joint long-term project with Prof. J.P. Peixoto, was published in early 1992 by the American Institute of Physics (1065). Excellent responses have been received so far, and a second printing is already in progress.

PLANS FY93

Analysis of the relative humidity climatology and its temporal and spatial variability will continue. The significance of observed changes in humidity will be further pursued in connection with the greenhouse warming issue.

Further diagnosis of the temporal evolution of the monsoonal circulation will be performed using both observational and model data, with special emphasis on the processes associated with abrupt atmospheric changes in various stages of the monsoon development.

The mechanisms contributing to the differences in the global atmospheric circulation during the two transition seasons will be examined. The relative importance of various factors (such as tropical air-sea interactions, orographic forcing, stationary and transient eddy transports, and land-sea contrasts in thermal inertia) in accounting for the spring-fall differences will be assessed using a linearized model as well as GCM experiments with altered lower boundary conditions.

The studies of temperature relationships with CO_2 and water vapor will continue. The studies will produce a nonparametric error analysis, regression diagnostics, an estimate of relative lags between temperature, CO_2 and water vapor, both at the surface and in the mid-troposphere, and information about the atmospheric transport times of carbon dioxide.

Time series of fossil fuel combustion and other human activities will be examined and statistical tests of anthropogenic influence on the climate will be constructed.

Diagnostic studies of the possible atmospheric response to changes in the oceanic thermohaline circulation will begin.

For ozone measurements, the study of the nonstationarity with more sophisticated tools and attempt to separate the dynamical effects from the radiative effects will continue. An investigation of the relationship of the upper tropospheric temperatures to other processes, such as variations in atmospheric carbon dioxide and the introduction of volcanic aerosols, is also planned.

5.3 ATMOSPHERIC DYNAMICS

M.W. Crane
*Y. Kushnir**
J. Lanzante
N.-C. Lau
H. Nakamura
M.J. Nath
*M.-F. Ting***

* *Lamont-Doherty Geological Observatory*
***Climate Monitoring and Diagnostics Laboratory/ERL*

ACTIVITIES FY92

5.3.1 Diagnosis of the Interaction Between Synoptic-Scale Disturbances and the Monthly-Averaged Circulation

The forcing of the monthly mean circulation due to vorticity and heat transports by synoptic-scale eddies was studied using the output from a 100-year integration of a rhomboidal 15-wave number GCM (sd). This experiment was carried out as part of the joint NOAA/Universities effort to diagnose regional climate changes using model data. Results based on eddy induced quasi-geostrophic geopotential tendencies indicate that the eddy forcing due to vorticity fluxes acts to reinforce the monthly averaged height anomalies throughout the troposphere. On the other hand, the eddy heat fluxes lead to dissipation of the monthly mean height anomalies in the upper troposphere, and enhancement of the height anomalies in the lower troposphere. The eddy heat fluxes exhibit a notable tendency to destroy the concurrent local monthly mean temperature anomalies. The above relationships based on model data are in agreement with the corresponding observational results (889, 1063). Concurrent computations using a stationary wave model linearized about the zonally varying GCM climatology confirms that, among the various known forcing mechanisms, the transient eddy vorticity fluxes exert the strongest influences on the monthly mean circulation.

The response to nonlinear effects is negligible, while the forcing due to diabatic heating is weak and acts in opposition to the corresponding GCM patterns in the upper troposphere. These findings suggest that the monthly mean anomalies in this GCM experiment are intimately linked to barotropic interactions between transient fluctuations of different time scales, and between the monthly mean anomalies and the climatological stationary waves.

5.3.2 GCM Comparisons

A comparison between control and increased CO_2 scenarios in several GCM experiments performed by the Climate Dynamics Group is being conducted. The experiments include equilibrium experiments for doubled CO_2 with R15 and R30 resolution for both fixed and variable cloud simulations, as well as a transient experiment (+1% CO_2 increase per year).

Preliminary results involving the eddy component of 200 mb geopotential height over the Northern Hemisphere indicate a different pattern of response during the winter (DJF) and summer (JJA). During DJF, the stationary wave train surrounding North America diminishes in amplitude and, in particular, eddy heights rise near Greenland. During JJA, the response can be characterized as a combination of: 1) wave number one at 40-80°N (with eddy height rises/falls in the Pacific/Europe) and 2) eddy rises/falls over ocean/land in the extratropics of the Northern Hemisphere. The JJA response (Fig. 5.1) is exemplified by the t-statistic based on the difference in 200 mb eddy height (experiment minus control) for the first 100 years of the transient run.

The time histories of the responses in the first 100 years of the transient run prove interesting. During DJF, the response is masked by "climate noise" until the last decade. In contrast, the summer response is much clearer and is apparent after less than 50 years; the progression is much more monotonic during JJA than DJF. This suggests that it may be possible to detect global warming sooner and with more confidence using summer data.

PLANS FY93

The intercomparisons involving the atmospheric circulation in the various increased CO_2 experiments will continue. The analyses will be extended to other vertical levels and to the zonally averaged zonal wind component. The observed data will then be examined in light of the GCM responses.

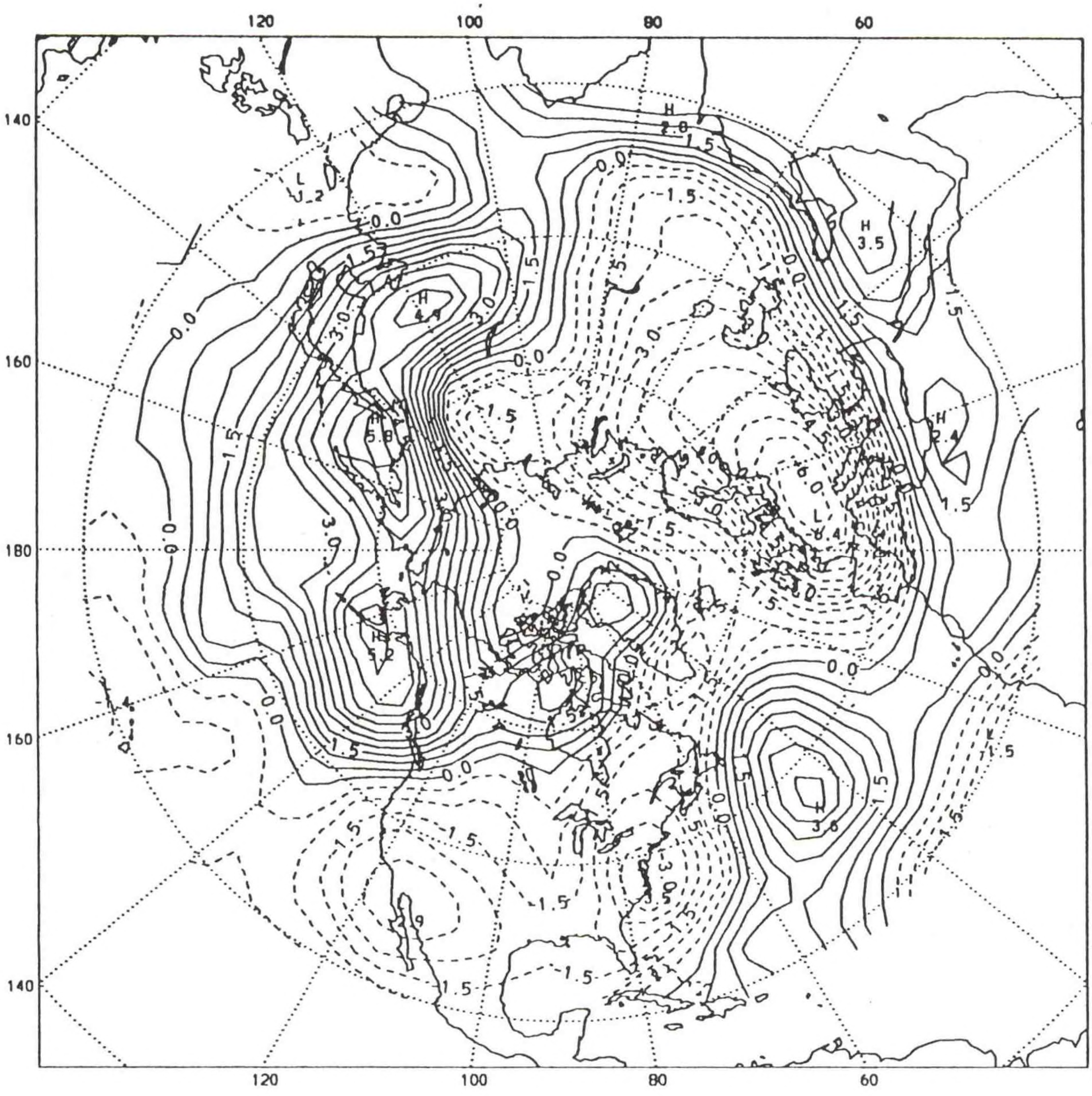

Fig. 5.1 T-statistic (for experiment minus control) based on the summer (JJA) 200 mb eddy geopotential height from the first 100 years of the transient CO_2 GCM simulation conducted by the Climate Dynamics Group. A value of t=2 indicates the 95% confidence limit.

5.4 AIR-SEA INTERACTIONS

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

ACTIVITIES FY92

5.4.1 Nature of Large-Scale Air-Sea Interaction in the Extratropics

The relative importance of various feedback processes associated with extratropical air-sea coupling has been investigated by analyzing the output from a suite of experiments with the same atmospheric GCM. By using different procedures for determining the SST, each of these experiments is designed to incorporate a distinct set of interactive processes. The model runs examined in this context include a 30-year integration in which the atmospheric GCM is coupled to a motionless mixed layer of the ocean; another 30-year integration with the GCM being forced by monthly varying SST anomalies in the North Pacific and North Atlantic as observed during the 1950-79 period; and a 100-year integration in which climatological SST conditions are prescribed at the lower boundary. The mixed-layer experiment facilitates simplified two-way interactions between the atmosphere and ocean through heat exchanges at the air-sea interface. In the experiment with prescribed SST anomalies, the air-sea coupling is restricted to forcing of the atmosphere by the oceanic changes only, whereas the SST variations are not affected by the overlying atmospheric fluctuations. The model run with climatological SST conditions provides for a set of time-varying atmospheric forcing at the ocean surface which could be used to drive a mixed layer. The history tapes from this climatological run could therefore be used to evaluate the impact of atmospheric changes on the ocean, whereas the resulting oceanic changes are not allowed to influence the model atmosphere. Intercomparison of the spatial patterns of covariability between the SST and near-surface atmospheric fields in these three experiments indicates that the dominant modes of air-sea coupling in the extratropics mainly result from the atmosphere driving the ocean, with oceanic forcing of the atmosphere playing a secondary role. This model result is in accord with the findings of recent observational studies.

In collaboration with Y. Kushnir, and as part of the joint NOAA/Universities effort on model diagnosis, several 6000-day experiments with an atmospheric GCM being forced by an idealized, temporally fixed SST anomaly in the North Atlantic have been completed. These integrations were conducted under perpetual January conditions, and are similar in experimental design to that used in an earlier study of the North Pacific (1078). The response of the model atmosphere to the prescribed SST anomaly with different amplitudes (1° and 4°C) and different signs (warm and cold) was examined. Preliminary results indicate that the simulated atmospheric changes do not exhibit a simple relationship with the strength and polarity of the SST forcing. Further investigations are necessary to delineate the apparent nonlinear atmospheric response to extratropical SST changes (see also Section 3.1).

5.4.2 Influences of Surface Conditions of the Global Ocean on Decadal Variability of the Atmosphere

In association with the NOAA/Universities collaborative effort, two experiments with an atmospheric GCM forced by observed month-to-month SST changes in the near-global ocean during the 1950-1988 period have been completed. The two integrations were initiated using distinct sets of atmospheric conditions, and were subjected to the identical sequence of SST forcing. The experimental design is similar to that used in an earlier study (1014). The characteristic extratropical model patterns in the individual runs associated with the global SST changes accompanying El Niño-Southern Oscillation events were identified using singular value decomposition techniques. The variations of the temporal coefficients for these model patterns exhibit secular trends on decadal time scales, and bear some similarity to the low-frequency variation of the occurrence of the Pacific-North American teleconnection pattern in the observed atmosphere. This finding suggests that secular changes of the observed atmospheric circulation during the recent decades could in part be related to influences of the global ocean. A search for the occurrence of the Sahel drought and decadal fluctuations of the North Atlantic climate in the model atmosphere has also been attempted, with less definitive results. The latter efforts were somewhat hampered by the considerable differences in the temporal evolution of the pertinent climate signals appearing in the two model runs. The high level of sampling fluctuations among the two available realizations apparently calls for an increase in the number of runs with a similar design.

5.4.3 Surface Generation of Oceanic Energy

Our data analyses show that global available potential energy is generated at the annual rate of 4 mW m^{-2} mainly through surface heating, whereas the global effects of evaporation minus precipitation tend to be small. The kinetic energy generation by atmospheric wind stress is found to be the largest term, *i.e.*, 6 mW m^{-2}. Progress is made with a complete formulation of the energy cycle in the oceans.

PLANS FY93

Additional model runs will be conducted with an atmospheric GCM forced by observed monthly SST fluctuations during the post-war period in different parts of the World Ocean, so as to discern the sensitivity of various low-frequency atmospheric phenomena to SST conditions at different maritime sites. Multiple runs with the same sequence of SST forcing will also be performed to enhance the statistical significance of the model results.

The processes through which the SST changes are driven by atmospheric circulation anomalies will be investigated using output from an experiment with an atmospheric GCM coupled to an ocean mixed layer, and from future experiments with fully coupled ocean-atmosphere GCMs.

Research on the observed energy cycle in the oceans and comparisons with models will continue.

5.5 SATELLITE DATA

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

ACTIVITIES FY92

5.5.1 ERBE Longwave Analysis

Extensive analyses have been conducted on 3 1/2 years data of the earth's longwave radiation budget from February 1985 through July 1988. Correlations between Outgoing Longwave Radiation (OLR) and SST were calculated using co-variations in the two fields over the course of a year. The OLR-SST correlations were found to be positive in mid-latitudes, but negative in the tropics.

Using a special binning method, the competing effects of SST and atmospheric water vapor on the outgoing flux were investigated. Fig. 5.2 shows that in cold (mid to high latitude) regions, the OLR primarily increases along with the SST, but that in warm (tropical) regions, the OLR drops strongly from dry to moist conditions. Thus, the negative OLR-SST correlations in the tropics are clearly spurious, and arise not by changes in SST, but by the dramatic changes in atmospheric moisture which accompany changes in SST.

