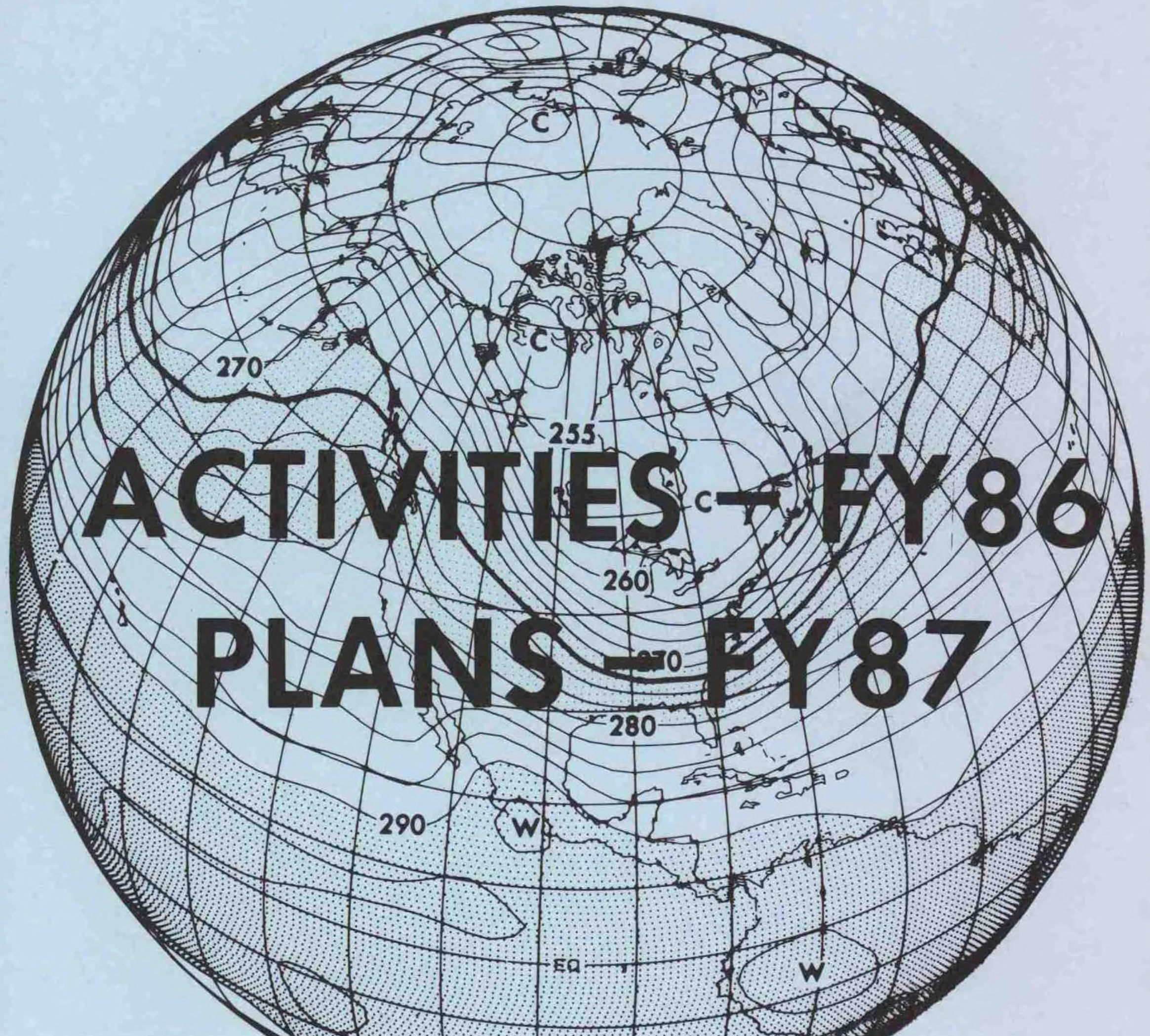
GEOPHYSICAL FLUID DYNAMICS LABORATORY



ACTIVITIES – FY86
PLANS – FY87

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

GEOPHYSICAL FLUID DYNAMICS LABORATORY

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September 1986

Geophysical Fluid Dynamics Laboratory
Princeton, New Jersey

UNITED STATES DEPARTMENT OF COMMERCE
Malcolm Baldrige, Secretary

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
Anthony J. Calio, Administrator

Environmental Research Laboratories
Vernon E. Derr, Director

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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 interested offices of the National Oceanic and Atmospheric Administration, and to other relevant government agencies and national organizations.

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

The appendices contain the following: a list of GFDL staff members and affiliates during Fiscal Year 1986; 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 FY87; a listing of seminars presented at GFDL during Fiscal Year 1986; a list of seminars and talks presented during Fiscal Year 1986 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 1986 Annual Report was co-edited by Ngar-Cheung Lau and Betty M. Williams.

September 1986

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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 Geophysical Fluid Dynamics Program which is conducted collaboratively with Princeton University. Under this program, regular Princeton faculty, visiting 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. Visiting scientists to 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 FY86

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, that have high spatial resolution, and that parameterize turbulent processes more accurately. Successful forecasts for periods up to a few days are now possible, and the limits of atmospheric predictability have been extended to several weeks. However, quantitative precipitation forecasts 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.

This success in the extension of atmospheric predictability encourages us to pose more challenging questions. Can the weather be predicted on time-scales of months? Are mesoscale weather systems and regional scale precipitation patterns predictable, and if so, 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 (FY86)

* A new parameterization of gravity wave drag has been developed and tested in a long range forecast model. Forecast skill was found to improve substantially; this is consistent with results on the impact of gravity wave drag that have been found at other institutions, including the U.K. Meteorological Office (3.1.2).

* Results of monthly forecasts for 8 January cases indicate that the model's systematic biases (climate drifts) account for a large portion of the forecast errors. For example, for the temperature error at 300 mb in the tropics, the climate drift contributes 83% of the forecast errors, and the forecast error due to the climate drift for northern hemisphere 500 mb geopotential height for day 10-30 is 64% (3.1.4).

* A fundamental new fluid dynamical instability was discovered. This mechanism breaks down non-circular two dimensional vortices into small scale three dimensional structures. This instability is believed to play a major role in the onset of turbulence in small scale flow (3.2.4).

* A simulation of the tropical ocean has been completed; the model has 1°x1° spatial resolution and is global in domain with 1/3° meridional resolution in the equatorial zone, and has 12 vertical levels. The model incorporates a turbulence closure scheme and a nonlinear viscosity for lateral diffusion. A test of this model for the 1982/83 El Niño case shows satisfactory performance; however, the impact of coarse vertical resolution is noted (3.3.1).

* Further study of the effect of mountains on the behavior of tropical cyclones shows that the structure of storms sometimes become considerably altered or disorganized during and after crossing the island terrain, making the storm position almost undefinable (7.1.1).

* The simulation results of the genesis of real tropical storms indicate that some of the tropical disturbances at pre-storm stage are significantly controlled by synoptic scale conditions and, hence, they are predictable to a certain degree (7.1.2).

* A theoretical study of the classical Eady baroclinic model has elucidated the influence of nongeostrophic effects on meso-baroclinic waves. The analysis also showed the existence of a secondary, weak instability due to inertial critical layers (8.1.2).

* A successful simulation of cyclogenesis on the lee of the Tibetan Plateau has recently been completed. The resulting vortices frequently produce heavy rainfall in the region and are believed to be caused by orographic effects. The numerical simulations indicate that orography alone only triggers weak vortices; however, in the presence of a moist stagnation region on the eastern flank of the plateau, these vortices intensify (8.3.1).

* The effect of mesoscale forcing and diabatic heating on the formation of convective systems has been investigated in realistic simulations of a squall line that developed over Texas and Oklahoma on 10-11 April 1979. The results of these experiments show that low-level convergence alone is sufficient in this case to initiate and organize the observed cloud systems. However, latent heating must be present to produce the observed deep convection and to maintain the low-level convergence (8.4.1).

* The moist convection model has been updated to include subgrid-scale condensation below cloud base with the concomitant latent heat release. For both shallow and deep convection, this scheme tends to produce a more uniform vertical velocity and to maintain the cloud over a longer lifetime by supplying low level heating. For shallow convection, rain reaching the ground is increased significantly (9.1).

SOME PLANS FOR FUTURE RESEARCH

* Numerical models will be under continual development to improve forecasting of the large scale, the mesoscale, hurricanes, and squall lines, with emphasis on improved parameterizations of orography, cloud-radiation interaction and various subgrid-scale effects.

* Diagnostic analysis will be employed to improve understanding of essential weather processes relevant to prediction of atmospheric and oceanic phenomena with short, medium and long time scales.

* Collaboration will continue with the National Meteorological Center, both in the development of the Medium Range Forecast Model and a new operational model for hurricane prediction.

II. CLIMATE

GOALS

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

ACCOMPLISHMENTS OVER THE PAST YEAR (FY86)

* In order to study the role of land surface processes in climate variability, a fifty-year integration of a general circulation model with prescribed sea surface temperatures and cloudiness has been conducted. Analysis shows that while the spectrum of precipitation over land is white at all latitudes, the spectrum of soil moisture (driven by the precipitation forcing) is red, and becomes increasingly red at higher latitudes. This may be the result of reduced potential evaporation and insolation at higher latitudes (1.1.1).

* The importance of geography on the transient response of an atmosphere-ocean model to a doubling of atmospheric CO_2 was investigated. An idealized model with two hemispheres is used in which the fractional coverage of continent and ocean at each latitude is approximately equal to the actual coverage. At the latitudes of the Drake Passage, the domain is completely covered by ocean. The results indicate a much slower rate of surface warming in high latitudes of the southern hemisphere (1.2.1).

* A series of experiments was conducted in which an atmosphere-mixed layer ocean model was used to study the contributions of continental ice, atmospheric CO_2 and changes in land albedo to the climate of the last glacial maximum (LGM). These experiments indicate that the most important contributor to the LGM climate cooling in the northern hemisphere is the presence of expanded continental ice. In contrast, the cooling in the southern hemisphere is associated primarily with the reduced atmospheric CO_2 content of glacial times (1.4).

* An analysis was made to determine the mechanisms responsible for the enhancement of the CO_2-induced warming of a model climate by cloud feedback processes. In response to a doubling of CO_2 both relative humidity and cloud amount are increased near the tropopause and are reduced in the middle troposphere. Thus, the effective cloud top height increases thereby reducing the outgoing terrestrial radiation. On the other hand, the reduction of tropospheric cloud cover with a high albedo increases the net insolation received by the system. Both processes act to enhance the CO_2-induced warming of a model climate (1.3).

* The extratropical atmospheric response to El-Niño surface temperature conditions in the Pacific as produced by a general circulation model has been diagnosed with idealized steady state barotropic and baroclinic models. These calculations demonstrate that the wavetrain over the North Pacific and North America cannot be thought of as directly forced by tropical latent heating. The wavetrain is more directly forced by anomalous mid-latitude transient eddy momentum fluxes which must, in turn, be related to the anomalous tropical forcing (1.5.1).

* Analysis of a spectral GCM integration and FGGE observation data shows that tropical intraseasonal oscillations take the form of an eastward moving Kelvin mode near the equator and an eastward moving Rossby mode away from the equator (1.6.1).

* Analysis of a general circulation model with a flat, saturated, zero-heat capacity surface has revealed the presence of eastward propagating waves at the equator with periods of 20-30 days that closely resemble observed atmospheric oscillations with somewhat longer periods (about 40 days). The presence of these waves in such an idealized model allows one to analyze the underlying dynamics in detail and rules out some current theories for their generation. Surprisingly, a well-defined eastward propagating tropical wave of even lower frequency (>100 day period) is also produced by this idealized GCM (1.6.1 and 6.1.5).

* Experiments using a GCM with a zonally uniform surface indicates that cyclone-scale waves enhance transient ultralong waves in the growing stage by wave-wave energy transfer, but reduce these waves in the mature stage by reducing the mean baroclinicity through wave-mean flow interactions (1.6.2).

* A modeling study of the errors expected from use of the TIROS-N Operational Vertical Sounder (TOVS) satellite system has revealed some pronounced effects. The satellite's analysis of the tropics is highly restricted due to poor sampling and inapplicability of geostrophic-type approximations. The regression technique currently used has been found to be severely limited by its dependence on the quality of the available "ground truth" data used in the algorithm (2.2.5).

* A set of model solutions has been obtained for atmospheric circulations over a wide range of rotation rates, obliquity, moisture, and surface friction. The results show that just 5 basic atmospheric circulation types emerge (5.1.2).

* The frequency and geographical dependence of the mode of propagation and physical structure of observed and simulated transient fluctuations have been analyzed using cross-spectral techniques. It is demonstrated that the current version of the GCM is capable of reproducing the full range of observed atmospheric phenomena with time scales from several days to a season (6.1.3).

* The distinctions between the principal mode of atmospheric variability associated with internal dynamics and the anomalous circulation pattern accompanying El Niño-Southern Oscillation episodes are highlighted by analyzing extended GCM simulations with and without sea surface temperature variations at the lower boundary. It is demonstrated that both internal atmospheric processes and external forcing are capable of imparting a considerable level of variability to the atmospheric circulation (6.2.2).

SOME PLANS FOR FUTURE RESEARCH

* A coupled ocean-atmosphere model with realistic geography will be used to investigate the transient response of climate to an increase of atmospheric carbon dioxide.

* An attempt will be made to simulate the climate of the last glacial maximum by use of a coupled ocean-atmosphere model.

* Detailed analysis will be continued on the spatial and temporal variability of soil wetness in the 50-year integration of a general circulation model of the atmosphere.

* The stationary eddies produced by a variety of GCM's, both realistic (present, ice-age, and increased CO_2 climates) and idealized, will be analyzed and compared with the predictions of a linear stationary wave model.

* A very efficient two-layer atmospheric model coupled to an oceanic mixed-layer will be used for a preliminary study of the climatic response to orbital parameter variations.

* Many diagnostic and theoretical analyses will be undertaken on transient and standing flows as well as their interaction. Diagnostic analysis will continue with emphasis on global dynamical climatology, as well as an increased emphasis on regional problems such as those of the southern hemisphere, polar regions, southeast Asia and the central Pacific.

III. ATMOSPHERIC QUALITY

GOALS

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

ACCOMPLISHMENTS OVER THE PAST YEAR (FY86)

* A new hypothesis has been advanced that the recent "Antarctic Ozone Hole" phenomenon is the result of a natural, but unusual dynamical process. The dynamical hypothesis asserts that the magnitude of winter dynamical forcing from the southern hemisphere high latitude decreased significantly after about 1980. This reduced forcing, which has been identified in observed data, is shown to produce most of the major features seen in the ozone data (2.1.6).

* A new shortwave radiation scheme has been developed for the SKYHI GCM to simulate the radiative influence of aerosols. This new scheme allows investigation of a new class of climate-aerosol interaction problems (2.3.1).

* The vertical mixing of passive tracers initially confined to the boundary layer has been examined. Calculations with a moist convection model have been carried out for a fully insoluble tracer, an infinitely soluble tracer and a partially soluble tracer. Calculations for the partially soluble tracer have been performed for SO_3. Preliminary results indicate that significant amounts of SO_3 are advected to upper cloud levels, a situation analogous to the vertical mixing of the fully insoluble tracer (9.3).

SOME PLANS FOR FUTURE RESEARCH

* Work will continue on the regional/global transport, chemistry, and removal of chemically and climatically important trace gases. A self-determined ozone chemistry will be inserted into the SKYHI GCM.

* Moist chemical removal parameterization processes will be developed for use in convective and large scale models.

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 in estuaries, the modeling of the dispersion of geochemical tracers (tritium, radon...) 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 such as the Hudson-Raritan and Delaware Estuaries 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 (FY86)

* The ongoing analysis of data obtained during the Transient Tracers in the Ocean (TTO) North and Tropical Atlantic studies, has led to a better understanding and clearer picture of the structure of the Deep Western Boundary Undercurrent and the benthic mixed layer (4.2.2).

* Two cruises were completed during FY86. The first, an intercalibration cruise, set out to collect water samples for interlaboratory comparisons of radium measurement techniques. The second involved using tracers in order to study cross-Gulf Stream exchange in the North Atlantic (4.2.3).

* A simulation of the entry of bomb-produced carbon-14 has been completed. This study verifies that the World Ocean model contains the main downward pathways indicated by transient tracer data. The model allows a forecast of the bomb-produced carbon-14 distribution during the period of WOCE, and demonstrates the usefulness of the model for predicting the response of the ocean to climatic transients on decadal time scales (4.3).

SOME PLANS FOR FUTURE RESEARCH

* An effort will be initiated to incorporate biological effects in a coupled carbon cycle/ocean GCM.

* A wide range of analyses of ocean tracer data relative to ocean dynamical structure will continue.

V. OCEAN SERVICE

GOALS

A variety of models that can be used for the prediction of oceanic conditions are being developed at GFDL. The simpler models are capable of predicting relatively few parameters. For example, one-dimensional models of the turbulent surface layer of the ocean predict the sea surface temperature and heat content of the upper ocean. More complex three-dimensional models are being developed to study phenomena such as the time dependent development of Gulf Stream meanders and rings, the generation of the Somali Current after onset of the southwest monsoons, the response of coastal zones to atmospheric storms, and the 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 (FY86)

* A realistic simulation of the seasonal cycle in the tropical Atlantic Ocean permits a study of the mass budget and indicates that upwelling near the equator, and intense downwelling in adjacent latitudes, are of central importance in closing the horizontal circulation (4.1.2).

* Unusual conditions in the tropical Atlantic Ocean in 1984 resemble El Niño episodes in the Pacific in many respects, but a crucial difference is that the Atlantic has no counterpart to the eastward movement of the convergence zone over the western Pacific (4.1.1).

* A comparison of the annual cycle of two monthly climatological sea surface temperature fields based on two different data sets has been made: the relatively data-rich COADS (Comprehensive Ocean-Atmosphere Data Set) merchant ship data file (70 million ship reports), and the relatively data sparse NODC (National Oceanographic Data Center) (1.5 million sea surface temperature measurements). The comparison shows that the NODC based analyses capture the first two harmonics of the annual cycle quite well. This finding gives greater confidence in the representativeness of the analyzed subsurface thermal fields (and thus heat storage) which are based only on the sparse NODC files (6.3.1).

* Computations of meridional Ekman heat transport in the world ocean have been completed. The Indian Ocean exhibits an annual mean southward heat flux across nearly all latitudes from 28°N to 30°S. This southward flux is in agreement with heat flux estimates based solely on surface heat balance (6.3.2).

SOME PLANS FOR FUTURE RESEARCH

* Work will continue on the development of coupled ocean-atmosphere general circulation models. The capability of such models to simulate the interannual variability of the ocean-atmosphere system will be assessed.

* Detailed analysis of the behavior of ocean models will be underway with special emphasis on the new higher resolution models.

* Work will continue on ocean model developments with emphasis on ice dynamics, turbulent closure, and isopycnal coordinates.

* Detailed comparisons of estuary model behavior against observations will be carried out.

PROJECT ACTIVITIES FY86

PROJECT PLANS FY87

1. CLIMATE DYNAMICS

Goals

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

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

* To identify and elucidate the physical and dynamical mechanisms which maintain climate and cause its variation.

* To evaluate the impact of human activities on climate.

1.1 LAND SURFACE PROCESSES AND CLIMATE

T. Delworth   R. T. Wetherald
S. Manabe

1.1.1 Hydrologic Variability

ACTIVITIES FY86

In order to investigate the role of land surface processes in climate variability, a fifty-year integration of a low resolution general circulation model with prescribed sea surface temperatures and cloudiness was performed. Much of the analysis of this integration has been devoted to documenting and studying the spatial and temporal variability of soil moisture and precipitation and their interactions with other components of the climate system.

One-point teleconnection analysis, used to uncover patterns of spatial variability, has revealed the existence of at least two large regions in which soil moisture is spatially well correlated. These regions are located on the flanks of large arid regions, one on the southern flank of the Sahara, the other in the arid steppes of central Asia. Analysis of time filtered data has shown that these patterns of spatial correlation are more pronounced at low frequencies (at time scales of one year or more).

Temporal variability has been studied by the computation of the spectra of soil moisture and precipitation over continents at each grid point. Zonal averaging shows that the spectrum of precipitation is almost white at all latitudes, with total variance decreasing poleward. In contrast, the spectrum of soil moisture is red, and becomes redder with increasing latitude. As a measure of this difference in redness, half of the total variance of the tropical soil moisture spectrum resides in periods longer than nine months, while at high latitudes, half of the total variance of the soil moisture spectrum resides in periods longer than twenty-two months. Longitudinal variations also occur in the spectrum of soil moisture.

The temporal variability results may be viewed in the light of Hasselmann's work on stochastic processes.[1] The formulation of the GFDL soil moisture parameterization is mathematically similar to such a stochastic process. According to this model, forcing of a system by an input white noise variable (precipitation) will yield an output variable (soil moisture) with a red spectrum, the redness of which is controlled by a damping term (potential evaporation in the soil moisture parameterization). Thus, the model soil moisture spectrum, which becomes increasingly red with latitude, may be caused by the decreasing values of potential evaporation at high latitudes. Physically, soil moisture excesses are dissipated more slowly at high latitudes where potential evaporation is small.

[1]Hasselman, K., 1976: Stochastic Climate Models: Part I. Theory. Tellus, 28, 473-484.

PLANS FY87

Further study of the spatial variability of soil moisture is planned. A zero-dimensional model will be used to (1) investigate the physical mechanisms of soil moisture variability, as well as (2) study the sensitivity of this variability to the soil moisture parameterization. The relationship of both temporal and spatial variability to climatic zones will also be investigated.

1.1.2 CO_2 and Soil Wetness

ACTIVITIES FY86

This long term project investigates the change of the hydrologic cycle in response to an increase of atmospheric concentration of carbon dioxide. Two versions of a general circulation model were used in this investigation, one with prescribed cloud cover and the other with predicted cloud cover. A detailed analysis on the CO_2-induced changes of soil wetness has been completed for both of these cases.

It is found that, in response to a doubling (or quadrupling) of atmospheric carbon dioxide, soil moisture is reduced in summer over extensive mid-continental regions of both North America and Eurasia in middle and high latitudes. Based upon the budget analysis of heat and water, the physical mechanisms responsible for the CO_2-induced changes of soil moisture are determined for the following four regions: Northern Canada, Northern Siberia, the Great Plains of North America and Southern Europe. Over Northern Canada and Northern Siberia, the CO_2-induced reduction of soil moisture in summer results from an earlier occurrence of the snowmelt season followed by a period of intense evaporation. Over the Great Plains of North America, the earlier termination of the snowmelt season also contributes to the reduction of soil moisture during the summer season. In addition, the rainy period of late spring ends earlier, thus enhancing the CO_2-induced reduction of soil moisture in summer. In the model with variable cloud cover, the summer dryness over the Great Plains is enhanced further by a reduction of cloud amount and precipitation in the lower model atmosphere. This reduction of cloud amount increases the solar energy reaching the continental surface and the rate of potential evaporation. Both the decrease of precipitation and the increase of potential evaporation further reduce the soil moisture during early summer and help to maintain it at a low level throughout the summer. Over Southern Europe, the CO_2-induced reduction of soil wetness occurs in a qualitatively similar manner, although the relative magnitude of the contribution from the change in snowmelt is smaller. For details, see (723).

1.2 OCEAN CIRCULATION AND CLIMATE

K. Bryan
K. Dixon

S. Manabe
M. J. Spelman
R. J. Stouffer

This project represents a close cooperation between the Climate Dynamics Group and the Ocean Circulation Group of the Laboratory.

1.2.1 Transient Response of Climate

ACTIVITIES FY86

A study of the interhemispheric asymmetry of the transient response of an atmosphere-ocean model to an increase of atmospheric carbon dioxide was started during the past year. Previous studies of the transient response to increased CO_2 (484,567,678,699) have used an idealized model in which the computational domain was extended from equator to pole and was bounded by two meridians of longitude 120° apart. The domain was divided into two equal areas of continent and ocean at each latitude. In the present study, the importance of geography on the transient climate response to doubling of atmospheric CO_2 is investigated. Therefore, the idealized model is extended to two hemispheres and the fractional coverage of continent and ocean at each latitude circle is approximately equal to the actual coverage. At the latitudes of the Drake Passage, the domain is completely covered by ocean. The transient response of this model to an abrupt doubling of atmospheric carbon dioxide is investigated.

In the Southern Hemisphere, which has a larger fraction of ocean, the response of sea surface temperature lags substantially behind the corresponding response in the Northern Hemisphere. This is partly because the thermal inertia is much greater in the Southern Hemisphere where the oceanic area is larger and the penetration of the thermal anomaly is deeper. Another factor is the hemispheric difference in ocean circulation. Poleward of 45°S latitude, the sea surface temperatures hardly increased during the 50 years following the doubling of atmospheric CO_2 because of upwelling and the equatorward advection of deep water which is unaffected by the CO_2-induced warming. A previous study (484) found that the transient response of surface temperature to increasing CO_2 becomes almost uniform with latitude approximately 25 years after an abrupt increase of CO_2. In the present study, this statement appears to be valid only in the Northern Hemisphere.