5.5.2 Processing and Analysis of ISCCP Data

After extensive evaluation of the information content of the ISCCP C-1 data set, and following consultations with scientists familiar with the actual production of this data set, a detailed data processing and reduction scheme has been designed to retain daily time series for the most useful parameters. Arrangements have also been made to acquire all available ISCCP C-1 data holdings at the Satellite Data Services Division of the National Climate Data Center. The data archiving scheme has been

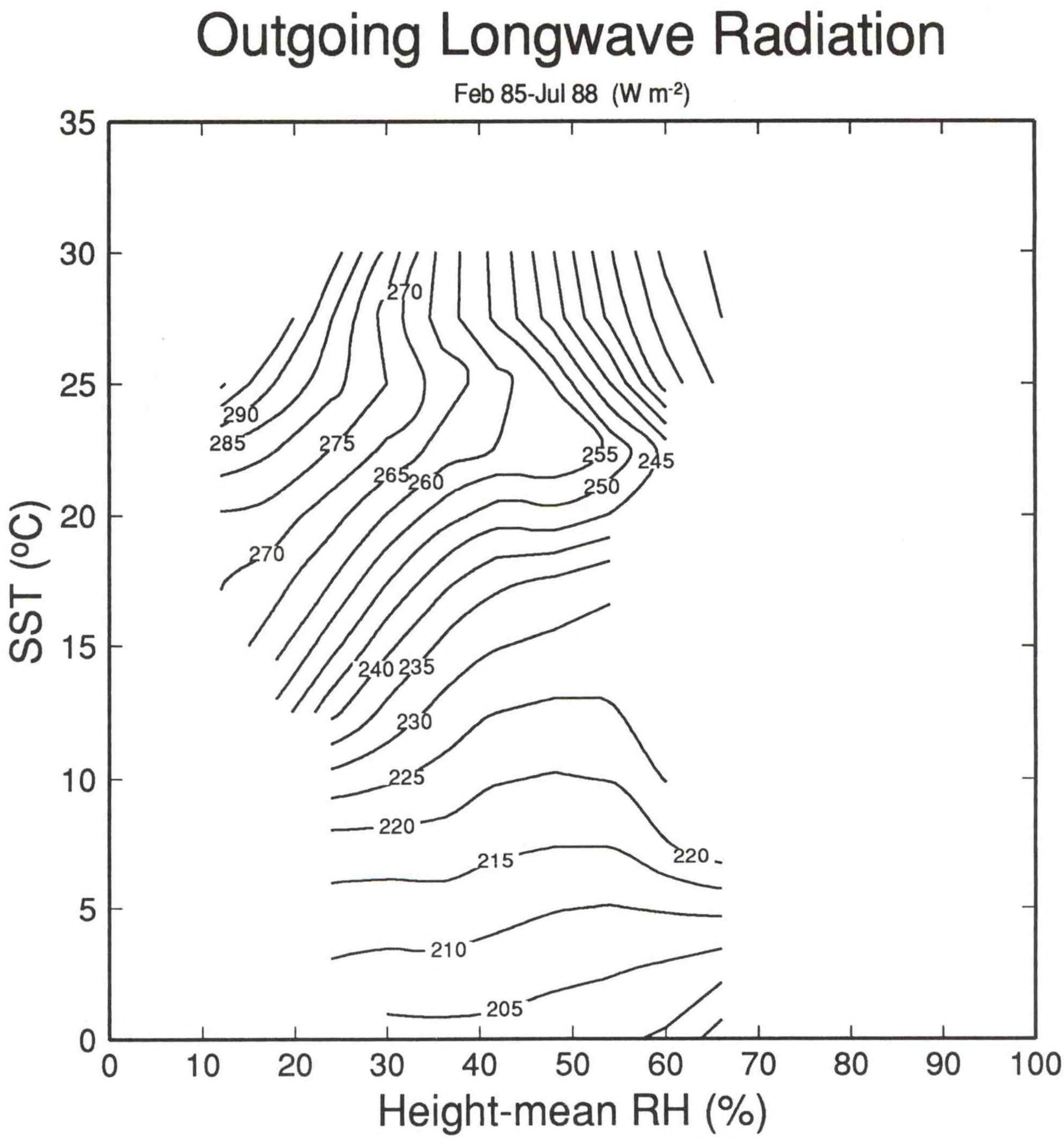

Fig. 5.2 Outgoing Longwave Radiation (OLR) from the Earth Radiation Budget Experiment (ERBE). The OLR is binned simultaneously with respect to two independent climate parameters: the Sea Surface Temperature (SST), and the Height-Mean Relative Humidity (RH). This type of graph separates the competing effects of two different variables on the outgoing flux.

implemented successfully, and processing of all data fields for the period from July 1983 to December 1990 has been completed. The processed data contain a vast amount of information on the day-to-day variations of the global distribution of various cloud types at different altitudes. Also available are satellite-derived mean cloud properties as well as temperature and precipitable water amount distributions on a daily basis. Preliminary computations indicate that the daily fluctuations in the amount of deep convective clouds in some parts of the world exhibit a strong temporal correlation with the local vertical velocity at 500 mb, as inferred independently from the gridded analyses produced by the European Centre for Medium-Range Weather Forecasts. Lagged correlation analysis also reveals that the ISCCP data set provides a realistic description of the temporal and spatial evolution of the cloud distribution in relation to sea level pressure variations in the mid-latitude storm track region (see Fig. 5.3). When analyzed in conjunction with concurrent radiative flux measurements from the ERBE, and with conventional meteorological analyses of the atmospheric circulation, the ISCCP data set will serve as a useful resource for delineating the nature of cloud formation and cloud/radiative forcing associated with different types of circulation systems in the atmosphere. Cloud statistics to be derived from the ISCCP data set will also be helpful in assessing the fidelity of cloud parameterization schemes used in current GCMs.

5.5.3 Satellite Workshop

A successful informal workshop was held on October 3-4, 1991 at GFDL on "Water vapor, clouds, radiative processes and climate; inferences from satellite observations." There were 11 participants and speakers from outside GFDL.

PLANS FY93

The 1985-1988 ERBE archives will be used to study the greenhouse effects due to clouds and, in conjunction with the conventional rawinsonde analyses, to perform in-depth studies of the energy budget of the earth.

The relationships between cloud formation, radiative forcing and various types of meteorological phenomena (such as transitory disturbances in both the tropics and extratropics, and interannual variations associated with El Niño) will be explored using the processed ISCCP and ERBE data sets.

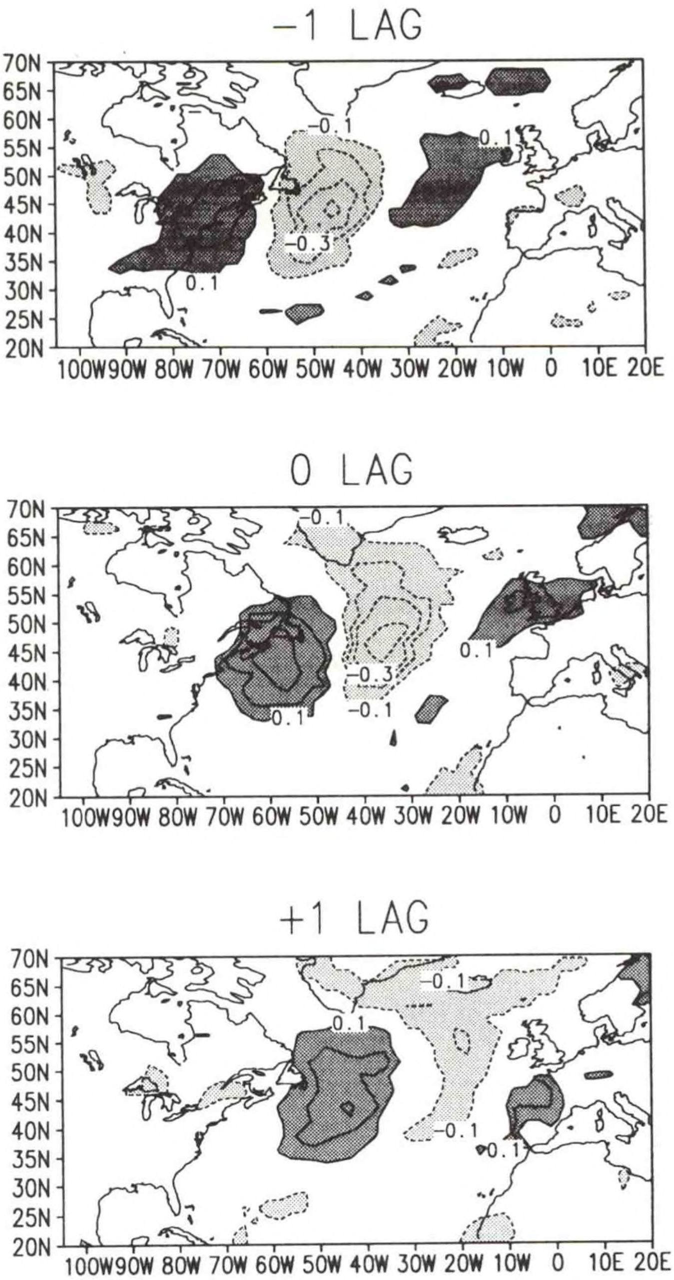

Fig. 5.3 Distribution of the temporal correlation between the sea level pressure fluctuations at 40°N, 45°W (position indicated by a solid dot) and the fraction of cloud cover within the 180-310 mb layer at individual grid points (a) cloud cover leading the pressure by 1 day, (b) cloud cover simultaneous with the pressure, and (c) cloud cover lagging the pressure by 1 day. Contour interval is 0.1. The zero contour has been omitted. Dense and light stippling indicate positive and negative correlations, respectively. Note the wave-like pattern of the cloud cover, and the systematic eastward movement of the individual extrema.

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 FY92

6.1.1 Prediction Experiments using Specified Vortices

An automated GFDL hurricane prediction system has been established by assembling the procedures of data acquisition, model initialization and time integration of the model. In this system a global analysis, global forecasts and a message containing observational data of a tropical cyclone are transferred via Internet from NMC to GFDL (6.5.2). Then, the initialization of GFDL's Multiply-nested Movable Mesh (MMM) hurricane model is achieved by a scheme of vortex specification in which observed wind information supplied by the tropical cyclone message is utilized (rt). The scheme was designed so that a poorly represented tropical cyclone vortex in the global analysis is replaced by a more realistic and model adapted vortex. This initialization method was successfully tested (rs) and is now automated (6.5.1). The hurricane prediction is performed with an improved MMM model (A91/P92) including the Fels-Schwarzkopf radiation scheme, vegetation dependent specification of land surface physical parameters and the prognosis of land surface temperature.

Hurricane prediction using the automated system was tested for seven cases of Atlantic storms including three cases for Hurricane Gloria, 1985, and one each for Gilbert, 1988, Bob, Fabian and Grace during 1991, as well as for a case of Connie off northwestern Australia. Since the specified initial vortices did not undergo initial adjustment and false spin-up, the system produced dramatic improvement in the track forecast, especially in the early period up to 48 hours. Furthermore, the experimental results clearly indicated the feasibility of forecasting the storm intensity. In Fig. 6.1, the mean position error from the present system for seven Atlantic storm cases is compared against that of the operational forecasts by the National Hurricane Center and that of CLIPER (a simple scheme combining climatology and persistence).

The automated prediction system was recently applied to five cases in Eastern Pacific hurricanes in the 1992 season. The results are presently being analyzed.

A joint project with NMC was initiated. The prediction system developed at GFDL is combined with various levels of reanalyses of 14 previous storm cases prepared at NMC in order to evaluate the impact of a hurricane observing system such as dropsonde observations on hurricane prediction.

6.1.2 Australian Monsoon Experiment

A set of forecast results of tropical cyclones observed during the Australian Monsoon Experiment (AMEX) has been submitted to the coordinator of the model intercomparison project sponsored by the Working Group on Numerical Experimentation (WGNE). Analysis data used in this study were provided by ECMWF. In this set of experiment, a uniform 1/4 degree mesh resolution version of the GFDL hurricane model was used without initialization but incorporating the improved model physics. The model produced a reasonably accurate simulation of the energy flux at the land surface. As previously suggested (A91/P92), the land surface condition of the Australian desert could strongly influence tropical cyclone behavior off the coast of Australia. Prediction results were verified favorably with analysis data.

PLANS FY93

The automated prediction system will be further evaluated by its application in near real time mode to the Atlantic and Eastern Pacific hurricanes in the 1992 season.

The study of the AMEX cases will be extended by utilizing the available radiosonde data provided by the Bureau of Meteorology Research Center, Australia, to more realistically specify the initial structure of Cyclones Connie and Irma.

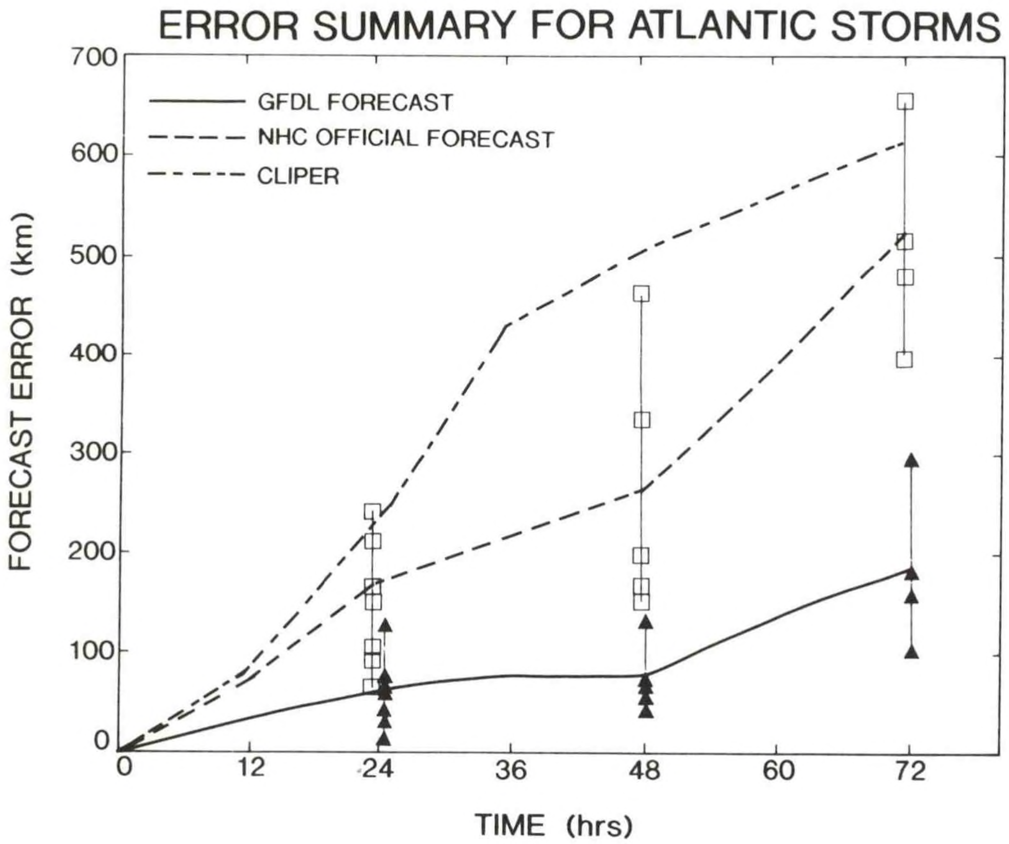

Fig. 6.1 Errors of tropical cyclone track predictions for 7 cases of Atlantic storms. Average errors for the forecasts by the GFDL automated hurricane prediction system (solid line), the official forecasts by the National Hurricane Center (dash line), and the CLIPER forecasts, *i.e.*, the simple forecast using a combination of the climatology and the persistence (dash-dot line) are compared. Errors at 24, 48 and 72h forecasts for individual cases are indicated by solid triangle for the GFDL forecasts and by open squares for official forecasts by NHC, respectively, which are plotted along thin vertical lines placed roughly at corresponding forecast times.