PLANS FY87

The study of the interhemispheric asymmetry of the transient climate response will be continued. A similar study using a detailed global model of the atmosphere-ocean system with realistic geography will be started.

1.2.2 Multiple Equilibria

ACTIVITIES FY86

During the past year, two experiments were conducted using a coupled global atmosphere-ocean model which incorporated realistic topography and annual mean insolation. The atmospheric component of the model is a spectral general circulation model with rhomboidal truncation at 15 wavenumbers (R15). The oceanic component is a grid point general circulation model with a grid spacing of 4° latitude. In these experiments, the model was time-integrated to a stable equilibrium from two different sets of initial conditions under an identical boundary condition. When the equilibrium climates of these two experiments were compared, it was found that they were different, especially in the region of the North Atlantic Ocean. One had a thermohaline circulation similar to today's observed climate in which the surface waters in the Atlantic Ocean flow northward to high latitudes where they sink and flow southward in the middle levels of the ocean. In the other experiment, this circulation did not exist.

Because of the difference in residence time of surface water, both surface temperature and salinity are quite different between the two experiments in the high latitudes of the North Atlantic Ocean, where the ocean surface is cooled strongly and is diluted due to the excess of precipitation and runoff over evaporation. For example, the difference in surface temperature reaches 8°C and that of surface salinity exceeds 4 parts per thousand in the North Atlantic Ocean of the model. This increased surface salinity accounts for the increased density that leads to the overturning in this region. Over the rest of the globe the surface temperature difference is much smaller. In the Northern Hemisphere, the zonal mean surface air temperatures are slightly warmer in the experiment with the thermohaline circulation while in the Southern Hemisphere, the surface air temperatures are slightly colder.

These results show that, under identical boundary conditions, at least two equilibria are possible in coupled atmosphere-ocean models. Therefore, one has to keep this possibility in mind when interpreting the results from sensitivity studies using such models. Also, the present results may be compared to paleoclimatic evidence in order to validate the model. Figure 1.1 is a comparison of the difference in surface air temperature from the models described above and paleoclimatic evidence compiled by Broecker et. al. (1985).[2] It is speculated by those authors that during the Younger Dryas period, the thermohaline circulation in the North Atlantic Ocean shut off abruptly, causing large regional climatic effects. The plusses (+) in Figure 1.1b are sites where there is evidence of an abrupt warm to cold to warm temperature change. The minuses (-) are sites where this oscillation is not present in the climatic record. One can see by comparing Figure 1.1a,b in the North Atlantic region that the area of largest temperature sensitivity obtained from the present results roughly corresponds to the region of plusses obtained from the paleoclimatic evidence. The fact that this pattern is produced by contrasting climates from models in which one has the thermohaline circulation in the North Atlantic and one which does not have this circulation seems to support the Broecker et. al. speculation.

PLANS FY87

During the next year, the effects of the thermohaline circulation in the Atlantic Ocean on climate will be studied. In particular, climatic differences due to changes in the strength of this circulation will be compared to the paleoclimatic evidence obtained from the Younger Dryas period.

1.2.3 Circumantarctic Currents and Climate

ACTIVITIES FY86

Geological evidence indicates that the deep zonal pathway around the Antarctic continent was completely opened by the late Oligocene (30 to 25 million years ago) due to the northward displacement of the Australian

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[2] Broecker, W., D. Peree and D. Rind, 1985: Does the Ocean-Atmosphere System Have More Than One Mode of Operation? Nature, 315, 21-26.

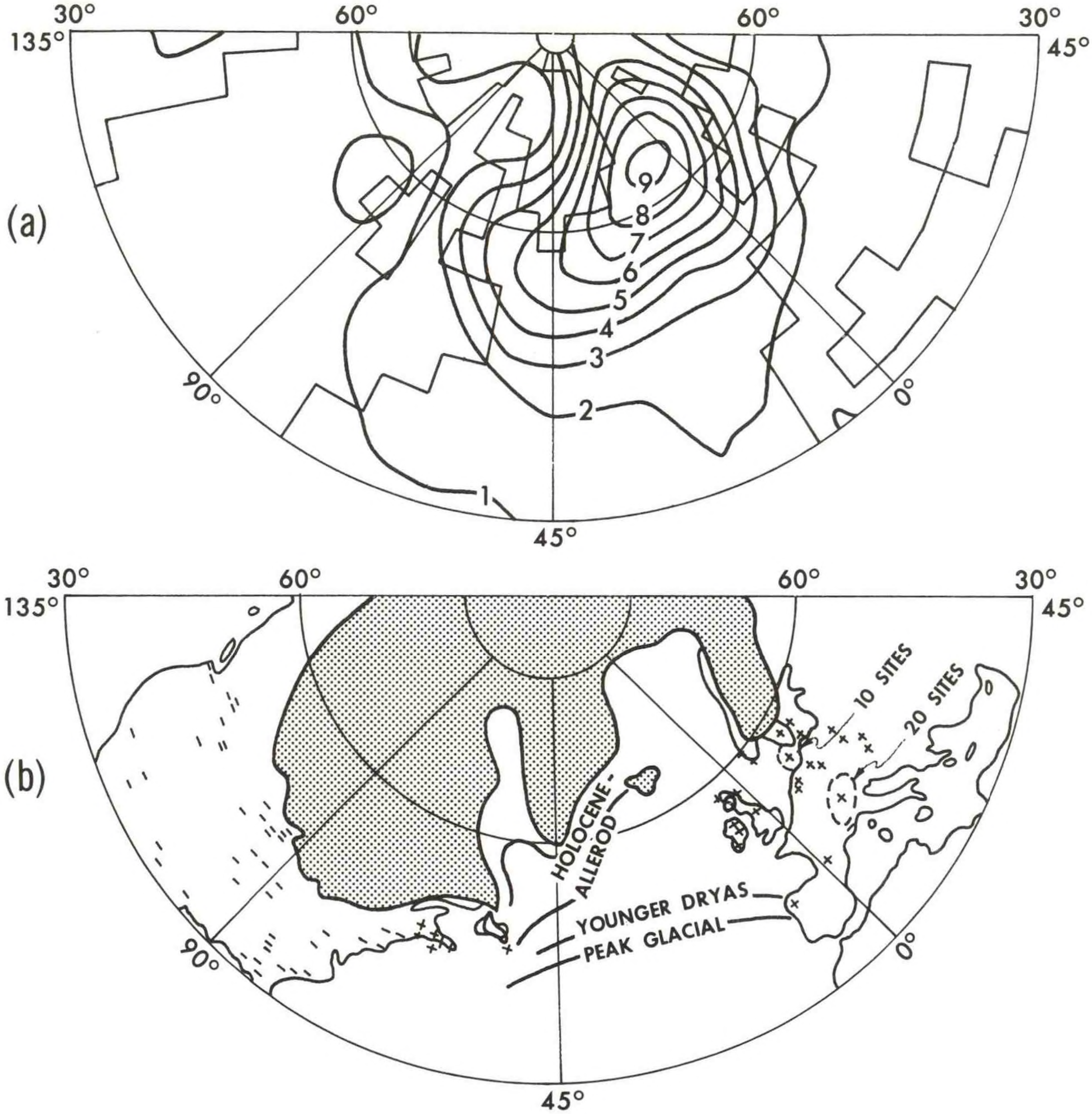

Fig. 1.1 - (Top Panel) Distribution of the differences in surface air temperature for two equilibrium climatic states, as obtained by subtracting the data values for a GCM experiment without the Atlantic thermohaline circulation from the corresponding values for another experiment with the thermohaline circulation. (Bottom panel) The sites where sediment records indicate a climatic oscillation during the Younger Dryas period (13-9 Kyr BP) are denoted by plus (+) signs. Sites where no such oscillation is detectable are denoted by minus (-) signs. The shaded region represents the area covered by land ice during this period. The location of the polar front for various geological periods are also indicated in the figure. The paleoclimatic data displayed here have been compiled by Broecker et al. (1985), who speculated that the Younger Dryas oscillation in surface temperatures is caused by the shutting off of the Atlantic thermohaline circulation.

continent (Kennett, 1977).[3] In order to evaluate the climatic impact of the opening of the zonal pathway at latitudes of the Drake passage, a pair of numerical experiments was conducted by use of a coupled ocean-atmosphere model with an idealized flat continent. The model has a limited computational domain bounded by two meridians separated by 120° longitude. In the first experiment, the fractional coverage of ocean and continent at each latitude is approximately equal to the actual coverage. At the latitudes of the Drake passage, the domain is completely covered by ocean. The second experiment is identical to the first except that the zonal Drake passage is interrupted by a narrow strip of land. Two equilibrium climates are obtained from the long term integrations of both versions in which oceanic and atmospheric components of the model are coupled asynchronously.

The closed Drake passage experiment develops an intense meridional circulation which sinks along the coast of the idealized Antarctic continent and rises in the Northern Hemisphere portion of the ocean. This inter-hemispheric, thermohaline circulation effectively transports heat southward to the periphery of the Antarctic continent. On the other hand, such an intense circulation does not develop in the open Drake passage experiment. Instead, a thermohaline circulation in the Southern Hemisphere is interrupted by a deep indirect meridional cell which develops around the latitudes of the Drake passage under the influence of intense surface westerlies. Such a cell transports heat equatorward contributing to the reduction of poleward heat transport by ocean currents at these latitudes. Thus the surface air temperature over the Antarctic continent in the open Drake passage experiment is several degrees colder than the corrresponding temperature in the closed Drake Passage experiment.

One can speculate that the fall of the Antarctic temperature during the Tertiary may partly result from the reduction of southward oceanic heat transport caused by a displacement of the continental barrier from the latitudes of the Drake passage.

PLANS FY87

Detailed analysis of the results from these numerical experiments and the assessment of their paleoclimatic implications will continue.

1.3 CLOUD FEEDBACK PROCESS

S. Manabe R. T. Wetherald

ACTIVITIES FY86

During the past year, an extensive analysis was made to determine the physical mechanisms responsible for the enhancement of the global climate sensitivity by cloud feedback processes. It is found that the cloud feedback process enhances the sensitivity of tropospheric and surface air temperature. In response to an increase of atmospheric carbon dioxide, both relative humidity and cloud amount increase near the tropopause, whereas they are

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[3] Kennett, J. P., 1977: Anozoic Evolution of Antarctic Glaciation, the Circum-Antarctic Ocean, and their Impact on Global Paleo-Oceanography. J. Geophys. Res., 82, (27), 3843-3860.

reduced in the middle troposphere of the model. These changes of the cloud distribution raise the effective source of upward terrestrial radiation at the top of the model atmosphere and decrease the radiative loss of energy from the earth-atmosphere system, thereby enhancing the CO_2-induced warming. In addition, the reduction of tropospheric cloud cover with a relatively high albedo lowers the planetary albedo of the system and further enhances the warming. As discussed in (721), the CO_2-induced changes of cloud cover described above are qualitatively similar to the changes obtained from the earlier GFDL study (420) as well as those from studies conducted at other institutions.

This study represents a continuation of a long term research project on cloud feedback processes conducted at GFDL. It has succeeded in clarifying the physical mechanisms involved in the interaction between cloud cover and radiation.

PLANS FY87

A model with increased resolution will be developed that will allow a more accurate calculation of cloud-moisture feedbacks in the upper troposphere.

1.4 ICE AGE CLIMATE

A. J. Broccoli I. M. Held
S. Manabe P. J. Phillipps

ACTIVITIES FY86

An atmosphere-mixed layer ocean model was used to study the contributions of expanded continental ice, reduced atmospheric CO_2 and changes in land albedo to the maintenance of the climate of the last glacial maximum (LGM). A series of experiments were performed in which these changes in boundary conditions were incorporated either singly or in combination. An earlier study (707) has shown that including all three of these factors produced a reasonable simulation of the LGM cooling. By comparing results from pairs of experiments in the series, the effects of each of these environmental changes were determined.

In the current study, an examination of changes in surface air temperature and sea surface temperature showed that both the ice sheet and CO_2 effects are required in order to simulate the LGM cooling on a global basis. The expansion of continental ice produces much of the Northern Hemisphere cooling, but has only a very minor influence on Southern Hemisphere temperature. This result is consistent with a previous study of the effects of continental ice on climate (616). Most of the cooling in the Southern Hemisphere results from the reduction of CO_2. Changes in land albedo have only a small effect on global temperature, although they have a substantial local influence in some low latitude locations. An example of these thermal effects is shown in Fig. 1.2 which contains the latitudinal distribution of changes in zonal mean sea surface temperature associated with each of the changes in boundary conditions.

The role of reduced CO_2 in maintaining an ice age climate is particularly interesting given the difficulties in reconciling the simultaneity of glacial

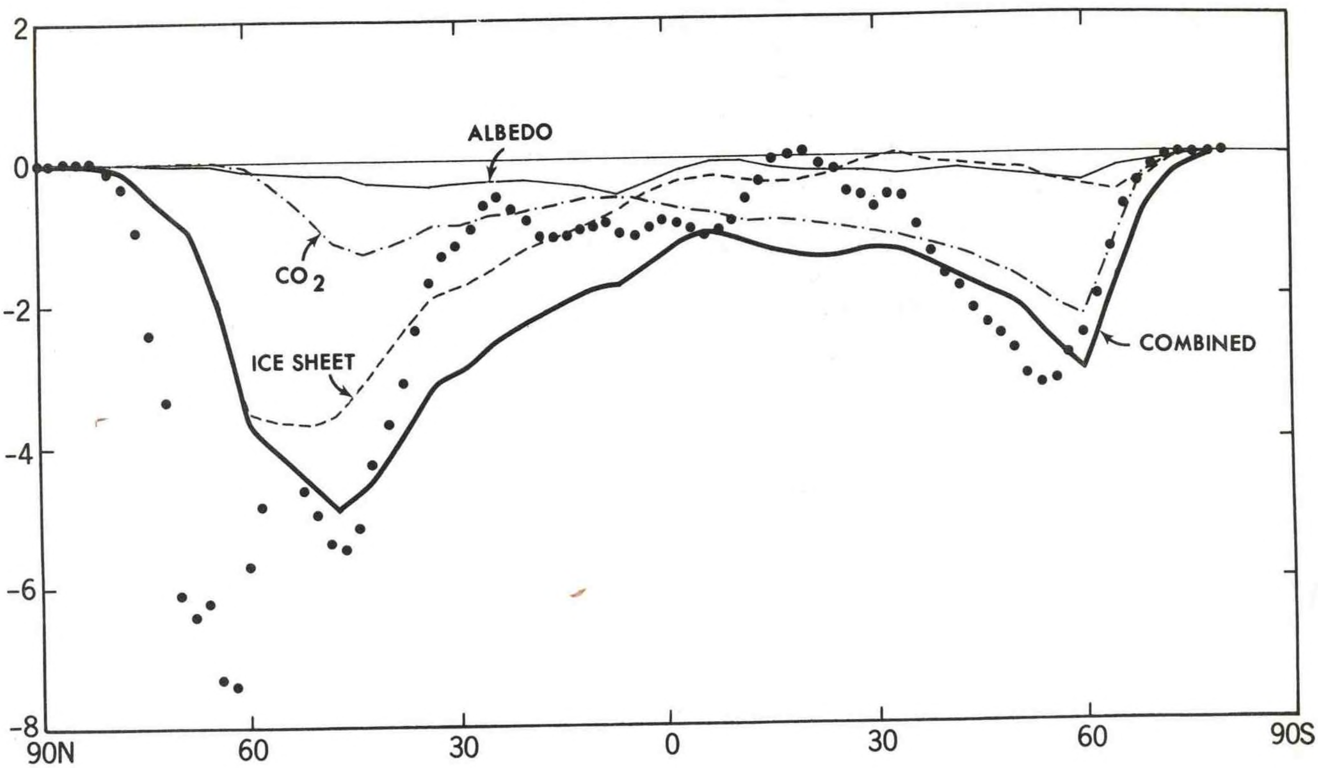

Fig. 1.2. Changes in annually-averaged zonal mean sea surface temperature (°C) produced by expanded continental ice sheets, reduced atmospheric CO_2, changes in land albedo, and all of these effects combined. Temperature differences between the last glacial maximum and the present as estimated by CLIMAP* are shown for comparison by the solid circles.

* CLIMAP Project Members, seasonal reconstructions of the earth's surface at the last glacial maximum, <u>Geol. Soc. Amer. Map Chart Ser. MC-36,</u> 1981.

periods in both hemispheres with the Milankovitch forcing of Pleistocene climate fluctuations. Mechanisms have been proposed by which Northern Hemisphere glaciation would trigger a reduction in atmospheric CO_2.[4] Such a mechanism may represent a way in which a Northern Hemisphere climatic signal could be transmitted into the Southern Hemisphere. The results from this study confirm the finding that the introduction of expanded continental ice to the model does little to cool the Southern Hemisphere. In addition, a reduction of atmospheric CO_2 to the levels estimated for the LGM produces substantial Southern Hemisphere cooling. This supports the hypothesis that glacial-interglacial variations in CO_2 concentration may provide a linkage between the two hemispheres.

In examining the atmospheric circulation, LGM boundary conditions were found to produce substantial modifications, particularly in the Northern Hemisphere during winter. An amplified ridge-trough pattern at the 500 mb level over North America and the nearby North Atlantic Ocean is associated with anomalous northerly flow over the eastern portions of the Laurentide ice dome. The middle latitude westerlies are strengthened from the western Atlantic across much of Eurasia. These enhanced westerlies are accompanied by a belt of reduced sea level pressure and increased storminess. In examining the effects of each of the changes in boundary conditions individually, it is noted that these alterations in tropospheric circulation result primarily from the ice sheet effect.

PLANS FY87

In collaboration with M. J. Suarez of the NASA Goddard Laboratory for Atmospheres, an extremely efficient two-layer, gridpoint atmospheric GCM coupled to a mixed layer ocean is being prepared for studies of the climatic response to the orbital parameter variations thought to be responsible for the Pleistocene glacial fluctuations. The execution time is roughly 1 second per model day on the CYBER 205. After preliminary tests, the model's sensitivity to solar constant variations will be examined, followed by examination of its responses to a variety of orbital parameter perturbations. No attempt will be made to model glacial formation at this stage. In light of the results, a few experiments with a full multi-level atmospheric GCM will be planned.

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[4]Broecker, W., 1984: Carbon Dioxide Circulation through Ocean and Atmosphere, Nature, 308, 602.

1.5 STATIONARY EDDIES

I. M. Held
K. H. Cook
N. C. Lau
I. S. Kang
D. Neelin
J.-P. Huot
R. Pierrehumbert
S. Feldstein

ACTIVITIES FY86

Work has continued on both linear and nonlinear models of tropospheric stationary waves. In addition to research on basic theoretical problems, an attempt has been made to simulate the stationary eddies produced by a variety of GCM's with idealized models. On the one hand, this allows study of realistic stationary wave patterns with the forcing functions (topography, diabatic heating, transient eddy flux convergences) known precisely; on the other hand, the stationary wave models provide a new diagnostic tool for analyzing the GCM's climate (fc). An example of these results is shown in Fig. 1.3. The upper figure shows the deviations from zonal symmetry of the 300 mb wintertime streamfunction which, according to the linear model, are due to the Tibetan plateau; the lower figure shows the corresponding response to the latent heating in the tropical western Pacific. Both factors contribute to the jet maximum off the east coast of Asia, with the orographic component being dominant.

1.5.1 The Extratropical Response to El Niño

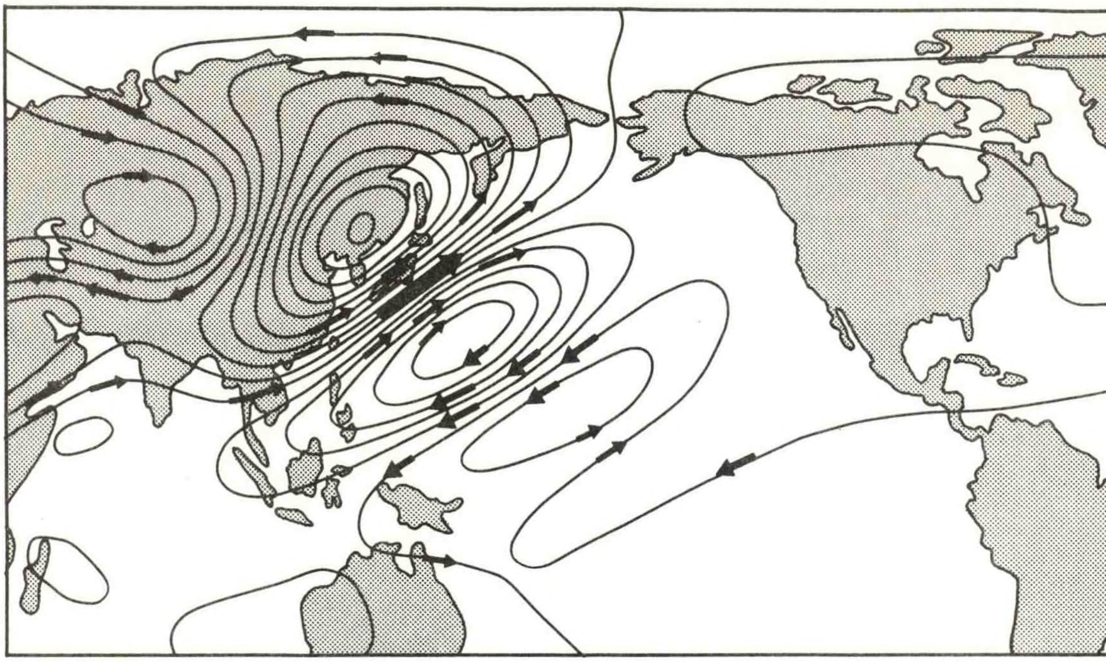
A nonlinear barotropic model and a linear baroclinic model have been used to study the extratropical response to El Niño conditions in the equatorial Pacific, as produced by an atmospheric GCM. The GCM results are those described in (702). The nonlinear barotropic model is forced by the GCM's 300 mb divergence. Contrary to much current speculation, neither the vortex stretching associated with anomalous upper tropospheric divergence (increased rainfall) in the tropical central Pacific nor the convergence (decreased rainfall) in the western Pacific is of major importance for the extratropical wavetrain over the North Pacific and North America in El Niño years. Surprisingly, the dominant part of the forcing is found to be the anomalous convergence, or subsidence, in the subtropical Pacific.

Linear baroclinic calculations shed some light on these results, but also complicate the problem further. In these calculations, one takes as given the diabatic heating field, transient eddy flux convergences and the zonal average of the time mean flow; the output is the deviation from zonal average of the time mean flow. These results indicate that the extratropical response, including the subtropical subsidence is, in large part, the response to anomalous transient eddy fluxes, particularly the momentum fluxes in the upper troposphere.

1.5.2 Ice Age Stationary Waves

The Laurentide ice sheet in North America undoubtedly had a very large effect on stationary waves. The distortion of the flow was important for the maintenance of the ice age climate, but also provides a stringent test of the robustness of a stationary wave model. Using a linear baroclinic model, we have simulated the topographically forced ice age stationary waves produced in

(a) RESPONSE TO TIBETAN PLATEAU



(b) RESPONSE TO WESTERN EQUATORIAL PACIFIC RAINFALL

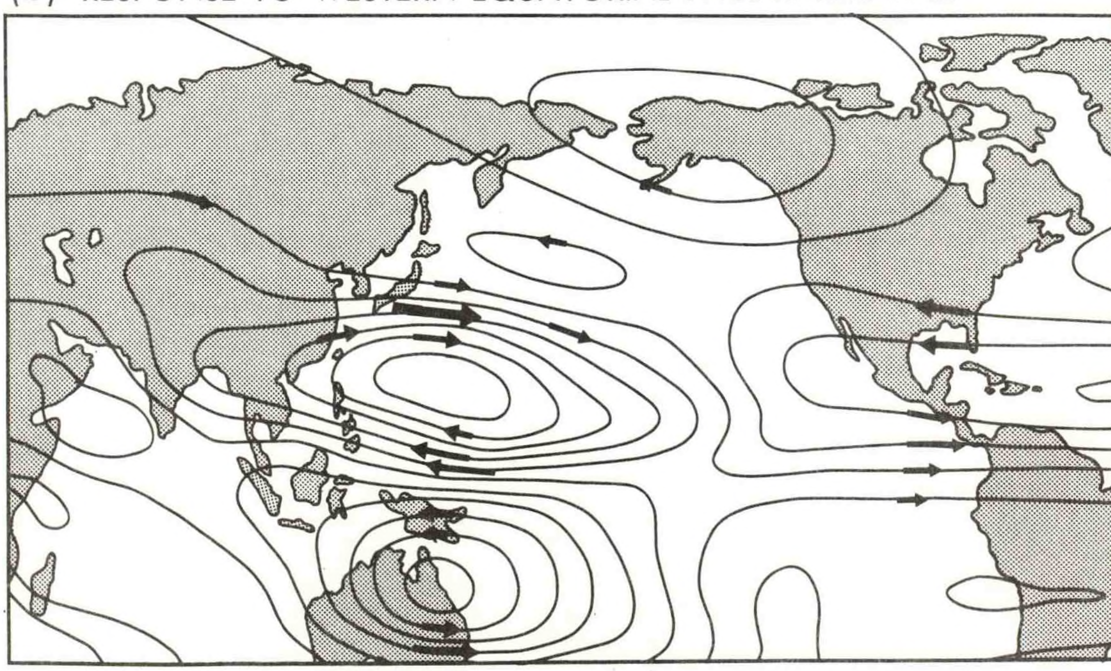


Fig. 1.3. The stationary response to (a) the Tibetan plateau and (b) the latent heating in the Pacific west of the dateline and south of 15°N, as computed with a baroclinic model linearized about a GCM's zonal mean flow in northern winter. The field shown is the 300 mb streamfunction, with a contour interval of $2 \times 10^6 m^2 sec^{-1}$.

the GCM described in (707). The results are very encouraging, but only if the zonal mean state about which the model is linearized is taken from the ice age climate. If the basic state is chosen from a model of the present day climate, the stationary waves produced by the Laurentide ice sheet are much too large. The key factor is the increase in low-level temperature gradient in the ice age climate. The reason why this should result in smaller stationary waves is under investigation.