6.2 GENESIS OF TROPICAL CYCLONES

Y. Kurihara *R.E. Tuleya*

ACTIVITIES FY92

A sensitivity study of tropical cyclone development has been carried out through a series of idealized experiments. At issue in this study is why tropical cyclones do not form over the land such as a tropical rainforest region. This basic issue has not been thoroughly investigated, although previous work (*e.g.*, 580) suggested that either the cut-off of the latent heat flux or relatively low surface temperatures over the land would retard the development of tropical cyclones. With improved treatment of the radiation and land surface condition, particularly the capability of the land surface temperature prediction, the GFDL MMM hurricane model is now a more physically complete model to study the impact of land conditions on tropical cyclogenesis. It was found from a series of numerical experiments that an important factor controlling the tropical cyclone evolution is the heat capacity and conductivity of the soil. As shown in Fig. 6.2, the storm for the maximum evaporation efficiency, *i.e.*, that for the most favorable land wetness, developed less as the thermal property (defined as the square root of the product of the heat capacity and the thermal conductivity) of the bulk subsurface layer was reduced. The corresponding surface temperature in the central area of the weaker storm over land was noticeably lower than the ocean surface temperature of the no land control experiment because of surface evaporational cooling and the reduction of net radiational fluxes at the surface. The wind-evaporation feedback process, known to be critical in the tropical cyclone development over ocean, was thus retarded over land even for wet land conditions. It was also found that the effect of radiation-cloud feedback on the storm over the land was different from that over the ocean because the cloud canopy significantly affected the land surface temperature.

Experiments were performed to study the effect of the diurnal cycle of radiation on the tropical climate. A model was integrated for an oceanic tropical belt without tropical storms. Interesting results obtained include a diurnal change in the precipitation with a pre-dawn peak over the ocean. Diurnal variations in surface heat flux, evaporation and convective available potential energy were also noted.

PLANS FY93

Studies will continue to analyze the results obtained in the previous year. In the sensitivity study, the structure of disturbances over land and ocean will be investigated. In the tropical climate study, attention will be paid to the diurnal change in the convective available potential energy and to the sensitivity to different mean tropical states.

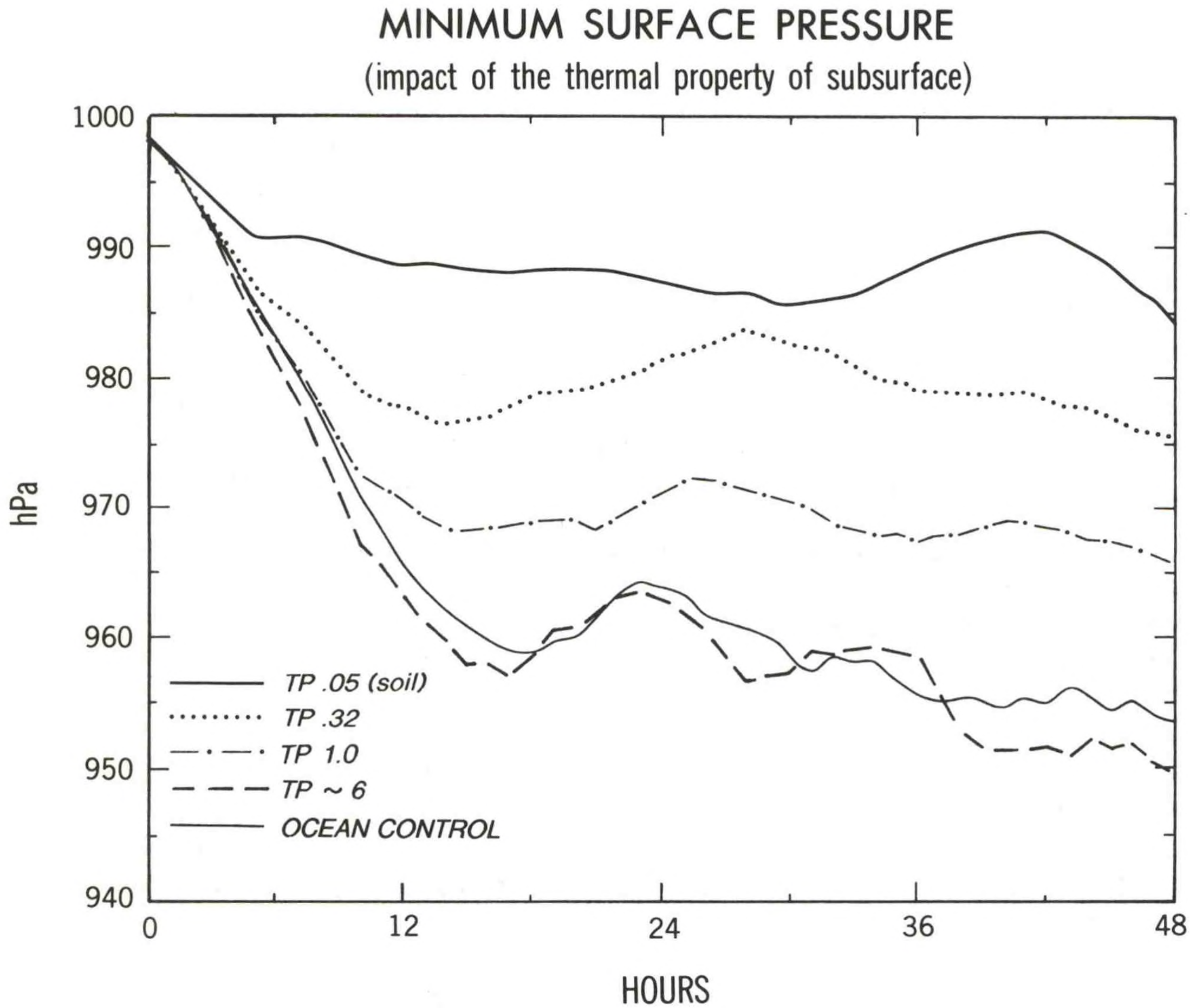

Fig. 6.2 The evolution of minimum surface pressure for an incipient disturbance in a tropical belt with a uniform easterly flow of ~5 ms^{-1}. A series of experiments with different heat capacity and conductivity of a bulk subsurface layer were contrasted with an ocean control case in which the fixed surface temperature of 302 K (infinite heat capacity) was assumed. The thermal property, TP, defined as the square root of the product of the heat capacity and the thermal conductivity of the subsurface is gradually changed from soil conditions (~.05) to mixed-layer ocean conditions (~6).

6.3 SCALE INTERACTION

Y. Kurihara *R.J. Ross*

ACTIVITIES FY92

A study was initiated to investigate the effects of tropical cyclones on the evolution of the surrounding environment. This issue has received little attention in the past, probably partly because the definition of the two flow components, *i.e.*, the tropical cyclone and the environmental flow, in a given field is not clean but rather ambiguous. It is one side of the two-fold aspect of scale interaction; the other side concerns the effects of the environmental flow on the tropical storm evolution. In the present study, two very large and intense hurricanes were chosen and their impacts on the environment have been evaluated. The one case involved Hurricane Gloria, 1985, which moved up along the coast of the eastern United States, and the other is Hurricane Gilbert, 1988, which moved westward at low latitudes.

The approach being taken is as follows. For each of the two cases chosen, the MMM hurricane model was integrated twice, first with the hurricane included and second with the hurricane removed at the initial time. The hurricane removal process used the same two filters of the vortex replacement scheme in the initialization of the hurricane model. Results of preliminary test integrations indicate interesting effects of Hurricane Gloria on the hydrological budget and an influence of Hurricane Gilbert on the maintenance of the easterly wave in which it was embedded.

PLANS FY93

The methodology used in the preliminary experiments in the previous year will be evaluated. The simulation experiments may be performed for a tropical storm at an early phase of development. Analysis will be focused on possible impacts of hurricanes on the behavior of synoptic scale systems.

6.4 HURRICANE-OCEAN INTERACTION

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

ACTIVITIES FY92

A joint hurricane-ocean model was established by coupling the MMM hurricane model and an ocean model consisting of a mixed layer, thermocline and deep ocean layers. A series of idealized experiments have been conducted to investigate the impact of hurricane ocean feedback processes on the structure, movement and intensity of a tropical cyclone. Also, the response of the ocean to the moving strong vortex has been studied. Initial conditions of the atmosphere were specified by superposing a vortex similar to Hurricane Gloria at 1200UTC 22 September 1985 onto simple easterly basic flows of 0, 2.5, 5 and 7.5 m/s. The initial ocean was assumed quiescent, horizontally homogeneous, with 302 K sea surface temperature, and vertically similar to the condition of the tropical Atlantic.

It was found that the magnitude and distribution of sea surface temperature anomalies induced by the hurricane-ocean interaction is dependent on the movement speed of the vortex. The maximum sea surface cooling from the initial temperature 302 K was 2.5 to 5.9 K. The impact of the interaction on the storm movement was significant only in slow moving cases. On the other hand, the sea surface cooling caused significant impact on the storm intensity. The minimum sea level pressure rose 15 to 20 hPa and the maximum low level wind speed decreased 5 to 8m/s compared with the experiments with constant sea surface temperature. An interesting result was that the storms in different basic flows deepened to nearly the same intensity when the interaction processes were included, while they deepened more for stronger basic flows when the sea surface temperature was fixed to the initial value. In the course of model integration, a beta gyre developed within the vortex, apparently contributing to asymmetric features in the distribution of precipitation and other variables.

PLANS FY93

Various numerical results produced in the previous year from the joint hurricane-ocean model will be analyzed in detail.

The MMM hurricane model may be coupled with the Princeton coastal ocean model to expand the research scope to more realistic problems involving an ocean with a sloped bottom or that of a bounded basin.

6.5 MODEL IMPROVEMENT

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

ACTIVITIES FY92

6.5.1 Initialization Scheme

The initialization package for the MMM hurricane model successfully resolved various undesirable problems such as the initial adjustment and false spin-up of the model vortex (rs). The scheme uses parameters defining the size of the vortex to be removed from the global analysis, that of the vortex to be implanted, the wind field to be approached in the vortex generation and the time scales controlling the generation process. An effort has been made to formulate empirical formulas and rules which automatically estimate values of these parameters for each individual case from the obtained hurricane message. The automated initialization scheme has been tested for several cases and produced very favorable skill in forecasts of hurricane track and intensity (rt).

The proposed initialization scheme may be extended to utilize supplemental wind data such as dropsonde and radiosonde data. Work to explore this potential was initiated. Also, the scheme may be used to derive the temperature and moisture fields if a complete three dimensional wind analysis is given. A study on this subject is under way using the high resolution wind analysis of Hurricane Gloria prepared at the Hurricane Research Division/Atlantic Oceanographic and Meteorological Laboratory (HRD/AOML).

6.5.2 Automated Hurricane Prediction System

As a part of the automated GFDL hurricane prediction system, the required networking for the transfer of analysis data, global model forecast data and the hurricane information messages from NMC to GFDL was established. The acquired data are processed by the initialization scheme to provide the initial conditions for the time integration of the hurricane prediction model. The data acquisition, processing and initialization steps have been streamlined and improved with data consistency checks. The prediction system can now run in a real-time mode.

6.5.3 Real-Time Hurricane Andrew Forecasts

The GFDL hurricane prediction system was put into real-time operation for nine cases during eight days of Hurricane Andrew, 1992, from its approach to the Bahamas, landfall in Florida, moving into the Gulf of Mexico, and landfall onto the Louisiana coast. Predictions of the movement, intensity change, and wind and pressure distributions were sent to the National Hurricane Center, where they served as useful information for a guidance of official forecasts of Hurricane Andrew. Post-analysis and evaluation of the prediction system are underway.

6.5.4 Model Physics

The improved MMM model (A91/P92) has been implemented as the production model in hurricane prediction (6.1) and sensitivity studies (6.2, 6.3).

The performance of the cumulus parameterization scheme used in the MMM hurricane model has been reexamined. This work is part of an effort to improve the treatment of the moist processes in the model and possibly to incorporate the cloud water budget into the model.

PLANS FY93

Performance of the automated GFDL hurricane prediction system will carefully be monitored and improved, if required. Also, an effort will be made to increase the time efficiency of the system.

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*
J. Katzfey — *J. Sheldon*
I. Orlanski

ACTIVITIES FY92

7.1.1 Downstream Development of Cyclone Systems

Recently, in an analysis on the life cycle of a strong cyclone which developed over the South Pacific in September 1987, it was found that the downstream dispersion of energy by the ageostrophic geopotential fluxes was the primary reason why the cyclone ceased to grow, and that the energy radiated downstream acted as a triggering mechanism for the growth of a new disturbance downstream (1053). These findings differ significantly from those of previous studies of the life cycle of baroclinic waves and provide a new perspective from which to analyze and understand the evolution of individual cyclones.

To further understand the role of the geopotential fluxes and baroclinicity in a growing cyclone, the characteristics of an evolving cyclone in idealized flow have been investigated (pn). Using a three-dimensional primitive equation model, it has been demonstrated that the convergence/divergence of ageostrophic geopotential fluxes can be 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 the wave development.