1.5.3 Lower Tropospheric Flow in the Tropics

Work has been completed on a possible way of modeling the relationship between tropical sea surface temperature and precipitation (ef). The method is based on a novel application of the vertically integrated moist static energy budget. A study of the relationship between the surface stress and the precipitation field in the tropics is nearing completion. In both cases, the goal is to provide idealized atmospheric models useful for analyzing the El Niño Southern Oscillation phenomenon. Once again, a GCM's response to SST anomalies is the target aimed for with these simpler models.

1.5.4 Stationary Wave Theory

The third in a series of studies on the far-field tropospheric response to localized orographic or thermal forcing is nearing completion [the first two are (651) and (722)]. The focus here is on the relationship between the responses in the two-layer model and those in continuous models. We feel the two-layer model will continue to play an important role in the theory of the midlatitude circulation, particularly when such complex issues as the interaction between stationary waves and baroclinic instability are addressed. On the basis of the results obtained, the value of the two-layer model appears to be considerably more positive than in the conventional wisdom. However, there are situations when the two-layer model predicts that an external Rossby wavetrain will emerge from a source in a direction exactly opposite to that predicted by continuous models.

PLANS FY87

Further analysis of the GCM's extratropical response to El Niño is planned, with emphasis on what now appears to be the central issue, i.e., the manner in which extratropical transient eddy fluxes are modified by the tropical heating anomaly.

The ice age stationary wave study will be completed. The generality of the result that the amplitude of topographically forced waves is strongly affected by low-level temperature gradients and the implications of this result for other climatic changes will be examined.

An attempt will be made to couple an idealized model of the tropical surface flow as determined by the sea surface temperatures to a low resolution version of the Pacific Ocean model described in (681). This work will complement the El Niño Southern Oscillation studies with the coupled atmosphere-ocean model described in Section 4.1.1.

An idealized model with a zonally symmetric climate will be perturbed in a series of calculations by an isolated topographic feature (similar in shape and location to the Tibetan plateau) with various heights. Detailed comparisons will be made between the resulting stationary waves and the predictions of linear theory. Particular attention will also be paid to the effect of the topography on the transients and the back effect of the asymmetric transients on the mean flow. Theoretical models of this transient-stationary wave interaction will be re-examined in light of the results.

1.6 TRANSIENT EDDIES

D. G. Golder — I. M. Held
Y. Hayashi — N. C. Lau
K. H. Cook — D. Neelin

ACTIVITIES FY86

1.6.1 Tropical Intraseasonal Oscillations

Detailed analyses have been made of the tropical intraseasonal oscillations during the northern summer appearing in a GFDL 30-wavenumber spectral general circulation model and the FGGE IIIb data set (ey). The model exhibits major and minor wavenumber-1 spectral peaks in the equatorial zonal velocity with eastward moving periods of 40-50 and 25-30 days, in agreement with two sets of the FGGE IIIb data, one processed at GFDL and the other at ECMWF. Both the 40-50 and 25-30 day oscillations are associated with a similar spatial structure. In particular, both of these oscillations exhibit a phase reversal between the 200 and 800 mb zonal velocities. They propagate eastward with a node near the dateline and an antinode in the western hemisphere. Their wave patterns take the form of an eastward moving Kelvin mode near the equator and an eastward moving Rossby mode away from the equator (Fig.1.4). Both spectral peaks are also detectable in the model's precipitation, corresponding to those in the observed outgoing longwave radiation. The 40-50 and 25-30 day precipitation oscillations are in phase with the vertical velocity and propagate eastward with major and minor antinodes in the eastern and western hemispheres, respectively. This eastward phase propagation may explain why the Kelvin and Rossby wave patterns propagate eastward. These results demonstrate that the intraseasonal oscillations can be simulated in a model with no air-sea interaction and no cloud-radiation feedback, which have been suggested as important mechanisms for the occurrence of these oscillations.

The low frequency variability of the tropical flow has also been analyzed in an annual mean R15 swamp GCM without topography. Space-time spectra of the zonal wind at the equator show substantial power in wavenumbers 1-3 with phase speed corresponding to a 25-30 day period for wavenumber 1. That this oscillation is captured in such an idealized model is itself of interest, and rules out a number of current theories. Analysis aimed at clarifying the cause of the oscillation is in progress. Comparison with a more realistic GCM with identical resolution [as described in (ek)] shows that the oscillation is modified somewhat by seasonal forcing and land-sea contrast, but not in an essential way. In particular, the period is more or less unchanged.

The space-time spectra of this idealized model also show a surprising peak in wavenumbers 1 and 2 at the equator with a very small eastward phase speed, corresponding to a period of 140 days for $m = 1$. Undergoing current

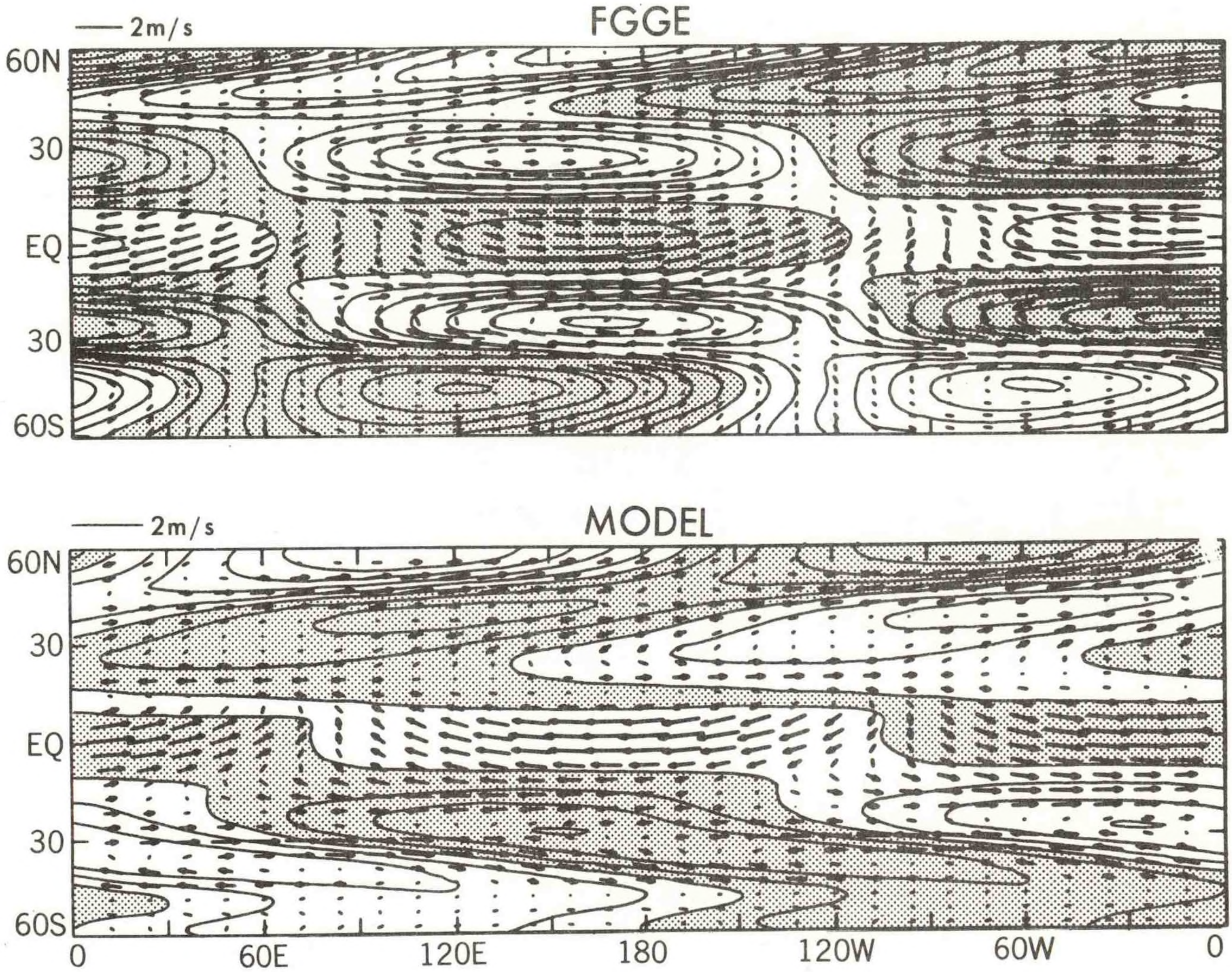


Fig. 1.4. Longitude-latitude distributions (200 mb) of the wavenumber 1 component of wind vectors and the geopotential height contours of the FGGE data (upper) and the model (lower). These wave patterns are subjected to a 40-50 day filter and are composited along the longitude-time phase line with eastward phase speed of 10.3 m/s during the period May through July. These figures suggest that the tropical 40-50 day oscillations take the form of an eastward moving Kelvin mode near the equator and an eastward moving Rossby mode away from the equator.

testing is an hypothesis that the east-west asymmetry of the evaporation anomaly induced by a heat source in the tropics causes eastward migration of precipitation and the corresponding large-scale flow field.

1.6.2 Extratropical Transient Waves

In order to clarify the effects of wave-wave and zonal-wave interactions on the growth and maintenance of extratropical transient waves, numerical experiments have been conducted using a GCM with a zonally uniform surface. After the model had reached its equilibrium in the presence of transient eddies, the disturbances were replaced by small perturbations. The model was then time integrated by either including all the zonal wavenumbers or restricting wavenumbers. It was found that, in the presence of all the wavenumbers, ultralong (wavenumber 1-3) waves and cyclone-scale (wavenumber 4-9) waves grow initially as fast as the short-scale (wavenumber 10-21) waves, whereas ultralong waves initially do not grow as fast in the absence of wave-wave interactions. However, in the mature state, ultralong waves nonlinearly attain smaller amplitudes than they do individually in the absence of higher wavenumber components. This is due to the fact that cyclone-scale waves reduce the zonal baroclinicity and that wave-wave energy transfer plays a less important role in the maintenance of transient ultralong waves than in the growth phase. These experiments demonstrate that cyclone-scale waves affect ultralong waves not only through wave-wave interaction but also through wave-mean flow interaction.

PLANS FY87

The study of the tropical and extratropical transient waves with the use of general circulation models will continue.

The analysis of the low frequency variability of the swamp model will be continued and described in two studies, one focusing on the 25-day peak and another on the effect of evaporation anomalies on the lower frequency power.

1.7 WAVE-MEAN FLOW INTERACTION

I. M. Held Y. Hayashi
P. Phillipps D. Golder

ACTIVITIES FY86

1.7.1 Hadley Cell - Rossby Wave Interaction

A model of the maintenance of the subtropical jet through competition between stresses induced by decaying Rossby waves and the acceleration of the jet by the Hadley cell has been finalized; its behavior is now being analyzed as a function of the strength of the Rossby wave forcing. The model consists of a high resolution fully nonlinear barotropic model coupled to a zonally symmetric model of the Hadley cell. Attention has been focused to date on idealized stationary Rossby wave forcing, and on the limitations of linear theory for the prediction of the stresses. Unexpected instabilities also emerge with time scales of 5-10 days. Work has been completed on the linear and nonlinear decay of Rossby waves on the sphere in the presence of meridional shear (fv).

1.7.2 Eulerian-Mean Heat-Momentum Equation

The Eulerian-mean momentum, heat and energy equations have been modified to give a simple description of wave-mean flow interactions in the presence of mean heating. The modified Eulerian-mean heat equation consists of the diabatic mean circulation and the effective heat flux convergence. The former represents the hypothetical steady state mean circulation which would occur even in the absence of eddies, while the latter represents the combined effects of eddy fluxes and the eddy-induced mean circulation. In the steady state, the latter depends not only on the meridional eddy heat flux convergence but also on the meridional derivative of the eddy momentum flux which effectively acts like an eddy heat flux convergence. The modified equations give simpler descriptions of wave-mean flow interaction than the conventional and transformed Eulerian-mean equations.

PLANS FY87

The analysis of the Hadley cell-Rossby wave model will continue with emphasis on the maintenance of the subtropical jet and the dynamics of the newly uncovered instability.

The modified energy equations will be applied to planetary waves in order to describe wave-mean flow interactions in a simpler manner.

1.8 MODEL DEVELOPMENT

S. B. Fels D. Daniel
M. D. Schwarzkopf R. J. Stouffer
A. J. Broccoli S. Manabe

1.8.1 Radiative Transfer Model Intercomparison Study

ACTIVITIES FY86

All line-by-line calculations for the 37 standard ICRCCM (Intercomparison of Radiation Codes in Climate Models) cases as well as several other supplementary cases, have been completed. The archived results have been made available to the radiative transfer and climate modelling community. The calculated infrared cooling rates are becoming recognized as a benchmark against which heavily parameterized models used in GCM's can be compared. Research groups inside and outside of GFDL have already begun to use these cooling rates for this purpose. An example of such comparisons is shown in Fig. 1.5, where the calculations of two non-GFDL parameterizations and the operational algorithm used in the SKYHI model are compared with line-by-line results. Each operational model displays its own biases, typically of the order of 0.1-0.4°K/day. Without the line-by line results, these would not have been detectable.

The accuracy of the line-by-line calculations must ultimately be checked by comparison with broad-band laboratory data, ideally taken in the appropriate range of temperature and pressure. While such comparisons with existing data for water and carbon dioxide show satisfactory agreement, the laboratory data for water is over forty years old. It was assumed that new data taken at SUNY Stony Brook would be available to GFDL for this comparison, but experimental difficulties have delayed the start of the intercomparison.

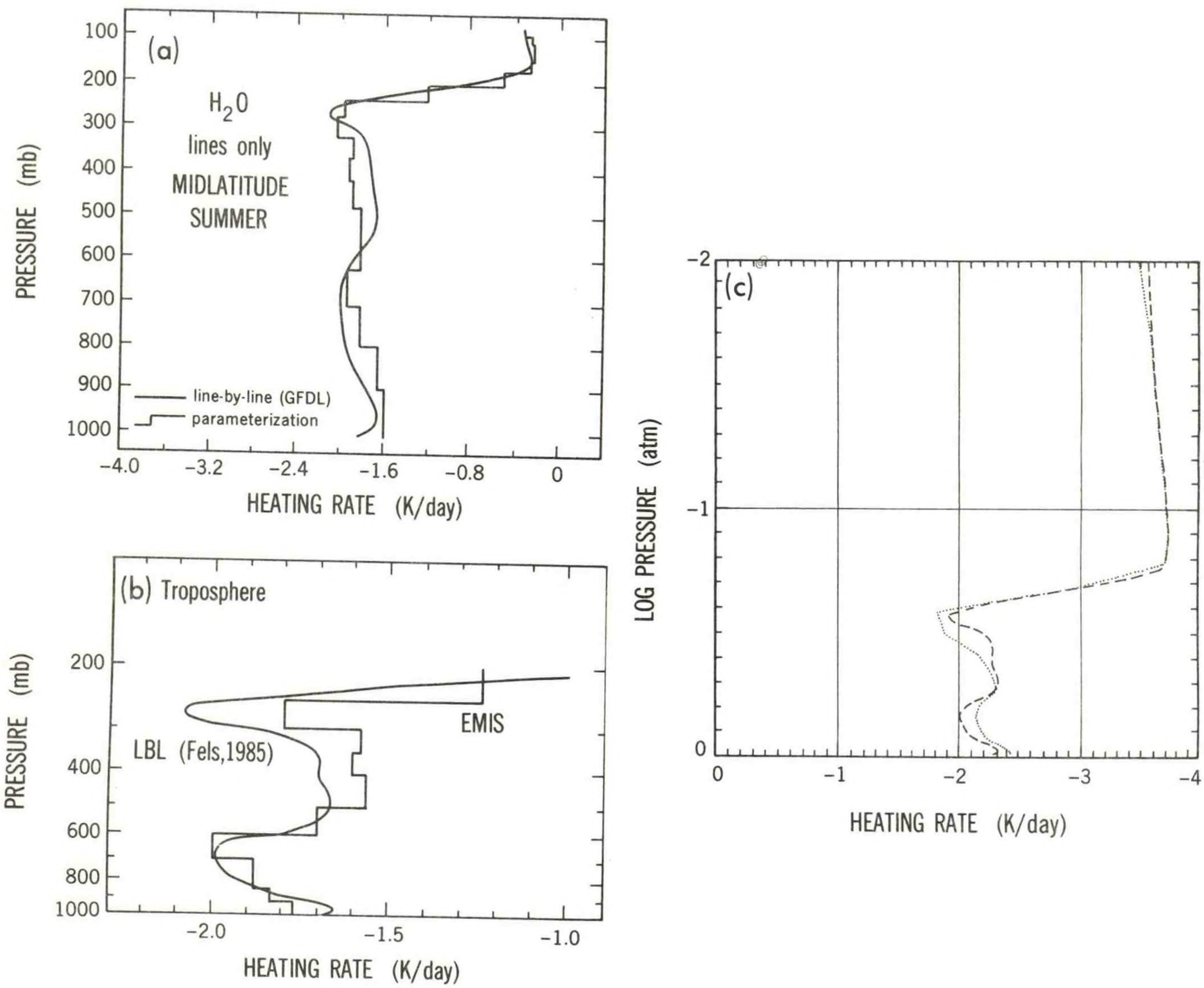


Fig. 1.5 - Three comparisons of infrared cooling rates calculated using heavily parameterized algorithms with the results from line-to-line calculations, taking into account only the contribution from water vapor lines.

a) Harshvardan (submitted to J.A.S. 1986)
b) Ramanathan and Downey, (submitted to J.A.S. 1986)
c) Fels and Schwarzkopf, unpublished. (This algorithm is the one used in the GFDL SKYHI and NWP models.)

Given the known inaccuracies in the radiation codes, an effort has been undertaken to assess the sensitivity of simple GCM's to perturbations in free atmospheric radiative cooling rates by introducing an artificial localized and fixed heating perturbation into the model. A similar experiment using identical forcing will be undertaken shortly at NCAR using the Community Climate Model, in an effort to cross-calibrate the responses of the two models. Initial results from the GFDL R15 spectral model show that at 350 mb in the tropics, a 1°/day heating rate perturbation results in a 5° change in the local temperature. The response is surprisingly linear in the size of the forcing, and has a meridional structure much broader than that of the forcing, due to advective effects.

On the basis of these calculations, it appears that errors in the longwave radiative cooling rates mentioned above may lead to cold biases in the upper troposphere of 1-2 degrees. This is considerably less than the 5-8 degree cold biases found in GCM's at GFDL and elsewhere, but should still be corrected.

A comprehensive comparison of numerous parameterizations of CO_2 infrared calculations has been carried out, using the line-by-line calculations as a benchmark (eg). These computations were performed for both the present mixing ratio, and for a hypothetical atmosphere consisting of one bar of pure CO_2. Several different strategies for the inclusion of Voigt effects were also evaluated. In general, the wideband exponential integral model was found to give the best results in the troposphere, and can be used with the rectangular-core line shape described previously to incorporate the Voigt profile (351).

PLANS FY87

Line-by-line calculations will be compared with the new laboratory data from Stony Brook, and the GCM sensitivity study will be extended to cover middle-latitude perturbations. High accuracy reference calculations incorporating both molecular line absorption and aerosol scattering will be started in conjunction with the second phase of the ICRCCM study. An effort will be made to correct the cooling rate biases in several of the operational radiative transfer models.

1.8.2 Improvement of Atmospheric GCM

ACTIVITIES FY86

An obstacle to the use of higher resolution spectral GCMs in climate studies has been a bias in the midlatitude westerlies that develops as the computational resolution is increased. During winter, the Northern Hemisphere surface westerlies become too strong and zonally symmetric.

In an effort to eliminate this bias, the Canadian Climate Centre[5] and the British Meteorological Office[6] have incorporated parameterizations of gravity wave drag in their GCMs. Gravity wave drag acts to retard the flow in regions of rugged orography, particularly if the thermal stratification is stable. During the past year a gravity wave drag parameterization has been developed for use in the GFDL climate models. Tests are currently underway to evaluate the impact of this parameterization on the surface flow and distribution of sea level pressure in a high resolution (rhomboidal 30 truncation) climate model. Preliminary results of this test indicates that the excessive surface westerlies mentioned above are reduced in strength when the effect of gravity wave drag is incorporated into the model.

PLANS FY87

Upon identifying an appropriate gravity wave drag parameterization, a multi-year integration of the high resolution climate model with the gravity wave drag parameterization will be performed. The model climatology will be compared to the observed climate and that of previous models.

1.8.3 Atmosphere-Mixed Layer Ocean Model

ACTIVITIES FY86

A number of climate sensitivity studies have been conducted at GFDL using an atmospheric GCM coupled with a simple model of the oceanic mixed layer (e.g., 428,630). Since such a model does not include the effects of heat transport by the ocean circulation, it has been difficult to simulate the distribution of sea surface temperature and sea ice. This can be quite significant, since too much or too little sea ice can distort the sensitivity of the model by exaggerating or underestimating the magnitude of the sea ice albedo feedback process.

In an effort to alleviate this problem, a modified version of the atmosphere-mixed layer ocean model has been developed. In this version a prescribed heat flux is imposed at the bottom of the mixed layer at each ocean gridpoint to represent the redistribution of heat by ocean currents. To determine this bottom heat flux, the atmospheric GCM is run with prescribed sea surface temperatures and sea ice. The heat gain or loss required to keep the mixed layer ocean at the prescribed temperature in equilibrium with the model atmosphere is the bottom heat flux.

When this modified version of the model is run, the addition of this bottom heat flux forces the model to simulate closely the observed distribution of sea surface temperature and sea ice. This improvement should lead to less distortion of model sensitivity, and a more realistic representation of the tropical circulation.

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[5] Boer, G. J., N. A. McFarlane, R. Laprise, J. D. Henderson and J.-P. Blancket, 1984: The Canadian Climate Centre Spectral Atmospheric General Circulation Model, Atmosphere-Ocean 22, 397-429.

[6] Palmer, T. N., G. J. Shutts and R. Swinbank, 1986: Alleviation of a Systematic Westerly Bias in General Circulation and Numerical Weather Prediction Models through an Orographic Gravity Wave Drag Parameterization. Submitted to Quart. J. R. Met. Soc.

PLANS FY87

The modified version of the atmosphere-mixed layer ocean model will be used to re-evaluate the results of previous sensitivity studies.

2. MIDDLE ATMOSPHERE DYNAMICS AND CHEMISTRY

Goals

* To understand the interactive three-dimensional radiative-chemical-dynamical structure of the middle atmosphere (10-100km), 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

C. Black
W. Chameides*
S. B. Fels
H. Levy II
S. C. Liu*
J. D. Mahlman
J. Merrill*
W. J. Moxim
* Other Institutions

ACTIVITIES FY86

2.1.1 Reactive Nitrogen in the Troposphere

Work has continued on refining the 3-D general circulation/transport model's parameterization of wet and dry removal. Integrations have been performed for a wide range of dry deposition velocities with the wet deposition (acid rain) constrained to equal or exceed observed values. This confirms the robustness of the earlier conclusions from this research regarding the role of dry deposition (ff). Even at the lower limit of deposition velocity, dry and wet depositions are equal over the United States and Canada, while for the most probable deposition velocity, dry deposition is twice as large as wet deposition (acid rain).

In a separate set of numerical experiments, the combustion source of nitrogen was turned off everywhere except in the northeastern United States and eastern Canada. By comparing the resulting dry, wet and total deposition over this region with the same results from an experiment with the full United States and Canadian source, it was found that over 80% of the dry deposition and 60% of the total deposition come from local and regional sources. Only the wet deposition, a minor component of the total deposition, is strongly influenced by distant sources. Further details may be found in (ff).