7.1.2 Energy Budget of Ridge/Trough Development in the Eastern Pacific

In order to investigate the effects of downstream development (see section 7.1.1) in a Northern Hemisphere system, a rapidly amplifying wave over the eastern Pacific/western U.S. in December 1990 was chosen as a case study of the factors contributing to the growth of such disturbances. This trough developed from a largely zonal flow to eventually produce a major cold outbreak in the western U.S. (see 7.2.2). A control simulation was run which demonstrated the skill of the model in simulating this event. A rather surprising result was obtained from the analysis of a simplified simulation in which all land surface was removed and surface heat fluxes and latent heating were turned off. It was found that the basic character of this storm was retained and its intensity was even slightly increased, contrary to the conventional belief that land-sea contrast and topography constitute major forcing mechanisms for the development of troughs along the west coast of North America.

It was also found 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. Fig. 7.1 depicts the storm near the mid-point of its development and shows the 500 mb height field in the upper panel, and the vertically averaged eddy kinetic energy and energy fluxes in the lower panel. These energy fluxes are represented by $((\vec{V}'\phi')_H + \vec{V}K')$, where $(\ )'$ represents the deviation of a quantity from its zonal average on a pressure surface (except for the v-component of the wind, which is left intact) and the subscript H indicates that a non-divergent component of the field has been removed. The fluxes clearly show a combination of kinetic energy advection (mainly within the energy center itself) and geopotential flux (between the energy centers). These results are consistent with the new findings regarding baroclinic wave growth discussed in section 7.1.1. The present findings suggest considerable potential for using these fluxes as a diagnostic in the identification of growing and decaying systems.

7.1.3 Energy Budget in Simulated Storm Tracks

The existence of latitudinally and longitudinally confined storm tracks in the Northern Hemisphere winter over the Pacific and Atlantic Oceans in the mid-latitudes has been well documented. The contrast between low land temperatures and the warm ocean currents of both oceans just off the east coast of the continents constitutes a source of enhanced baroclinicity over these regions, especially in the winter season. In a recently completed study (qy), an idealized model was used to show that the existence of a localized source of enhanced baroclinicity, while leading to localized maxima in the baroclinicity at, or immediately downstream of, the

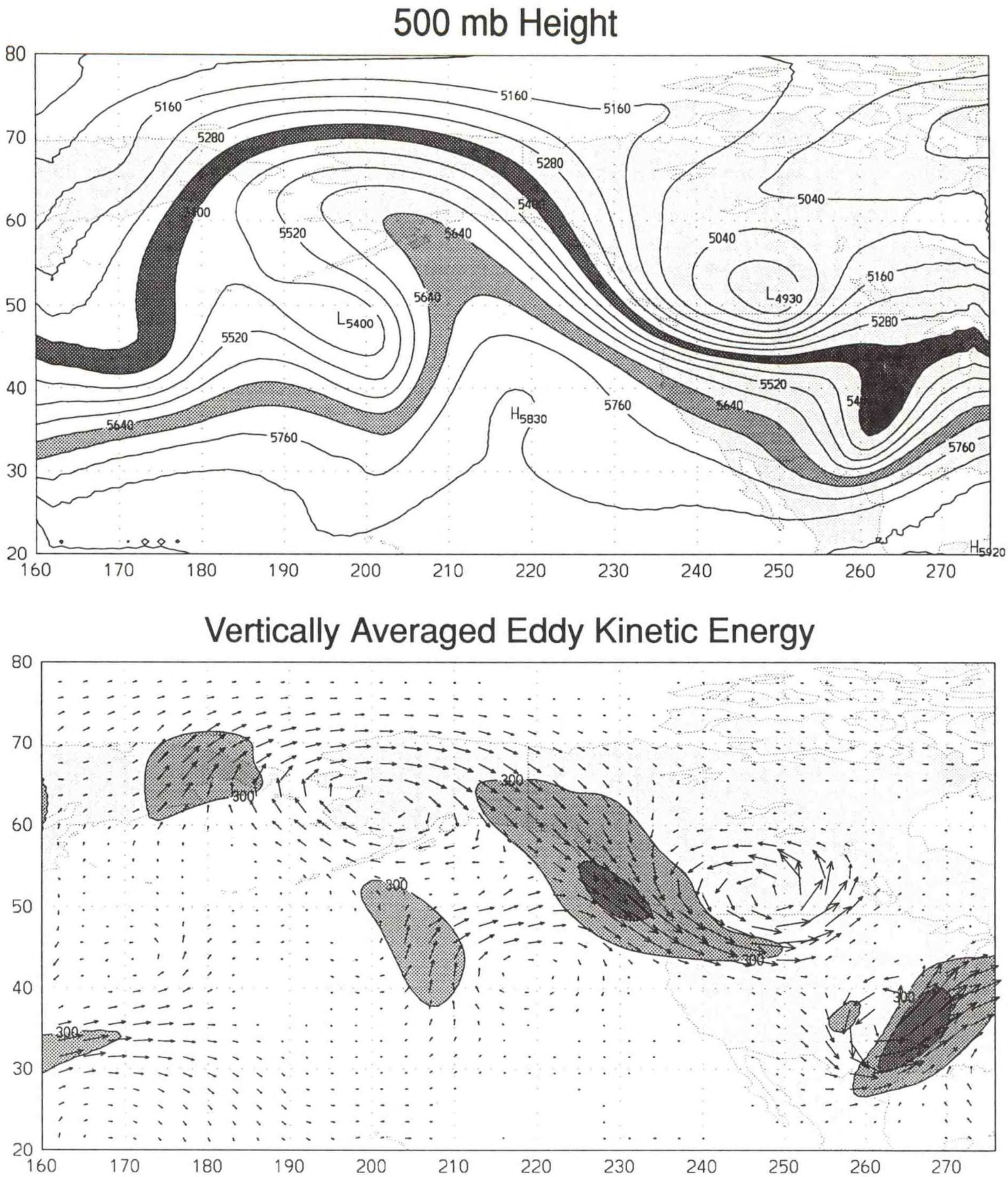

Fig. 7.1 Simulation of the development of the December 1990 storm/cold outbreak. All land surfaces have been removed and surface heat fluxes and latent heating are turned off. Upper panel shows the 500 mb height field at 12Z 18 December, with the developing system over western North America. Lower panel is the eddy kinetic energy vertically averaged from 50 mb to the surface (light shading: 300-600 m^2s^{-2}, dark shading: > 600 m^2s^{-2}). The vectors are energy flux, expressed as $((\vec{V}'\phi')_H + \vec{V}K')$ (see section 7.1.2), showing advection within the energy centers and geopotential flux between centers. Note in particular the flux of energy from the decaying center in the central Pacific to the developing center over the western North American coast.

baroclinic region, does not necessarily lead to the localization of eddy activity. While baroclinic conversion is indeed a maximum immediately downstream of the source of enhanced baroclinicity, energy radiated downstream by eddies which developed in this highly baroclinic region will trigger and sustain eddies in the downstream region, despite the lower baroclinicity. Hence, the localization of the baroclinic source does not determine completely the spatial extent of the storm track. These results underscore the importance of the ageostrophic geopotential fluxes discussed elsewhere (1053, pn), and represent a fundamental difference between downstream development and normal-mode lifecycles.

PLANS FY93

Additional case studies will be initiated to better understand the role of geopotential fluxes and baroclinic conversion in the development of cyclones. From the new perspective gained so far, the explosive development of storms will be analyzed to identify the roles played by localized baroclinicity and the decay of upstream systems. While previous studies of storm tracks did not clearly reveal downstream development as a major development mechanism, there are indications that the time filter used for those studies precluded the detection of such a mechanism, and an effort will be made to address this problem using an alternative approach.

7.2 SENSITIVITY STUDIES OF MID-LATITUDE CYCLONES

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

**Center for Ocean and Atmospheric Research*
Buenos Aires, Argentina

ACTIVITIES FY92

7.2.1 Extratropical Cyclone in the Southern Hemisphere

A rapidly deepening cyclone that occurred over the South Pacific on 5 September 1987 was investigated in order to assess the possible factors contributing to its development. The results of an investigation into the energetics of this system were discussed in section 7.1.1. In addition, sensitivity experiments were conducted to determine the role of surface processes in the development of the storm (1060). It was found that development was quite insensitive to both surface heat fluxes and to the presence of South American topography, with little change in either the circulation or kinetic energy of the storm. Intensification of the storm was, however, substantially affected by surface frictional effects, with significant increases in the vertically averaged kinetic energy when surface roughness was reduced. The results suggest a need to reduce the roughness heights not only over sea ice, but over the ocean in areas of strong winds as well.

7.2.2 Cold Outbreak in the Western U.S.

In late December 1990, a flow which had been highly zonal over the Pacific for weeks was transformed into a high amplitude pattern marked by a strong ridge located over Alaska and off the west coast of North America by 18 December. A shortwave developed at the crest of the ridge at that time and plunged almost due south, gaining energy over the next two days and bringing extreme cold to the western United States, including the west coast as far south as southern California (see also section 7.1.2).

In an effort to determine the extent to which the development of this storm was influenced by the lower boundary conditions, a number of additional simulations were run with varying surface heat and momentum flux conditions. Among these was an experiment in which the surface exchange coefficients for momentum, heat, and moisture over open water were determined from empirically derived values, based on wind speed and stability. The resulting values for the exchange coefficients in regions of cold advection over warmer water were significantly lower than the values produced by the control run, and the resulting sensible and latent heat fluxes showed dramatic (factor of 2) reductions. However, the changes in these fluxes had little impact on the overall simulation, since the growth of the system in question was driven primarily by geopotential flux convergence at upper levels, as discussed in section 7.1.2. Nevertheless, the impact of these surface heat flux changes could be profound in preconditioning the lower atmosphere and in modifying the cold air which is eventually entrained into the system.

In another experiment, the drag coefficient, C_D, was made a function of topographic height, increasing C_D in high terrain. Again, this change had minimal impact on the overall system, but the simulation of the lower level circulation and surface pressure was substantially improved. The subdued circulation intensity over land also had ramifications with respect to the C_D issues, as cold advection from the land to the open ocean was lessened and both the area and the magnitude of the low level instability was reduced. There was also evidence of reduced energy loss via geopotential fluxes at low levels when C_D was increased. All of these results are still preliminary, and research is continuing.

PLANS FY93

The sensitivity of the simulations to boundary layer parameterization will be investigated in greater detail, especially with respect to the impact of increased drag over mountainous terrain. Sensitivity to changes in the surface heat fluxes may become more pronounced in other 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 FY92

7.3.1 A New Look at Lee Cyclogenesis

Simulations that portray mature storm systems interacting with a mountain ridge have been used to clarify the physical processes associated with lee cyclogenesis. In these simulations, Eady waves grow on a zonally symmetric jet and impinge on a topographic ridge oriented east-west. As the mature wave passes over the mountain, the cyclone center, characterized by relatively warm air, low pressure, and positive relative vorticity is positioned directly north of the mountain ridge, but has been elongated in the eastward direction by the attendant mountain anticyclone. The most important feature generated by the interaction of the wave and mountain is the slicing of the warm ascending branch which supplies the cyclonic circulation ahead of the cold front. Consequently, the low pressure center is displaced southward, and its eastward movement is retarded by the mountain anticyclone, producing an intensification of the relative vorticity south of the mountain barrier. This cyclonic vortex extends vertically through the entire depth of the troposphere.

The physical mechanisms responsible for the generation of this warm core low pressure center may be clarified by examining the evolution of a flow in which a stationary circulation with the characteristics of a cold front interacts with an elongated mountain ridge. A two-dimensional region of cyclonic shear, with southerly flow and warm air to the east and northerly flow and cold air to the west, is placed over a ridge. The principal feature that develops from this interaction is an isolated low pressure center south and slightly west of the center of the ridge. This cyclone is associated hydrostatically with the southerly flow of warm air that has been deflected to the west by the mountain anticyclone. As a consequence, a substantial pressure gradient develops between the low pressure center and the high over the mountain, producing an intense narrow region of easterly geostrophic flow that exacerbates warm air advection and the attendant pressure falls. The circulation arising from this idealized flow can be seen in Fig. 7.2.