Work has also started on a detailed analysis of the mechanisms of regional synoptic transport of combustion nitrogen. The seasonal variation of these transport processes is also being examined.

2.1.2 Combustion Sulfur

A detailed multilevel combustion sulfur source for the United States and Canada has been developed. A series of numerical experiments, similar to those for combustion nitrogen, is now underway.

2.1.3 Wet Removal Parameterization Development

In collaboration with W. Chameides of Georgia Institute of Technology, an accurate and species-dependent parameterization of both rainout and washout of soluble gases is being developed. A formulation based on Henry's Law solubility and basic principles of cloud physics have been developed and tested in both a simple 1-D model and the general circulation/transport model.

2.1.4 Asian Dust Storm Transport Simulation

In collaboration with J. Merrill of the University of Rhode Island, a preliminary Asian dust "burst" simulation has been run using the GFDL 3-D transport model. An examination of the model's wind fields was performed to determine a favorable synoptic period for an Asian dust event to occur. The model's surface dust source was activated for 48 hours during this predetermined period and then switched off while the experiment was integrated for another month.

The trajectory analysis agrees well with available observations. It was found that after the initial synoptic lifting, the dust was transported across the Pacific within the 500-685 mb layer. It then subsided in association with the Pacific anticyclone, became caught up in the sub-tropical easterlies, was transported westward near 940 mb, and eventually reached Enewitak (11°N, 126°E) in about 16 days.

2.1.5 Development of a 2-D Transport Model

Work has been completed on the evaluation of the feasibility of deriving a 2-D transport model self consistently from the GFDL 3-D transport model. New conclusions have now been obtained from this analysis on some defects in the capabilities of the 3-D transport model. Interestingly, these defects are related to the sources of the well known polar cold bias of this model. The model shows too weak wave mixing in the meridional plane. The source for this difficulty is that the model transient wave amplitudes and degree of wave non-linearity are too weak.

On the other hand, this work shows a vigorous cross equatorial exchange in the GFDL 2-D and 3-D models that appear to fit various troposphere data far better than that of other 3-D transport models. Details are available in (ep).

2.1.6 Antarctic Ozone Depletion

A short term project has been underway to investigate possible causes of the recently observed large ozone depletions over Antarctica in late winter and early spring. Most publicized explanations have focussed on chemical possibilities, usually involving chlorine radicals. Because of difficulties with these explanations, a hypothesis has been developed that proposes a dynamical cause.

The dynamical hypothesis assumes that the magnitude of dynamical wave forcing from the high latitude troposphere has decreased after about 1980 or so. The effect of the assumed decreased forcing would be to weaken the diabatic meridional circulation, thus bringing down less ozone into the Antarctic lower stratosphere. In addition, this weakened forcing would have led to a longer late winter integrity of the polar vortex, thus protecting it against the final reversal and concomitant eddy produced ozone increases. Finally, this reduced forcing can possibly lead to a regime in which the return of the sun to high latitudes in late winter acts to induce a local rising motion that reduces the ozone even further. This latter mechanism is speculative and may depend upon enhanced absorption by stratospheric clouds within the colder pole vortex. Details are available in (gp).

PLANS FY87

Efforts will continue on the studies of combustion nitrogen and sulfur. Explicit chemistry, a more sophisticated wet removal scheme, and a global source for combustion nitrogen will be developed. Analysis of individual synoptic transport events will also continue.

A new wet removal parameterization will be incorporated into the general circulation/transport model to determine the relative importance of rainout, washout and dry removal for a set of idealized tracers. The influence of source location (stratospheric vs. surface) and spatial variability will also be studied.

A source parameterization development is underway which will enable the model to determine when an Asian dust event occurs. The transport model will then be integrated for a year to analyze seasonal variations in the dust concentration and its deposition. The exploratory work on Antarctic ozone will continue.

2.2 MODELS OF THE TROPOSPHERE-STRATOSPHERE-MESOSPHERE

S. B. Fels
D. G. Golder
D. S. Graves
Y. Hayashi
H. Kida
C. Kranz
J. D. Mahlman
M. D. Schwarzkopf
L. J. Umscheid

ACTIVITIES 1986

2.2.1 Model Improvements

Over the year, a number of improvements have been tested for the SKYHI GCM. To increase model efficiency, an option has been developed to do the computations in half (32-bit word) precision while preserving conservation properties as much as possible. However, the effects of round-off error increase significantly for higher model resolution. A medium resolution experiment is well under way to study and reduce these effects. Execution speed is increased by 35-45% depending on resolution.

A new version of the Fels-Schwarzkopf radiation code with improved physics and algorithms has been added. Execution speed of the radiation code has been increased by approximately 50%. A medium resolution (3° latitude) experiment is in progress to study the effects of these changes.

2.2.2 Higher Resolution Seasonal Cycle Experiments

The seasonal cycle of the middle atmosphere is being investigated with 3° latitude and 1° latitude versions of the 40-level SKYHI GCM. The 1° version provides an experimental exploration of the biases and missing processes that may result simply from an inadequate computational resolution.

Although extremely expensive to run, the 1° model has been run for over 4 months (October to early February). Early analysis of the December-January structure of the 1° model suggests that the sudden warming dynamics may be substantially improved, mainly due to the higher amplitude and non-linear character of the simulated planetary waves.

Another new discovery is that the 1° model apparently does a far better job of simulating the Southern Hemisphere summer mid-latitude cyclone wave activity. Specifically, the zonally propagating mixed 5-6 wave pattern in the model is very much like that seen in observational analyses.

2.2.3 Sources of Systematic Errors in SKYHI Climatology

In Activities FY85, Plans FY86, it was noted that three model problems were apparently unsolved by increasing the resolution to 1° latitude. These were position of the polar night jet, lower stratosphere cold bias, and the cold bias of the tropical upper troposphere.

Some "progress" has been gained on the position of the polar night jet problem. A comparison of recent limb scanning satellite temperature data against older regression analysis of Nadir viewing satellites suggests a warm bias error as large as 10° in the temperature of the polar vortex. The inappropriately warm polar upper stratosphere temperatures apparently led to an underestimation by as much as 30-40 m sec^{-1} in the magnitude of the polar night westerlies near 60°N. By correcting these inappropriate data, the SKYHI magnitudes and position of the polar night jet may be much closer to observation than previously assumed.

The most robust remaining error appears to be the approximately 5°C cold bias in the tropical upper troposphere. The problem may be either in the moist convection parameterization or in the treatment of high cirrus clouds. Further investigation is in process.

2.2.4 Effects of Gravity Waves on Large-Scale Flows

Preliminary calculations using the 1° latitude resolution version of the 40-level SKYHI GCM show marked increases in the magnitude of gravity wave momentum flux convergence in December. This increase is consistent with the December mesospheric zonal flow in the 1° latitude version which is 40 m sec^{-1} weaker and more realistic than that in the 3° latitude version. Space-time spectral analysis indicates that the phase speeds of gravity waves (which have been distorted due to the finite difference approximation) are improved in the 1° latitude version for wavenumbers 1-75. However, phase speeds for wavelengths between 2 and 4 grid intervals remain significantly retarded. Preliminary results are available in (dg).

2.2.5 Evaluation of Satellite Sampling of the Middle Atmosphere

An investigation has been completed to evaluate the accuracy of derived dynamical quantities in the middle atmosphere as inferred from simulated satellite radiance data. The study uses the 3° latitude resolution SKYHI GCM as a reference atmosphere that is sampled by a simulation of the Nadir-viewing TIROS-N Operational Vertical Sounder (TOVS) instruments (HIRS-2, MSU,SSU). In addition, a radiosonde temperature data network is simulated to define linear regression coefficients as currently used in the NOAA/NESDIS algorithm.

This study has discovered several classes of important limitations of the satellite data as currently obtained in the operational system. The analysis of tropical phenomena is especially difficult because of the relatively crude sampling (10 km in the vertical, 3000 km in the horizontal) relative to the "full" spectrum of gravity waves there and the severe limitations of geostrophic-type approximations.

Another class of limitations is more influenced by deficiencies in processing/analysis algorithms. For example, the Fast Fourier Synoptic Mapping (FFSM) method (560), while mathematically exact, is found to be severely limited by sampling errors and the requirement for time series detrending. This latter problem is especially severe during sudden warming periods where the mean fields are rapidly evolving.

The most serious error is that the NOAA/NESDIS regression algorithm appears to be strongly constrained by the quality and applicability of the available "ground truth" data used in the regression algorithm. Specifically, phenomena such as sudden warmings and the cold polar vortex over Greenland are misrepresented due to unavailability of sufficient data in the regression set to cover such extremes of temperature. For details see (gn).

2.2.6 Lagrangian Analysis of Stratospheric Wave Breaking

A new research effort is underway to evaluate the character of various stratospheric "wave breaking" phenomena as simulated in the 1° latitude resolution SKYHI GCM. It has been recognized in the recent literature that such breaking processes are expected for both gravity waves and planetary waves.

One of the most penetrating ways to view these processes is through the movement and dispersion of marked particles in the vicinity of breaking events. A complete Lagrangian particle trajectory code has been developed for such studies as well as for more general transport studies.

PLANS FY87

Efforts will continue on developing the high resolution (1°) SKYHI model with emphasis on model efficiency and various subscale parameterizations. Analysis on this model will be underway investigating systematic climatic biases, role of gravity waves, wave breaking, transport, semi-annual oscillation, and Southern Hemisphere wave disturbances.

2.3 PHYSICAL PROCESSES IN THE MIDDLE ATMOSPHERE

S. B. Fels
S. C. Liu*
J. D. Mahlman
V. Ramaswamy
M. D. Schwarzkopf
L. J. Umscheid
* Aeronomy Laboratory/NOAA

ACTIVITIES FY86

2.3.1 Aerosol Radiative Transfer

A new shortwave radiation scheme has been implemented in the SKYHI GCM to simulate the radiative effects due to aerosols. The algorithm accounts for multiple scattering processes explicitly using the Delta-Eddington approximation, in contrast to the Lacis-Hansen parameterization scheme employed in the standard routine. Salient features of the new scheme include: specification of gaseous and particulate concentrations in any layer; direct calculation of cloud and aerosol optical properties using the Mie equations; and consideration of several discrete visible and mean-infrared wavelength bands. Wintertime simulations of the global climate using the new algorithm compare well with those obtained by using the standard routine. It was also found that a correct formulation of near-infrared absorption by CO_2 is necessary for an accurate determination of stratospheric temperatures.

2.3.2 Modeling of Cirrus Cloud Effects

Understanding the physical characteristics of cirrus clouds is essential for determining cloud-climate relationships. Towards this end, a microphysical-radiative interaction model has been developed (Ramaswamy and Detliner, 1986).[1] The large size of ice crystals, together with their occurrence high in the troposphere, implies a substantial contribution to the radiative divergence through shortwave absorption (Ramaswamy and Ramanathan, 1986)[2] and longwave absorption/emission. The residence time and, thus, the importance of the radiative influence due to the cloud is determined by the relative humidity (which controls growth rate) and the crystal size (which controls sedimentation rate).

2.3.3 Ozone Photochemistry

Preparations have continued on the effort to incorporate a limited, but self consistent ozone chemistry into the SKYHI GCM. The chemical theory and the scaling of the chemical equations have been re-examined in the context of a 3-D GCM. This has led to a hierarchy of approximations, the simplest of which has been prepared for incorporation into SKYHI. It will involve odd oxygen, nitric acid, and "remaining" odd nitrogen as dependent variables. Chemical partitioning will be handled by a semi-prognostic method, while long lived gases will be prescribed in accordance with a previously developed simple theory (716).

PLANS FY87

The long-term effort to incorporate a self consistent ozone chemistry into SKYHI will continue. The new aerosol radiative transfer code will be tested with specific model experiments and will be adapted to investigate the climatic effects of upper tropospheric cirrus clouds.

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[1]Ramaswamy, F., and A. Detliner, 1986, Interdependence of radiation and Microphysics in Cirrus Clouds, (Submitted to Journal of the Atmospheric Sciences, March 1986).

[2]Ramaswamy, V., and V. Ramanathan, 1986, Influence of cirrus shortwave radiative properties on the simulated climate of a General Circulation Model, Preprints, Sixth Conference on Atmospheric Radiation, Williamsburg, VA, May, 1986.

3. EXPERIMENTAL PREDICTION

GOALS

* To develop more accurate and efficient atmospheric and oceanic GCM's suitable for monthly and seasonal forecasting, and to reduce the systematic biases of the models.

* To identify external forcing mechanisms important in the forecast range of several weeks to several months, and to develop means of accurately specifying the initial states of the atmosphere, oceans, soil moisture and snow/ice cover.