LEE CYCLONE FORMATION
POTENTIAL TEMPERATURE AND WINDS

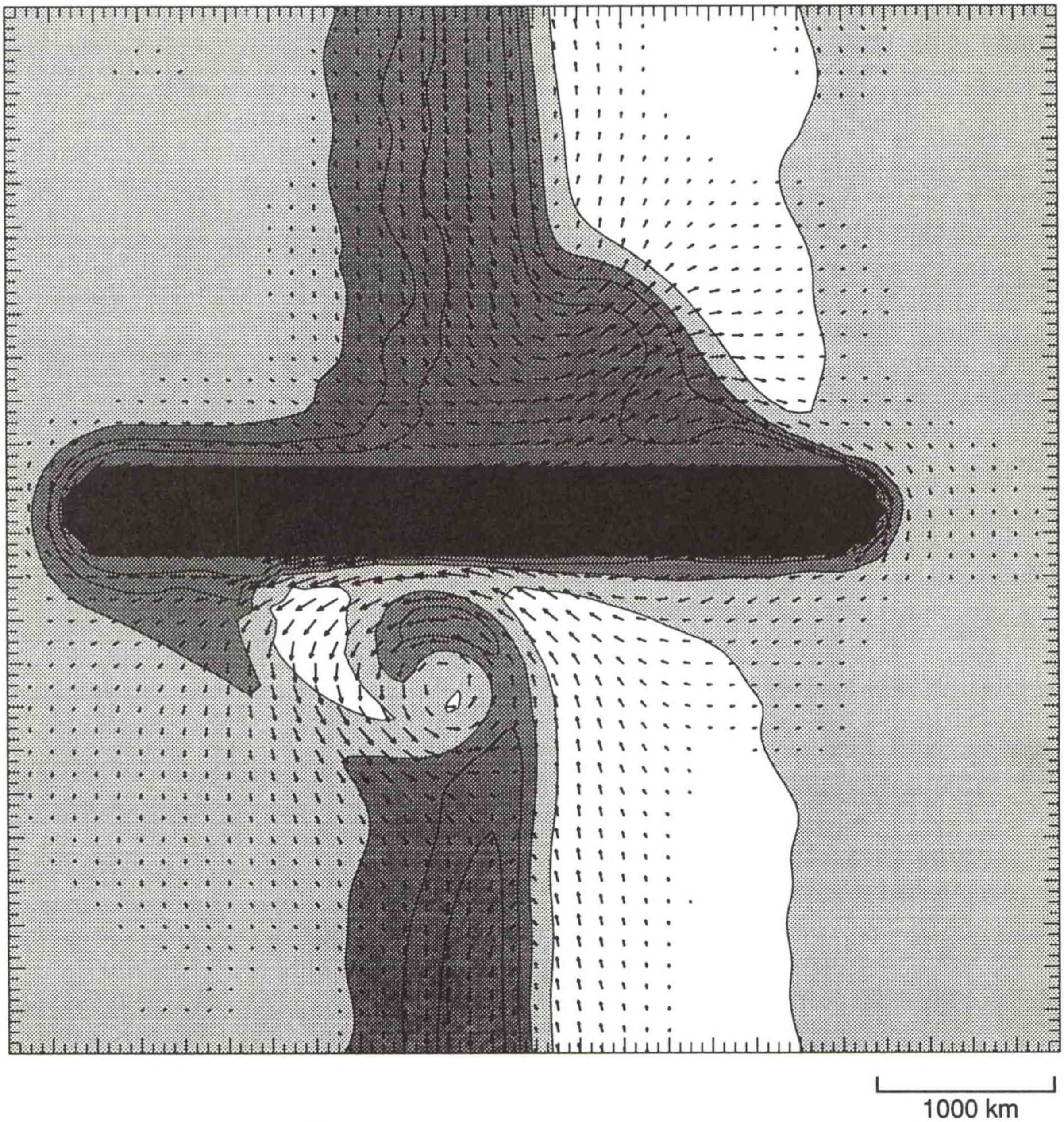

Fig. 7.2 Horizontal velocity and potential temperature distribution at 1000 m, resulting from the interaction of a stationary cold front and an elongated mountain ridge, represented by the dark ellipse. Contours represent values of 2, 2.5, 3, and 4°K, and the bands correspond to intervals of < 3°K (medium shading), 3°K to 4°K (light shading), and > 4°K (unshaded). Wind speeds greater than 1 ms^{-1} are plotted, and the maximum wind speed is 16.5 ms^{-1}. Tick marks are placed every 60 km. On the south side of the ridge, the deflection of warm southerly flow to the west produces a warm core cyclone. The enhanced flow between this cyclone and the mountain anticyclone is clearly depicted.

7.3.2 Frontal Interaction with Topography

The interaction of fronts with topography has been implicated in the generation of several important atmospheric circulation systems, including squall lines and lee cyclones. However, with few exceptions, efforts to understand the basic physical mechanisms important to this interaction have focused on relatively simple models of flow over orography. Here, nonlinear three-dimensional simulations of the interaction of a front with an isolated topographic ridge have been examined in order to determine the influence of orography on frontal distortion, frontogenesis, and frontolysis.

The principal response to frontal passage over the ridge consists of an anticyclonic distortion of the front due to temperature advection by the mountain anticyclone, frontolysis on the windward slope, and frontogenesis on the lee slope. This response is similar to that found when a passive scalar is advected over an isolated mountain. In the present time-dependent simulation, however, an appreciable anticyclone is generated only when the frontal circulation reaches the mountain. Furthermore, very strong surface confluence produces large temperature gradients in the front on the lee side. This confluence is associated with a swift, shallow gravity current flowing down the lee slope. This unbalanced current is generated by a relatively strong cross-mountain pressure gradient that develops as the cold anticyclone in the mature Eady wave is blocked by the mountain ridge. In contrast, a high mountain ridge can completely block the progression of the front. In this case, the flow is diverted anticyclonically around the end of the mountain in the form of a strong ageostrophic current.

7.3.3 Blocking and Frontogenesis Due to Topography

Fronts can form as a consequence of blocking by a topographic ridge, according to non-hydrostatic numerical simulations with a high-resolution terrain-following model. For realistic choices of ambient static stability and baroclinicity, it is found that a flow can easily become blocked by ridges like the northern Appalachians if the undisturbed incident wind speed lies between 5 and 10 ms^{-1}. The Rossby number for these cases is large (the mountain is narrow) but not large enough to produce blocking in barotropic conditions. A weakly nonlinear analysis suggests that the barrier enhancement occurs because the static stability just upstream from the ridge increases during warm advection. The blocked solutions cannot become steady without momentum dissipation. However, it is shown that the front that forms upstream can hold its position if the temperature gradient achieves approximate balance with the vertical shear.

7.3.4 Gravity Waves Generated by an Eady-Type Front

The generation of neutral gravity-inertia waves in the frontal regions of a growing Eady wave has been studied using a fully Lagrangian primitive-equation numerical model. At issue is whether such waves can contribute to the equilibration of the large-scale wave by dissipating eddy kinetic energy or disrupting the crucial communication between boundaries. In an earlier paper (pu), it was shown that equilibration takes place as a result of frontal zones growing into the interior after the minimum resolvable or sustainable horizontal scale is achieved on the boundary. However, the models used in that study suppressed gravity waves. With the relatively inviscid Lagrangian model, there are significant departures from balance-model solutions when the Richardson number is small enough to allow quasi-resonant standing waves between the boundaries and the critical layers (Ri $< \pi$). However, frontal collapse is not prevented even in these cases.

PLANS FY93

Studies of the mesoscale circulation generated by the interaction of the planetary circulation with topography will continue.

7.4 MODEL DEVELOPMENT

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

ACTIVITIES FY92

7.4.1 The Zeta Model

A new terrain-following coordinate model has been coded into the current version of the primitive-equation zeta model, which is hydrostatic and Boussinesq. The model is also dry, inviscid, and adiabatic, except that weak second-order diffusion is included to control noise. The domain is bounded by impermeable walls at the north and south boundaries, a rigid lid at the upper boundary, and topography at the lower boundary. Either periodic or sponge boundary conditions may be used at the east and west boundaries. The vertical terrain-following coordinate is given by

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

where $h(x,y)$ represents the topographic height and H is the height of the rigid lid. Larger values of ε place more model levels near the ground. Model output may be analyzed on coordinate surfaces, height surfaces, and isentropic surfaces, or on arbitrary cross-sections through the domain. This model has been used to address the problems outlined in Sections 7.3.1 and 7.3.2.

7.4.2 Surface Flux Parameterization

To support the sensitivity experiments discussed above in sections 7.2.1 and 7.2.2, the Limited Area HIBU Model (LAHM) was modified to include several options for treating the surface exchange coefficients. One of these involved the incorporation of empirically derived wind speed and stability dependent surface exchange coefficients for momentum, heat and moisture. Another option was the modification of the exchange coefficients depending on terrain height, raising them by a multiplicative factor in high terrain. Simpler options included switches to either turn off surface heat fluxes or set the exchange coefficients to a constant value.

PLANS FY93

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. A Richardson number dependent vertical flux option will be investigated in an effort to promote a greater 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.

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 FY92

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 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, five 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.

During FY92, eighteen additional desktop workstations and one additional server were integrated into the network. The increase in desktop workstations has allowed almost every user to have a workstation on his/her desk. In addition, all the Silicon Graphics workstations were enhanced to run in true color mode. A software server, video workstation, and additional server disk space were also integrated into the network. The video workstation and newly acquired video equipment provide the capability to produce VHS and VHS/S videos in-house. A newly acquired high-resolution PostScript printer provides publication-quality output.

The Silicon Graphics workstations received a major operating systems upgrade providing, among other things, a standards-based windowing system. Mathematical and statistical software packages were installed for use on the workstations. Several public domain graphical software packages were installed that significantly enhance GFDL's data analysis capabilities. Modifications to the existing contract for Silicon

Graphics workstations were negotiated to add options for a number of software packages and expansion peripherals. A contract modification to replace the discontinued Personal Iris 4D/25 with the Iris Indigo is under review and is expected to be complete by the end of FY92.

In an effort to provide a safe, productive, and amicable computing environment, policy documents were developed to address computer use and building access. In addition, a formal security plan was completed and submitted to Information Resource Management in NOAA and the Department of Commerce.

Work on the acquisition of a high-speed backbone network continued during FY92. Efforts to develop mass storage solutions for GFDL also continued during FY92. Partial specifications for a Mass Storage Server were prepared for possible use in a future procurement.

A major upgrade of the Cray Y-MP operating system software was installed, providing increased system operating efficiency and improved utilization of magnetic tape storage. An upgrade to disk drives with newer technology is expected to be completed by the end of FY92.

Table 8.1 User Processor Time and Amount of Total Archive Data

Month	Hours	Gigabytes
Oct 91	5,180	3,022
Nov 91	4,893	3,340
Dec 91	5,137	3,644
Jan 92	4,941	3,877
Feb 92	4,451	4,138
Mar 92	4,555	4,422
Apr 92	4,831	4,714
May 92	4,701	4,981
Jun 92	4,978	5,264
Jul 92	5,021	5,546
Aug 92	5,032	5,845
Sep 92	N/A	N/A

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. This table indicates the continued high system utilization of the GFDL supercomputer. It also shows the rapid growth of the Laboratory's data archive.

PLANS FY93

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. Improvements in mass storage capabilities will be pursued. Alternatives to be considered include possible upgrades to the Y-MP and the competitive procurement of a stand-alone Mass Storage Server. The process of acquiring and installing an FDDI backbone will continue. Ways to increase PostScript printer throughput will be explored. A full risk analysis will be completed, and formal accreditation of the GFDL Scientific Computing Facility will be sought in FY93. Additional public domain and third-party software packages will be installed for the various hardware platforms. Preliminary work on the acquisition of a massively parallel processor computer system will start, including the preparation of benchmark programs and continuing evaluation of the state of the industry.

APPENDIX A

GFDL STAFF MEMBERS

and

AFFILIATED PERSONNEL

during

Fiscal Year 1992

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, Cheng-ta	Student	PU
Chen, Yang	Student	PU
Delworth, Thomas L.	Sr. Research Associate	FTP
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
Pavan, Valentina	Student	PU
Phillipps, Peter J.	Research Associate	FTP
Sun, Dezheng	Program Scientist	PU
Zhang, Jiawei	Student	PU
Knutson, Thomas R.	Sr. Research Associate	FTP
Lofgren, Brent M.	Student	PU
Milly, P.C.D.	Research Scientist	RA**
Dunne, Krista	Research Associate	RA**
Ramaswamy, V.	Research Scientist	PU
Schwarzkopf, M. Daniel	Sr. Research Associate	FTP
Spelman, Michael J.	Sr. Research Associate	FTP
Stouffer, Ronald J.	Sr. Research Associate	FTP
Vinnikov, Konstantine	Program Scientist	PU
Wetherald, Richard T.	Sr. Research Associate	FTP
Wichansky, Paul S.	Summer Student	FTT*
Williams, Gareth P.	Sr. Research Scientist	FTP

* Affiliation terminated prior to September 30, 1992.

**United States Geological Survey (USGS) on detail to GFDL.

MIDDLE ATMOSPHERE DYNAMICS AND CHEMISTRY

Mahlman, Jerry D.	Director	FTP
Hamilton, Kevin P.	Research Scientist	FTP
Manzini, Eliza	Student	PU*
Nakamura, Noboru	Program Scientist	PU
Wilson, Robert J.	Research Associate	FTP
Yuan, Li	Student	PU
Hemler, Richard S.	Sr. Research Associate	FTP
Levy II, Hiram	Research Scientist	FTP
Kasibhatla, Prasad	Georgia Tech. Res. Scientist	GIT
Moxim, Walter J.	Sr. Research Associate	FTP
Richardson, Jennifer	Georgia Tech. Grad. Student	GIT
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
Navarra, Antonio	Program Scientist	PU*
Pinardi, Nadia	Program Scientist	PU*
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
Wyman, Bruce L.	Research Associate	FTP

* Affiliation terminated prior to September 30, 1992.

OCEANIC CIRCULATION

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

OBSERVATIONAL STUDIES

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

* University of British Columbia
** University of Oregon
***Affiliation terminated prior to September 30, 1992.

HURRICANE DYNAMICS

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Ginis, Isaac	Program Scientist	PU
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Warren, James	Student	PU

MESOSCALE DYNAMICS

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

CENTRALIZED SUPPORT SERVICES

Administrative and Technical Support

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

SYSTEMS AND SUPPORT GROUP

Ross, Bruce B.	Assistant Director, GFDL	FTP**
Umscheid, Ludwig J.	Major Systems Specialist	FTP
Baker, Philip L.	Computer Specialist	FTP
Kranz, Christopher L.	Computer Systems Programmer	FTP
Lau, Vivian	Computer Clerk	PTT*
Lewis, Lawrence J.	Computer Systems Analyst	FTP
Taylor III, Thomas E.	Computer Assistant	FTP
White, Robert K.	Computer Systems Programmer	FTP
Yeager, William T.	Computer Systems Programmer	FTP

* Affiliation terminated prior to September 30, 1992.
**Acting Head

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
Gough, Douglas	Student (Computer Operator)	PTT*
Josil, Lyonel	Student (Computer Operator)	PTT*
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, 1992.

ATMOSPHERIC AND OCEANIC SCIENCES PROGRAM

Philander, S.G.H.	Professor, Program Director	PU
Callan, Johann V.	Technical Research Secretary	PU
Goddard, Lisa M.	Student	PU
Koberle, Cornelia	Visiting Research Staff	PU
Li, Jingdong	Student	PU
Liu, Zhengyu	UCAR Fellow	PU
Nicoletti, Mary Ann	Program Manager	PU
Ravelo, Christina	Program Scientist	PU
Valerio, Anna	Technical Research Secretary	PU
Xie, Shang-Ping	Program Scientist	PU
Mellor, George	Professor	PU
Ezer, Tal	Program Scientist	PU
Goubeaud, Diana F.	Student	PU*
McCarthy, Robert	Program Scientist	PU
Zavatarelli, Marco	Program Scientist	PU*
Sarmiento, Jorge	Professor	PU
Anderson, Laurence A.	Student	PU
Figueroa, Horacio	Research Staff	PU
Key, Robert M.	Research Scientist	PU
McDonald, Gerard	Technical Staff	PU
Murnane, Richard J.	Research Staff	PU
Olszewski, Jason	Research Assistant	PU
Orr, James	Research Staff	PU
Rayner, Peter	Technical Staff	PU
Rotter, Richard	Technical Staff	PU
Slater, Richard D.	Technical Staff	PU
Tromp, Tracy	Technical Staff	PU*
Webb, Vincent	Student	PU

* Affiliation terminated prior to September 30, 1992.

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, 1992

GFDL/NOAA	
Full Time Permanent (FTP)	88
Part Time Permanent (PTP)	2
Part Time Temporary (PTT)	2
Research Affiliates (RA)	2
Georgia Tech Research Associates (GIT)	2
PRINCETON UNIVERSITY (PU)	
Program Scientists	15
Students	13
Professors	3
Research Scientists	2
Research Staff	4
Visiting Research Staff	1
Support Staff	3
Technical Staff	4
UCAR Fellows	2
Visiting Fellow - University of Oregon	1
Visiting Fellow - University of British Columbia	1
CRAY RESEARCH INC.	
Computer Support Staff	5
TOTAL	**150**

APPENDIX B

GFDL

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1987-1992

GFDL PUBLICATIONS

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

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

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APPENDIX C

Seminars Given at GFDL

During Fiscal Year 1992

1 October 1991	ENSO SST's: COADS vs Coupled Model (an application of complex eigenvector analysis and animated color graphics), by Dr. John Lanzante, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
2 October 1991	Climate Variability of the North Pacific, by Dr. Kimio Hanawa, Tokyo University, Sendai, Japan
7 October 1991	The Structure of Major Glaciation Cycles, by Professor John Imbrie, Brown University, Providence, RI
8 October 1991	The Interaction Between Shallow Convection and Large-Scale Flow in the Marine Boundary Layer, by Dr. Alexander Khain, Institute of Earth Science, Hebrew University of Jerusalem, Givat Ram, Jerusalem, Israel
8 October 1991	Reconciliation of Remote Sensing Data into Operational Forecasting: 1957-1987, by Dr. Marjorie Courain, Orange, NJ
15 October 1991	Acoustic Applications in Ocean Modeling, by Dong-shah Ko, Institute for Naval Oceanography, Stennis Space Center, Bay St. Louis, MI
15 October 1991	Some Ecological Implications of a Flexible Model of Spatial Competition, by Dr. Robert Armstrong, AT & T Bell Laboratories, Holmdel, NJ
17 October 1991	3-D Turbulence and Vorticity, by Dr. Alexandre Chorin, Institute of Advanced Study, Princeton, NJ
22 October 1991	Changes of the Coupled Troposphere-Lower-Stratosphere, after Solar Activity Events, by Dr. C. Schuurmans, Royal Netherlands Meteorological Institute, De Bilt, The Netherlands
25 October 1991	Some Aspects of the Interaction of Convection with Large Scale Flows, by Dr. Kerry Emanuel, Center for Meteorology, Massachusetts Institute of Technology, Cambridge, MA
29 October 1991	Large-Scale Overturning of the Indian and Pacific Oceans, by Dr. J.R. Toggweiler and B. Samuels, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
6 November 1991	Operational Global Assimilation and Prediction in the Australian Bureau of Meteorology, by Dr. William Bourke, Bureau Meteorology and Research Center, Melbourne, Australia
12 November 1991	Band Limited Regression: A Robust Technique Applied to Global Temperature Measurements, by Craig Lindberg, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
15 November 1991	One-Dimensional Theory of the Wave Boundary Layer, by Dr. Christopher L. Kerr, Cray Research Inc, Princeton, NJ

18 November 1991	Models of Air Sea Interaction in the Tropics, by Prof. David Neelin, Department of Atmospheric Sciences, University of California, Los Angeles, CA
19 November 1991	Downstream Developments, Class B, Cyclogenesis and Other Things, by Dr. I. Orlanski and J. Sheldon, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
19 November 1991	Modes of Tropical Variability under Convective Adjustment and the Madden-Julian Oscillation, by Prof. David Neelin, Department of Atmospheric Sciences, University of California, Los Angeles, CA
21 November 1991	One-Dimensional Theory of the Wave Boundary Layer, by Prof. Dmitry Chalikov, St. Petersburg Branch, Institute of Oceanology, USSR Academy of Sciences, St. Petersburg, USSR
22 November 1991	Wind Waves as an Active Element of Ocean-Atmosphere Dynamical System, by Prof. Dimitry Chalikov, St. Petersburg Branch, Institute of Oceanography, St. Petersburg, USSR
26 November 1991	On the Dynamics of Storm Tracks, by E. Chang and Dr. I. Orlanski, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
3 December 1991	Evaporation-Wind Feedback and the Organizing of Tropical Convection on the Planetary Scale, by Shang-Ping Xie, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
5 December 1991	El Niño-Southern Oscillation and CO_2 Climate Change, by Dr. Jerry Meehl, National Center for Atmospheric Research, Boulder, CO
6 December 1991	On the Fluid Dynamics of Oceanic Thermocline Ventilation, by Dr. John Marshall, Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA
10 December 1991	A Comparison of the Stationary Wave Responses in Several GFDL Increased CO_2 GCM Experiments, by Dr. John Lanzante, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
17 December 1991	An Orographic Mechanism for Rapid Frontogenesis, by Dr. Stephen Garner, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
6 January 1992	Implications of the Wind Forced Overturning of the Deep Ocean for the Carbon Cycle, by Dr. J.R. Toggweiler, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
7 January 1992	Spin-up and Spin-down of Ventilated Thermocline, by Mr. Zhengyu Liu, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ

13 January 1992	Idealized 3-D Modeling of the QBO, by Dr. R. Saravanan, Department of Applied Mathematical & Theoretical Physics, Cambridge University, Cambridge, England
14 January 1992	Thermocline Forced by Annual and Decadal Surface Temperature Variation, by Mr. Zhengyu Liu, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
16 January 1992	PCCM: A Distributed-Memory Parallel Implementation of the Community Climate Model, by Dr. John B. Drake, Oak Ridge National Laboratory, Mathematical Sciences Division, Oak Ridge, TN
17 January 1992	Analysis of the Height-Time-Delay Structure of the QBO, by Dr. Steven Pawson, Institute for Meteorology, Free University of Berlin, Berlin, Germany
21 January 1992	Radiative-Convective Equilibrium with Explicit 2-Dimensional Moist Convection, by Dr. Isaac Held, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
23 January 1992	The Modellion Concept, by Dr. W. J. Shuttleworth, Institute of Hydrology, Wallingford, Oxfordshire, England
28 January 1992	Decadal Trends in North Atlantic SST and Associated Meteorological Fields, by Dr. Y. Kushnir, Lamont-Doherty Geological Observatory, Palisades, NY
30 January 1992	Moist Baroclinic Waves, by Dr. Christopher Davis, National Center for Atmospheric Research, Boulder, CO
3 February 1992	The Atmospheres of Magnetic Neutron Stars, by Mr. Robert Nelson, Cornell University, Ithaca, NY
5 February 1992	Climate Forcing by Anthropogenic Aerosols, by Prof. Robert Charlson, Department of Atmospheric Science, University of Washington, Seattle, WA
6 February 1992	Radiative and Microphysical Properties of Marine Stratocumulus Clouds, by Dr. Michael King, Climate and Radiation Branch, NASA Goddard Space Flight Center, Greenbelt, MD
7 February 1992	Cavitating Fluid Sea Ice Model, by Dr. Gregory M. Flato, Thayer School of Engineering, Dartmouth College, Hanover, NH
11 February 1992	Polar Amplification in Model and Empirical Study, by Prof. K. Vinnikov, Program in Atmospheric and Oceanic Sciences, Princeton University, Princeton, NJ

12 February 1992	On the Vertical Distributions of Tropical Tropospheric Temperature and Moisture: Towards a Better Understanding of Their Interdependence, by Mr. De-Zheng Sun, Massachusetts Institute of Technology, Cambridge, MA
18 February 1992	Decadal Variability of the Thermohaline Circulation in a Coupled Model, by Mr. Thomas Delworth, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
20 February 1992	Deep-Sea Biodiversity, by Dr. Frederick Grassle, Institute for Marine & Coastal Sciences, Rutgers University, New Brunswick, NJ
25 February 1992	A Numerical Study of the Mediterranean Sea Circulations, by Marco Zavatarelli and Prof. George Mellor, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
27 February 1992	Assimilation of Satellite Altimeter Data into Ocean Circulation Models, Dr. Ichiro Fukumori, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA
3 March 1992	A Numerical Study of the Ocean Response to a Hurricane, by Dr. Isaac Ginis, Program in Atmospheric and Oceanic Sciences, Princeton University, Princeton, NJ
6 March 1992	Finding the Steady State of a General Circulation Model through Data Assimilation: Application to the North Atlantic Ocean, by Dr. Jochem Marotzke, Department Earth, Atmospheric & Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA
17 March 1992	Nowcasting/Forecasting and Numerical Simulations of the Gulf Stream, by Tal Ezer, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
17 March 1992	Surface Wave Growth in Response to Unsteady Winds, by Mr. Daifang Gu, Meteorology Department, Johns Hopkins University, Baltimore, MD
19 March 1992	The Energy Spectrum of Fronts, by Dr. John Boyd, University of Michigan, Ann Arbor, MI
23 March 1992	Parameterization of Boundary Layer Processes in Large-Scale Models, by Prof. Sergei Zilitinkevich, Max Planck Institute, Hamburg, Germany
25 March 1992	Numerical Simulations of Gravity Wave Generated by Deep Convection, by Prof. Dale R. Durran, Department of Atmospheric Sciences, University of Washington, Seattle, WA
31 March 1992	Effect of Antarctic Sea-Ice on the Salinity of Antarctic Bottom Water, by Dr. J.R. Toggweiler, Geophysical Fluid Dynamics Laboratory, Princeton, NJ

1 April 1992	Conveyor Belt Sensitivity Experiments with the CME Ocean Model, by Dr. William R. Holland, National Center for Atmospheric Research, Boulder, CO
7 April 1992	Assimilation of the Model Generated Altimeter Date Using the Adjoint Technique, by Dr. Rafal Lewandowicz, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
9 April 1992	Solar Variability: Implications for Global Change, by Dr. Judith Lean, Department of the Navy, Naval Research Laboratory, Washington, DC
10 April 1992	Thermohaline Circulation Forced by Evaporation and Precipitation, by Dr. Rui-Xin Huang, Woods Hole Oceanographic Institute, Woods Hole, MA
13 April 1992	Two-Component Representation of Sparsely Vegetated Surface Heat Flux Calculations, by Prof. J. Otterman, Tel Aviv University, Tel Aviv, Israel
14 April 1992	Decadal Simulations with a GCM and Implications for Extended Range NWP, by K. Miyakoda and W. Stern, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
16 April 1992	Basin Scale Boundary Pressure Adjustment Processes, by Dr. Ralph Milliff, National Center for Atmospheric Research, Boulder, CO
17 April 1992	Incompatible Wind and Buoyancy Forcing in Ocean Models, by Dr. Pe-Cheng Chu, Naval Postgraduate School, Monterey, CA
21 April 1992	Sensitivity of Modeled Climate to Continental Evaporation, by Dr. C. Milly and K. Dunne, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
24 April 1992	Inverting a Finite Difference Inverse Model for the North Atlantic Circulation, by Dr. Carl Wunsch, Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA
28 April 1992	Some Positive Feedbacks of a Simple Air-Sea Model in the Extratropics, by Z. Liu, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
30 April 1992	Adjoint of a Complex Mesoscale Forecast Model and Its Application, by Dr. Tomislava Vukicevic, National Center for Atmospheric Research, Boulder, CO
4 May 1992	Observed and Simulated Variabilities of Soil Moisture, by Alan Robock, Adam Schlosser, Nina Speranskaya, and Konstantin Vinnikov, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ

7 May 1992	Numerical Simulation of 3-D Convective Flows in a Freezing Oceanic Surface Layer, by Dr. Steven A. Piacsek, Naval Research Laboratory, Stennis Space Center, MS
8 May 1992	Variability in Equatorial Pacific Sea Surface Temperatures on Interannual Time Scales and ENSO, by Dr. Muthuvel Chelliah, Diagnostics Branch, National Weather Service, Camp Springs, MD
11 May 1992	The Middle Atmosphere in the UK Universities Global Atmospheric Modeling Program, by Dr. Keith P. Shine, Department of Meteorology, University of Reading, England
12 May 1992	Some Aspects of Radiative Forcing and Radiative Feedbacks, by Dr. Keith Shine, Department of Meteorology, University of Reading, England
14 May 1992	Hurricane Evolution in Simple Models, by Dr. Lloyd Shapiro, Hurricane Research Division, Atlantic Oceanographic & Meteorological Laboratories, Miami, FL
15 May 1992	Atmospheric Solitary Inertial Waves, by Dr. William Blumen, University of Colorado, Boulder, CO
15 May 1992	Some Results of Data Assimilation in the Northeast/North Central Atlantic in 1986-1988, by Dr. Pierre DeMey, GRGS, CNES, Toulouse, France
19 May 1992	Salt Transport to the Southern Ocean, by Dr. J.R. Toggweiler and B. Samuels, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
20 May 1992	Development of the CSIRO Global Coupled Ocean-Atmosphere Model, by Dr. Andrew Moore, CSIRO, Mordialloc, Victoria, Australia
28 May 1992	Assessing Climate-Induced Vegetation Change: The Past as a Key to the Future, by Dr. Jonathan Overpeck, National Geophysical Data Center/NOAA, Boulder, CO
1 June 1992	Convective Parameterization at GFDL, by Dr. Leo Donner, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
2 June 1992	Surface Processes and Their Impact on Hurricanes Over Land, by Robert Tuleya, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
3 June 1992	On the Barotropic Model of the Gulf Stream Recirculation Zone, by Prof. Vladimir Kamenkovich, Lamont-Doherty Geological Observatory, Palisades, NY
4 June 1992	Forecasting Mountain Waves in the Stratosphere, by Dr. Julio Bacmeister, NASA, Goddard Space Flight Center, Greenbelt, MD

8 June 1992	Comparison of Plastic Sea Ice Rheologies with Ice Drifts Statistics, by Mr. Chi Ip, Thayer School of Engineering, Dartmouth College, Hanover, NH
16 June 1992	Annual and Interannual Modes of Oscillation of the Coupled Ocean-Atmosphere, by Dr. F. Jin, University of California, Los Angeles, CA
16 June 1992	Relationships Between Seasonal-Mean Anomalies and the Activity of Intra-Seasonal Variability, by Dr. H. Nakamura, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
17 June 1992	Development of a New Spectral Model, by William Stern, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
22 June 1992	The Effect of Radiative Transfer on Small-Scale Potential Vorticity Anomalies, by Dr. Peter Haynes, Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge, England
23 June 1992	Transport of Salty Atlantic Deep Water to the Southern Ocean, by Dr. J.R. Toggweiler and B. Samuels, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
1 July 1992	Modeling Problems that Arise at High Resolution, by Dr. Yoshio Kurihara, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
14 July 1992	Toward GCM Seasonal Predictions, by Dr. Kikuro Miyakoda, Anthony Rosati, and William Stern, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
14 July 1992	The Use of Clustered Work Stations to Solve Scientific Problems, by Jonathan Goldstein, Personal Systems Development, IBM, Austin, TX
28 July 1992	Variations in ENSO and Teleconnection Structure, by Dr. Rob Allan, CSIRO, Melbourne, Australia
4 August 1992	Recent Work in Tropospheric Ozone, by Dr. H. Levy and Jennifer Richardson, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
26 August 1992	Nonlinear Wave-Vortex Interaction on the Beta-Plane, by Dr. G. Sutyrin, P.P. Shirshov Institute of Oceanology, Academy of Science, Moscow, Russia
27 August 1992	A Late Winter Hydrographic Section between Tasmania and Antarctica: Circulation, Transport, and Water Mass Formation, by Dr. Steven Rintoul, CSIRO, Tasmania, Australia
31 August 1992	Surface Versus Rigid Lid Models of Ocean Circulation, by Dr. John K. Dukowicz, Los Alamos National Laboratory, Los Alamos, NM

1 September 1992	Ground-Based Measurements of Antarctic 0_3,NO_2 and OC10 During 1991, by Dr. Lori Perliski, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
8 September 1992	Evaluation of SKYHI's Diabatic Meridional Circulation using Aircraft N_20 Measurements, by Dr. Susan Strahan, Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ
15 September 1992	Transport, Radiative, and Dynamical Effects of the Antarctic Ozone Hole, by Drs. Jerry Mahlman, Joseph Pinto, and Lou Umscheid, Geophysical Fluid Dynamics Laboratory, Princeton, NJ

APPENDIX D

Talks, Seminars, and Papers Presented Outside GFDL

During Fiscal Year 1992

8 October 1991	Dr. Jerry D. Mahlman "Uncertainties in Global Warming Predictions", U.S. House of Representatives, Subcommittee on Science, Hearing on "Priorities in Global Change Research", Washington, DC
9 October 1991	Dr. Jerry D. Mahlman "Chemistry Research Opportunities in the Atmospheric Sciences", Department of Chemistry, Princeton University, Princeton, NJ
14 October 1991	Dr. Ngar-Cheung Lau "Variability of the Baroclinic and Barotropic Transient Eddy Forcing Associated with Monthly Changes in the Midlatitude Storm Tracks", American Meteorological Society's Fifth Conference on Climate Variations, Denver, CO
14 October 1991	Mr. William F. Stern "The Feasibility of Seasonal NWP from Decadal Simulations", American Meteorological Society's Ninth Conference on Numerical Weather Prediction, Denver CO
14 October 1991	Dr. Leo Donner "A Flux Momentum Parameterization for Cumulus Convection: Vertical Structures and Mesoscale Effects", American Meteorological Society's Ninth Conference on Numerical Weather Prediction, Denver, CO
14 October 1991	Dr. Isaac Held "QG Turbulence in a 3-Layer Model", American Meteorological Society's Ninth Conference on Numerical Weather Prediction, Denver, CO
14 October 1991	Dr. Kikuro Miyakoda "Perspective for Extended Range Dynamic Prediction", American Meteorological Society's Ninth Conference on Numerical Weather Prediction, Denver, CO
15 October 1991	Dr. Isidoro Orlanski "Ageostrophic Fluxes in Downstream and Upstream Development", American Meteorological Society's Ninth Conference on Numerical Weather Prediction, Denver, CO
18 October 1991	Dr. Kirk Bryan "High Resolution Models of the Ocean Circulation", K. Hasselmann Symposium, Max Planck Institute, Hamburg, Germany
21 October 1991	Dr. Jerry D. Mahlman "Assessing Global Climate Change: When Will We Have Better Evidence?", Conference on "Global Climate Change: It Mitigation Through Improved Production and Utilization of Energy", Los Alamos, NM

22 October 1991	Dr. Kikuro Miyakoda "Seasonal Forecast Experiment Using an Air-Sea Model and Heat Flux Correction", Los Alamos National Laboratory, Los Alamos, NM
24 October 1991	Dr. Kikuro Miyakoda "Systematic Error Correction in the Air-Sea Model", Naval Environmental Prediction Facility, Monterey, CA
28 October 1991	Dr. Syukuro Manabe "Role of Oceans in Future Climate Change" Symposium on Climate Variability and Global Change, Chianciano, Terme, Italy
28 October 1991	Dr. Kikuro Miyakoda "Experimental Seasonal Forecasts Using An Air-Sea Model", Climate Diagnostic Workshop, Los Angeles, CA
1 November 1991	Dr. George L. Mellor "The Gulf Stream and Data Assimilation", Department of Appied Mathematics, Princeton University, Princeton, NJ
6 November 1991	Dr. Jerry D. Mahlman "Greenhouse Warming: What Do We Really Know?", University of Pennsylvania Physics Colloquium, Philadelphia, PA
11 November 1991	Dr. John R. Toggweiler "Is the Atlantic Outflow Actually Driven by Southern Hemisphere Winds?", North Atlantic Deep Water Formation Mini Conference, Palisades, NY
11 November 1991	Dr. Syukuro Manabe "Stability of the Atlantic Thermohaline Circulation in a Coupled Ocean-Atmosphere Model", Conference on Influence of Fresh Water Transports on Ocean Circulation, Palisades, NY
12 November 1991	Dr. Kirk Bryan "Heat and Fresh Water Fluxes in 3-D Models - Are they Modeled Properly?", North Atlantic Deep Water Formation Mini-Conference, Palisades, NY
14 November 1991	Dr. Kirk Bryan "The Role of Ocean Models in Monitoring and Predicting Climate Variability", NASA Conference- Climate Modeling: Prospects and Needs for the Next Decade", Alexandria, Va
18 November 1991	Dr. Bruce R. Ross "Computing Challenges in Weather and Ocean Modeling", Supercomputing '91 Conference, Albuquerque, NM
20 November 1991	Dr. Jerry D. Mahlman "Understanding Climate Change", Science and Policy Associates, Inc., "Climate Research Needs Workshop", New Paltz, NY

22 November 1991	Dr. Syukuro Manabe "Modeling Study of Glacial Climate", 1991 Victor Starr Memorial Lecture, Massachusetts Institute of Technology, Cambridge, MA
25 November 1991	Dr. Isaac Held "Stationary Waves: Theory and GCM's", Columbia University, New York, NY
5 December 1991	Dr. Jerry D. Mahlman "Climatic and Dynamical Implications of the Antarctic Ozone Hole", University of Maryland, Department of Meteorology, College Park, MD
6 December 1991	Dr. Kirk Bryan "The Role of the Ocean in Climate Change and Climate Variability", Office of Space & Science Instruments, Guest Lecture Series on Global Climate Change, Jet Propulsion Laboratory, Pasadena, CA
9 December 1991	Mr. Anthony J. Rosati "The Effects of Initial Conditions on ENSO Forecasts", American Geophysical Union Fall Meeting, San Francisco, CA
9 December 1991	Dr. Syukuro Manabe "The Change of Arctic Climate as Simulated by a Coupled Ocean-Atmosphere Model", American Geophysical Union Fall Meeting, San Francisco, CA
9 December 1991	Dr. Isidoro Orlanski "The Role of Surface Fluxes over Ocean and Sea-Ice in the Development of Sub-Antarctic Ozone", American Geophysical Union Fall Meeting, San Francisco, CA
9 December 1991	Dr. P.C.D. Milly "Sensitivity of Climate to Continental Evaporation", American Geophysical Union Fall Meeting, San Francisco, CA
9 December 1991	Dr. P.C.D. Milly "Balance of a Climate Model", American Geophysical Union Fall Meeting, San Francisco, CA
9 December 1991	Dr. J. Sarmiento "Iron Fertilization: Carbon Dioxide Mitigation", American Geophysical Union Fall Meeting, San Francisco, CA
10 December, 1991	Dr. Kikuro Miyakoda "Extended Range Predictability", National Aeronautics Space Administration, Greenbelt, MD
12 December 1991	Dr. Robert Toggweiler "Implications of the Wind Forced Overturning of the Deep Ocean for the Carbon Cycle", Sayre Hall, Princeton University, Princeton, NJ

13 December 1991	Dr. John R. Toggweiler "New Radiocarbon Constraints on the Upwelling of Abyssal Water to the Ocean's Surface", Goddard Institute of Space Studies, New York, NY
6 January 1992	Dr. Stephen Garner "An Orographic Mechanism for Rapid Frontogenesis", 72nd Annual Meeting of the American Meteorological Society, Atlanta, GA
7 January 1992	Dr. Kevin Hamilton "Stratospheric Warmings in the GFDL "SKYHI" Troposphere-Stratosphere-Mesosphere General Circulation Model", 72nd Annual Meeting of the American Meteorological Society, Atlanta, GA
7 January 1992	Dr. Jerry D. Mahlman 1. "Issues of Stratospheric Transport and Chemistry: A Three-Dimensional Perspective", 2. "Transport, Radiative and Dynamical Effects of the Antarctic Ozone Hole: A GFDL SKYHI Model Experiment", 72nd Annual Meeting of the American Meteorological Society, Atlanta, GA
15 January 1992	Dr. Jerry D. Mahlman "NOAA's Role in the High Performance Computing and Communication Initiative", OAR Retreat, Silver Spring, MD
23 January 1992	Dr. Kirk Bryan "North Atlantic Climate Variability", Dartmouth College, Hanover, NH
27 January 1992	Mr. William J. Hurlin "Interannual Variability in a Model Simulation of the Tropical Atlantic", American Geophysical Union 1992 Ocean Sciences Meeting, New Orleans, LA
28 January 1992	Dr. Jorge Sarmiento "Net Uptake of CO_2 by Ocean: Oceanic Models", NATO Research Workshop on Biogeochemical Ocean-Atmosphere Transfers, Bermuda Biological Station for Research, Bermuda
27 January 1992	Mr. Keith W. Dixon "Analysis of a Coarse Resolution Global Ocean Model Using Chlorofluorocarbons as Tracers", American Geophysical Union 1992 Ocean Sciences Meeting, New Orleans, LA
4 February 1992	Dr. Jerry D. Mahlman "Monitoring Issues from a Modeling Perspective", Workshop on Long Term Monitoring of Climate Forcings and Feedbacks, GISS, New York, NY

6 February 1992	Dr. Kevin P. Hamilton "Comprehensive Modeling of the Terrestrial and Martian Atmospheres", Department of Astrophysical Sciences, Princeton University, Princeton, NJ
10 February 1992	Dr. Kikuro Miyakoda "Review on Coupled Ocean-Atmosphere Models for Long-Range Forecasting", World Meteorological Organization Meeting on Medium and Long-Range Weather Prediction Research, Toulouse, France
11 February 1992	Mr. Anthony J. Broccoli "Effects of Topography on Northern Hemisphere Midlatitude Dry Climates", Cornell University, Department of Soil, Crop and Atmospheric Sciences, Ithaca, NY
12 February 1992	Dr. Jorge Sarmiento "The Global Carbon Cycle and Anthropogenic CO_2 Budget", American Society of Limnology and Oceanography Aquatic Sciences Meeting, Santa Fe, NM
21 February 1992	Mr. William Stern "Results from Decadal Simulations with a GCM and Implications for Extended Range NWP", Atmospheric Model Intercomparison Project Meeting, Berkeley, CA
27 February 1992	Dr. Jerry D. Mahlman "Modeling Perspectives on Global Warming Indicators", Senate Commerce Committee Hearing on "Indicators of Global Warming and Solar Variability", Washington, DC
28 February 1992	Dr. Syukuro Manabe "Prediction of Greenhouse Warming by a Coupled Ocean-Atmosphere Model", Symposium on Greenhouse Warming sponsored by Japan Meteorological Agency, Tokyo, Japan
2 March 1992	Dr. Syukuro Manabe "Study of Interaction between Thermohaline Circulation and Climate by use of a Coupled Ocean-Atmosphere Model", Center for Climate System Research of Tokyo University, Shimoda, Japan
5 March 1992	Dr. George L. Mellor "Numerical Model Studies of the Gulf Stream", Kyushu University, Fukuoka, Japan
9 March 1992	Dr. Kirk Bryan "Retrospective Study of the North Atlantic", NOAA Atlantic Climate Change Program Meeting, University of Miami, Miami, FL

9 March 1992	Mr. Thomas L. Delworth "Decadal Variability of the Thermohaline Circulation in a Coupled Ocean-Atmosphere Model", Atlantic Climate Change Program Meeting, University of Miami, Miami, FL
13 March 1992	Dr. George L. Mellor "Numerical Model Studies of the Gulf Stream", Kyoto University, Kyoto, Japan
16 March 1992	Dr. Syukuro Manabe "The 30-50 Year Oscillation in a Coupled Ocean-Atmosphere Climate Model", McGill University, Montreal, Canada
16 March 1992	Dr. George L. Mellor "An Ice-Ocean Coupled Model of the Arctic Ocen", Hokkaido University, Sapporo, Japan
17 March 1992	Mr. Morris Bender Dr. Yoshio Kurihara Mr. Robert E. Tuleya "Recent Progress in the Experimental Prediction of Hurricanes at GFDL", National Meteorological Center, Washington, DC
18 March 1992	Dr. Jorge Sarmiento "A Coupled Model of Large Scale Ocean Circulation and Ecology", University of Alberta, Edmonton, Canada
18 March 1992	Dr. Jorge Sarmiento "The Role of the Ocean in Global Climate Change", University of Alberta, Edmonton, Canada
19 March 1992	Dr. George L. Mellor "Gulf Stream Modeling Studies and Data Assimilation", University of Tokyo, Tokyo, Japan
24 March 1992	Dr. George L. Mellor "Numerical Model Studies of the Gulf Stream", Meteorological Research Institute, Tsukuba, Japan
25 March 1992	Dr. George L. Mellor "Assimilation of Altimetric Satellite Data into Numerical Ocean Models", Meteorological Research Institute, Tsukuba, Japan
26 March 1992	Dr. Ngar-Cheung Lau "Variability of the Transient Eddy Forcing Associated with Monthly Changes in the Midlatitude Storm Tracks", Department of Meteorology, University of Maryland, College Park, MD
2 April 1992	Dr. Syukuro Manabe "Role of Oceans in Greenhouse Warming", Department of Applied Science, Brookhaven National Laboratory, Upton, NY

4 April 1992	Dr. John R. Toggweiler "New Radiocarbon Constraints on the Upwelling of Abyssal Water to the Ocean's Surface", Ocean-Climate Interactions Through Time Meeting, Yale University, New Haven, CT
6 April 1992	Mr. Anthony J. Rosati "Computational Considerations for Air-Sea Coupled Models", CHAMMP Model Development Meeting, Santa Fe, NM
8 April 1992	Dr. Isaac M. Held "Dynamics of Global Warming", University of Maryland, College Park, MD
9 April 1992	Dr. Isaac M. Held "Radiative-Convective Equilibrium with Explicit Moist Convection: Preliminary Results", Goddard Space Center, Greenbelt, MD
13 April 1992	Dr. Jerry D. Mahlman "OAR Achievements in Climate Modeling", OAR Program Review, Silver Spring, MD
15 April 1992	Dr. Bruce B. Ross "GFDL's Use of Desktop Workstations for Climate and Weather Research", NOAA Symposium on Scientific Workstations, Gaithersburg, MD
21 April 1992	Dr. Abraham H. Oort "Observed Temperature and Humidity Trends in the Atmosphere", NASA, Greenbelt, MD
22 April 1992	Dr. Isaac M. Held "Dynamics of Global Warming", Ogura Lecture, University of Illinois at Urbana-Champaign, Urbana, IL
2 May 1992	Mr. Richard T. Wetherald "A Summary of CO_2-Induced Hydrologic Changes as Simulated by Recent GCM's", Department of Earth & Space Sciences Conference, State University of New York, Stony Brook, NY
6 May 1992	Dr. Kirk Bryan "Present Status of Atlantic Climate Research Program (NOAA/ACCP)", Climate Variability Research and Prediction Meeting, Paris, France
6 May 1992	Dr. Jorge Sarmiento "Insertion of Ecosystem Models in 3-D GCMs" NATO Advanced Research Workshop, Chateau de Bonas, France
8 May 1992	Dr. Hiram Levy II "Surface Ozone Over the Western North Atlantic", American Geophysical Union Spring Meeting, Montreal, Canada

8 May 1992	Dr. George L. Mellor "A Numerical Model of the Mediterranean Sea", National Institute of Oceanography and Fisheries, Alexandria, Egypt
11 May 1992	Mr. Anthony J. Broccoli "Simulation of Mid-latitude Arid Climates: The Effect of Mountains and the Role of Land Surface Interaction", Spring Meeting of the American Geophysical Union, Montreal, Canada
12 May 1992	Mr. Thomas L. Delworth "Inter-decadal Variability of the Thermohaline Circulation in a Coupled Ocean-Atmosphere Model", Spring Meeting of the American Geophysical Union, Montreal, Canada
13 May 1992	Mr. Marcel Daniel Schwarzkopf "Global Lower Stratosphere Ozone Depletions: Effect on Radiative Forcing of Climate", Spring Meeting of the American Geophysical Union, Montreal, Canada
13 May 1992	Dr. George L. Mellor "Modeling Studies of the Mediterranean Sea", University of Thessaloniki, Thessaloniki, Greece
25 May 1992	Dr. Kevin P. Hamilton "What We Can Learn from General Circulation Models about the Spectrum of Stratospheric Motions", National Atlantic Treaty Organization Study Workshop on "Coupling Processes in the Lower and Middle Atmosphere", Loen, Norway
28 May 1992	Dr. Jorge Sarmiento "Carbon Cycle Models of the Ocean", National Research Council, Committee on Oceanic Carbon, Washington, DC
29 May 1992	Dr. John R. Toggweiler "Response of the Atlantic Overturning to Southern Hemisphere Winds", Yale University, New Haven, CT
3 June 1992	Mr. Marcel D. Schwarzkopf "Ozone Forcing in the 1980's: Sensitivity to the Altitude Profile", Quadrennial Ozone Symposium, Charlottesville, VA
3 June 1992	Mr. Anthony J. Broccoli "Forecasting Possible Climate Change", NOAA Colloquium on Operational Environmental Prediction, Camp Springs, MD
5 June 1992	Dr. Hiram Levy II "Tropospheric Ozone: The Role of Transport from the Stratosphere", Quadrennial Ozone Symposium, Charlottesville, VA

5 June 1992	Dr. George L. Mellor "Modeling and Data Assimilation Studies of the Gulf Stream", National Meteorological Center, Washington, DC
11 June 1992	Dr. Yoshio Kurihara "Research on Improving Hurricane Prediction", NOAA Colloquium on Operational Environmental Prediction, Camp Springs, MD
16 June 1992	Dr. George L. Mellor "The Gulf Stream and Data Assimilation", University of Rhode Island, RI
18 June 1992	Dr. Jerry D. Mahlman "Climate and Ocean Modeling at GFDL: Perspectives on Global Monitoring Issues", National Research Council Committee on Earth Studies Meeting, Washington, DC
22 June 1992	Dr. Ngar-Cheung Lau "Dynamical Processes Associated with Storm Track Variability", Department of Atmospheric Sciences, University of Washington, Seattle, WA
23 June 1992	Dr. Jerry D. Mahlman "High Performance Computing and Communication in NOAA", Meeting on Budget Initiative on High Performance Computing, Department of Commerce, Washington, DC
24 June 1992	Dr. Jorge Sarmiento "Ocean's Role in Climate", Cornell University Summer School Long Time Series Analysis and Interpretation in Terrestrial Marine and Freshwater Ecosystems, Ithaca, NY
25 June 1992	Dr. P.C.D. Milly "Evaporation from the Continents", U.S. Geological Survey, Reston, VA
25 June 1992	Dr.Jorge Sarmiento "Coupled Models of Ocean Circulation and Ecology", Cornell University Summer School on Long Time Series Analysis and Interpretation in Terrestrial Marine and Freshwater Ecosystems, Ithaca, NY
26 June 1992	Dr. P.C.D. Milly "Land-Surface Parameterization in the GFDL Climate Model", Workshop of Project for Intercomparison of Land-Surface Parameterization Schemes, Columbia, MD

13 July 1992	Mr. Thomas L. Delworth "Interdecadal Variability of the Thermohaline Circulation in a Coupled Ocean-Atmosphere Model", Workshop on North Atlantic Climate Variability on Interdecadal Time Scales, Moscow, Russia
20 July 1992	Mr. Thomas L. Delworth "Interdecadal Variability of the Thermohaline Circulation in a Coupled Ocean-Atmosphere Model", Institute for Arctic and Antarctic Research, St. Petersburg, Russia
20 July 1992	Mr. Keith W. Dixon "GFDL Modular Ocean Model Development: Plans and Expectations", Institute of Ocean Sciences, Sidney, British Columbia, Canada
22 July 1992	Mr. Keith W. Dixon "World Ocean Climate Studies at GFDL", Institute of Ocean Sciences, Sidney, British Columbia, Canada
3 August 1992	Dr. Syukuro Manabe "The Stability and Oscillation of the Thermohaline Circulation in the Atlantic Ocean", Mediterranean Workshop sponsored by the International Institute for Theoretical Physics, Venice, Italy
24 August 1992	Dr. Kevin P. Hamilton "Modeling of Middle Atmosphere Interannual Variations", Fifth Cospar Colloquium - "Initial Results from STEP Facilities and Theory Campaigns", Baltimore, MD
3 August 1992	Mr. Ronald J. Stouffer "Variability of the Coupled Ocean-Atmosphere System", Coupled Climate System and Global Change Meeting, Aspen, CO
3 August 1992	Dr. Leo J. Donner "Radiative Interactions with Convective Systems:Implications for Cumulus Parameterization", International Radiation Symposium, Tallinn, Estonia
3 August 1992	Mr. Marcel D. Schwarzkopf "Tropospheric Radiative Forcing: Effect of Changes in Ozone Profile", International Radiation Symposium, Tallinn, Estonia
3 August 1992	Dr. Isaac Held 1. "Problems in Baroclinic Instability Theory", 2. "Radiative-Convective Equilibrium with Explicit Moist Convection", National Center for Atmospheric Research, Boulder, CO
24 August 1992	Dr. Hiram Levy II "Global Transport and Transformations of Nitrogen Oxides", NATO Advanced Research Workshop, "The Tropospheric Chemistry of Ozone in Polar Regions", Halifax, Novia Scotia

24 August 1992	Mr. Anthony J. Broccoli "The Use of Climate Models in Forecasting Future Climate Change", Global Climate Change Symposium sponsored by the American Chemical Society Meeting, Washington, DC
31 August 1992	Dr. Ngar-Cheung Lau "Simulation of Air-Sea Interaction", National Central University, Taipei, Taiwan
31 August 1992	Dr. Ngar-Cheung Lau "Variability of Transient Eddy Forcing Associated with Monthly Changes in the Midlatitude Storm Tracks", Department of Atmospheric Sciences, National Taiwan University, Taipei, Taiwan
1 September 1992	Dr. Ngar-Cheung Lau "Simulation of the Climatological March of the Asian Summer Monsoon in a 40-Year GCM Experiment", Department of Atmospheric Sciences, National Central University, Taipei, Taiwan
1 September 1992	Dr. John R. Toggweiler "Transport of Atlantic Deep Water to the Southern Ocean", World Ocean Circulation Experiment NEG/CP1/CP3 Workshop, Wiltshire, UK
1 September 1992	Dr. Syukuro Manabe "Study of Greenhouse Warming and Interdecadal Climate Variability by a Coupled Ocean-Atmosphere Model", Harris Lecturer, Texas A & M University, Department of Meteorology, College Station, TX
2 September 1992	Dr. Ngar-Cheung Lau "Simulation of El Niño-Southern Oscillation Phenomena using a Hierarchy of GCM's", Department of Atmospheric Sciences, National Taiwan University, Taipei, Taiwan
2 September 1992	Dr. Ngar-Cheung Lau "Storm Track Variability", National Taiwan University, Taipei, Taiwan
3 September 1992	Dr. Jerry D. Mahlman "The Stratosphere Polar Vortex", Russia-USA Conference on Geophysical Wave-and-Vortex Systems: Dynamics, Data Assimilation and Predictability, Rutgers University, New Brunswick, NJ
3 September 1992	Dr. Jorge Sarmiento "Ocean Biogeochemistry of Nutrients, 0_2, CO_2, and N_20", Department of Geography, University of California, Berkeley, CA
4 September 1992	Dr. Jorge Sarmiento "Ocean/Climate Interactions and Ocean Productivity", Department of Geography, University of California, Berkeley, CA

7 September 1992	Dr. Ngar-Cheung Lau "Simulation of the Asian Monsoon in a 40-year Experiment with a General Circulation Model", Second International Conference on East Asia and Western Pacific Meteorology and Climate, Hong Kong
7 September 1992	Mr. Anthony Broccoli "Climate Model Studies of Interactions Between Ice Sheets and the Atmosphere-Ocean System", NATO Advanced Research Workshop, "Ice in the Climate System", Aussois, France
10 September 1992	Mr. Ronald J. Stouffer "Variability of the GFDL Coupled Model", Second International Conference on Modeling of Global Climate Change and Variability, Hamburg, Germany
14 September 1992	Mr. Ronald J. Stouffer "An Update of Coupled Modeling Activities", Committee Meeting of the Steering Group of Global Coupled Models, Hamburg, Germany
21 September 1992	Dr. Syukuro Manabe "Prediction of the Global Warming by Climate Models", Academic Award Ceremony for the Blue Planet Prize, Asahi Glass Foundation, Tokyo, Japan
21 September 1992	Mr. Thomas L. Delworth "North Atlantic Interdecadal Variability in a Coupled Model", Decade to Century Time Scales of Natural Climate Variability Workshop, sponsored by the National Research Council, Irvine, CA
21 September 1992	Dr. Kirk Bryan "A Stochastic Model of North Atlantic Variability", Decade to Century Time Scales of Natural Climate Variability Workshop, sponsored by the National Research Council, Irvine, CA

APPENDIX E

ACRONYMS

ACRONYMS

ABLE	Atmospheric Boundary Layer Experiment
AMEX	Australian Monsoon Experiment
AMIP	Atmospheric Model Intercomparison Project
AOML	Atlantic Oceanographic and Meteorological Laboratory/NOAA
ARL	Atmospheric Research Laboratory/NOAA
A91/P92	GFDL Activities FY91, Plans FY92
CEM	Cumulus Ensemble Model
CFC	Chlorofluorocarbon
CHAMMP	Computer Hardware, Advanced Mathematics and Model Physics project
CLIPER	A simple model combining CLIMatology and PERsistence used in hurricane prediction.
CMDL	Climate Monitoring and Diagnostic Laboratory/NOAA
COADS	Comprehensive Ocean-Atmosphere Data Set
COARE	Coupled Ocean-Atmosphere Response Experiment
COSPAR	Congress for Space Research
CRAY	Cray Research, Inc.
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

ENSO	El Niño - Southern Oscillation
ERBE	Earth Radiation Budget Experiment
E"n"	Horizontal model resolution corresponding to "n" points between a pole and the equator on the E-grid.
FDDI	Fiber Distributed Data Interface
FDH	Fixed Dynamic Heating model
FIRE	First ISCCP Regional Experiment
GATE	GARP Atlantic Tropical Experiment
GARP	Global Atmospheric Research Program
GCM	General Circulation Model
GCTM	Global Chemical Transport Model
GEOSAT	Geodetic Satellite
GFDL	Geophysical Fluid Dynamics Laboratory/NOAA
GMT	Greenwich Mean Time
GTE	Global Tropospheric Experiment
HIBU	Federal Hydrological Institute and Belgrade University
HRD	Hurricane Research Division/AOML
IPCC	Intergovernmental Panel on Climate Change
ISCCP	International Satellite Cloud Climatology Project
ITCZ	Intertropical Convergence Zone
JGOFS	Joint Global Ocean Flux Study
JJA	June, July, August (summer)

LAHM	Limited Area HIBU Model
LBL	Line by line
L"n"	Vertical model resolution of "n" levels.
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
PMEL	Pacific Marine Environmental Laboratory
QBO	Quasi-biennial oscillation
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
SPCZ	South Pacific Convergence Zone
SST	Sea Surface Temperature
SUN	Sun Microsystems, Inc.
TOGA	Tropical Ocean and Global Atmosphere (project)
TOMS	Total Ozone Mapping Spectrometer
THC	Thermohaline circulation
T"n"	Horizontal resolution of spectral model with triangular truncation at wave number "n".
TTO	Transient Tracers in the Oceans
WGNE	Working Group on Numerical Experimentation
WMO	World Meteorological Organization
WOCE/HP	World Ocean Circulation Experiment/Hydrographic Program