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

* To advance the understanding of a broad range of phenomena of importance in the atmosphere, including blocking, orographic cyclogenesis, equatorial ocean-atmosphere interaction, tropical circulations, teleconnections, transient eddy fluxes and dynamics of regions of concentrated vorticity.

3.1 MODEL IMPROVEMENT

C. T. Gordon
J. Sirutis
T. Knutson
M. D. Schwarzkopf
R. T. Pierrehumbert
W. F. Stern
P. L. Baker
R. Smith
K. Miyakoda
B. Wyman
S. B. Fels

ACTIVITIES FY86

3.1.1 Spectral Model for Seasonal Integrations

An advanced spectral model suitable for integration over seasonal time scales is being developed. The important thrusts of this project are the improvement of computational efficiency of the model and the development of greater accuracy of forecasting. During FY86, the one-day integration time for the model (R42L18) has been improved from 90 through 58 to 53 minutes. The first improvement was achieved by more efficient coding of the main dynamics and the second part is due to more efficient radiation calculation.

The forecasting accuracy is being improved by incorporating more appropriate physics, as the model's spatial resolution increases. In particular, orographic gravity wave drag, cloud-radiation interaction, shallow convection in the Arakawa-Schubert cumulus parameterization, and surface roughness have been tested. Numerical experiments reveal that the performance of the gravity wave drag is spectacular (see 3.1.2).

3.1.2 Orographic Effects

It is becoming widely appreciated that gravity wave drag can have a substantial impact on model performance. An unrealistic feature of all previous parameterizations of gravity wave drag in general circulation models has been the reliance on linear theory, even though the height of the major mountain ranges puts them in the strongly nonlinear range. To address this problem, a parameterization incorporating the nonlinear saturation effects discussed in (650) was developed. The parameterization was checked for consistency with available numerical and observational results on momentum flux, and then tested in a spectral prediction model. As was found at other institutions, notably, the U.K. Meteorological Office, incorporation of gravity wave drag was found to have a substantial beneficial impact on forecast skill (see Fig. 3.1).

3.1.3 Cloud-Radiation Interaction

The sensitivity of the GCM-predicted time mean circulation to specified cloud-radiation forcing has been further explored. Based upon one summer case, the predicted day 25-30 and day 20-50 mean mid-latitude circulation is moderately sensitive to observed daily mean vs. monthly mean cloud fields obtained from NESDIS. For the El Niño case of January, 1983, the predicted tropical circulation is considerably more sensitive to the specification of observed vs. climatological sea surface temperature fields than to observed vs. zonal mean observed cloud fields.

In collaboration with V. Ramaswamy, more realistic treatment of cloud-radiative properties, e.g., emissivity, reflectivity and absorptivity

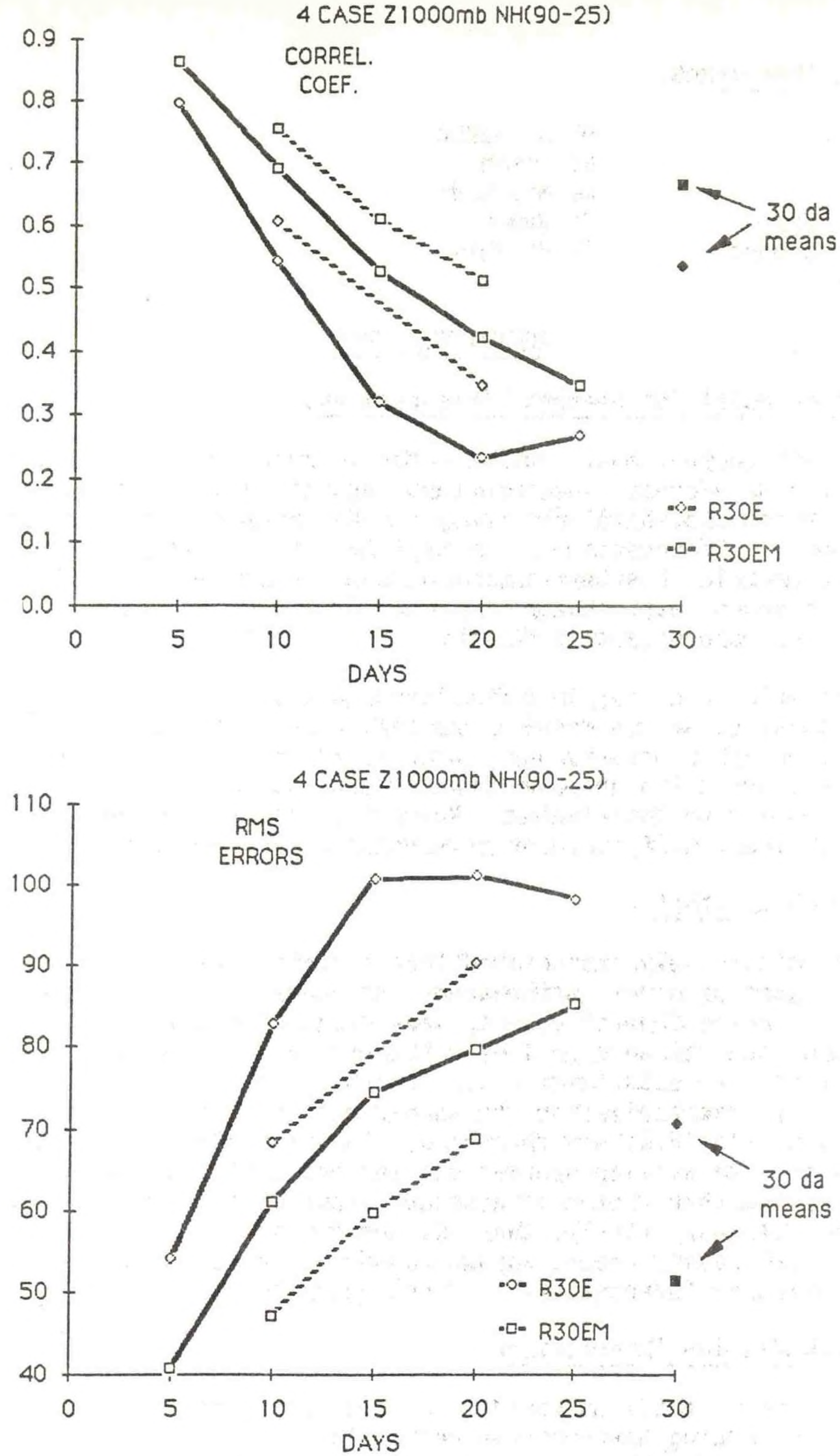

Fig. 3.1. Four monthly forecasts of time mean geopotential height for 1000 mb. Anomaly correlation coefficients are shown at the top and rms errors at the bottom. The control cases are "R30E" and the cases using mountain drag are denoted by "R30EM". Solid lines indicate 10 day means, dashed lines represent 20 day means and solid symbols are plotted for the 30 day means.

is being incorporated into the GCM's radiation code. Also, cloud liquid water, which can affect buoyancy, is being incorporated into our version of the Mellor-Yamada turbulence closure parameterization.

3.1.4 Comparison of Various Versions of Subgrid-Scale (SGS) Processes

Investigation of the relative merits of four different SGS parameterization packages [A, E, F, and FM in order of increasing sophistication (627)] have continued. 30-day integrations have been carried out for eight January cases and three different initial conditions. The results are compared with observations in hope of gaining some beneficial impact on forecasts. The investigation of the systematic bias of models (climate drift) is another important objective (ea, ga).

So far, 71 monthly forecasts have been completed; this represents 80% of the total calculations. The earlier tentative conclusions (627) are being confirmed based on a larger number of samples.

PLANS FY87

The GCM's efficiency will be further improved by a more appropriate treatment of the polar night jet at the top model level. Further reduction of the climate drift will be pursued by incorporating a better treatment of the truncated orography, and a more appropriate process for lateral diffusion, as NMC has already accomplished. Experiments will be initiated to examine the sensitivity of long range forecasts to fully interactive cloud-radiation (i.e., model-predicted clouds), to improved treatment of cloud-radiative properties and to the modified Mellor-Yamada turbulence closure parameterization with cloud-liquid water terms.

3.2 THEORETICAL STUDIES OF ATMOSPHERIC DYNAMICS

R. T. Pierrehumbert
B. Wyman
K. Miyakoda
J. T. Bacmeister
A. Navarra
F. Parham
B. C. Carissimo
T. Knutson
S. J. Lin

ACTIVITIES FY86

3.2.1 Orographic Effects

Work continues on a number of theoretical and observational aspects of this problem. A study of mountain drag during the ALPEX period is nearing completion, and reveals strong fluctuations in association with frontal passages. Ertel potential vorticity analyses of lee cyclogenesis events have revealed that the interaction with the mountain occurs at a highly nonlinear stage of the event. Numerical studies with a nonhydrostatic model of flow over a mountain ridge have conclusively shown that, barring inhomogeneities of the oncoming flow, upstream influence first occurs in association with the momentum flux absorption due to wave-breaking (ew).

3.2.2 Tropical 40-Day Oscillation

The 40-day oscillation forms a major component of the low frequency variability in the tropics. A number of efforts toward understanding the mechanism of this oscillation are underway. An observational study of composite lifecycles has revealed the phase relationships between the convection and atmospheric flow. Diagnosis of long-range forecast models shows that such models destroy the information about the initial phase of the oscillation, leading to deterioration of the forecasts; some convection schemes produce convection that is too weak and shallow to permit the oscillation to take place at all. Work on diagnosis of general circulation model output also continues in collaboration with the Climate Group.

3.2.3. Planetary Waves, Low Frequency Variability

The fate of a Rossby wave at a critical layer affects a variety of other large scale atmospheric phenomenom. Work has progressed toward the development of a critical layer theory for external mode Rossby waves in a baroclinic atmosphere that impinge on a tilted boundary between westerlies and easterlies, such as is characteristic of the real atmosphere. A complete WKB theory has been developed for the two-layer model, and substantial progress has been made toward solving the problem for a vertically continuous atmosphere. In the latter case, the theory suggests that absorption at a tilted critical level is smooth and gradual rather than discontinuous. The theory also indicates that there can be substantial tunnelling of Rossby wave energy through westerly wave-guides above the region of easterlies.

Work has also continued on the role of baroclinic instability in low-frequency variability (dz). Extensions being pursued include the effects of Ekman friction and diabatic processes.

3.2.4 Dynamics of Concentrated Regions of Vorticity

Organized two-dimensional eddies have been observed to play a role in transition to three-dimensional turbulence in a variety of small scale flows (for which rotation is unimportant). The ubiquity of the phenomenon has been explained through the discovery of a new class of fluid dynamical instabilities, which act on any two-dimensional eddy with non-circular streamlines. This instability has no shortwave cutoff, and can inject energy directly into the dissipation range without the need for an intervening cascade. The calculation also reveals the important result that continuum modes can be destabilized by weak non-parallel effects (gl).

3.2.5 Anomaly Models

The three-dimensional anomaly models (cw) constitute a series of hierarchial models of different complexities, which may be useful as a tool for investigation of the effects of various atmospheric processes on teleconnection patterns. Using the stationary linear version of the model, sensitivity to the form of tropical heating was studied, revealing a substantial discrepancy in the Pacific/North American teleconnection pattern from the GCM solutions. However, if the time-dependent nonlinear anomaly model was applied to the tropical heating, the solutions appeared to agree with the general feature of GCM's solutions, implying that transient effects may be crucial in accordance with the results of other researchers(fc).

PLANS FY87

Effects of gravity wave drag on zonal mean flow in the climate group's idealized GCM will be diagnosed. Investigation of effects of Ekman friction on spatial baroclinic instability will be completed. The destabilization of continuum modes by non-parallel effects will be investigated. The time-dependent nonlinear anomaly model will be further studied.

3.3 AIR-SEA COUPLING FOR UPPER OCEAN FORECASTS

A. Rosati	R. Gudgel
K. Miyakoda	J. Sirutis
S. G. H. Philander	Y. Chao

ACTIVITIES FY86

3.3.1 Development of Upper Ocean GCM

A GCM that emphasizes the simulation of the upper ocean has been developed (605). The horizontal grid spacing is 1°x1° and is global in domain. The resolution of the equatorial region (10N-10S) is further refined in the north-south direction to 1/3°. There are 12 vertical levels, with 6 levels in the top 70 m and varying bottom topography is incorporated.

The basic model is the primitive equation model of Bryan and Cox (694) with the additions of the Mellor-Yamada level 2.5 turbulence closure scheme (517) and nonlinear viscosity in the horizontal. These modifications are intended to improve the upper ocean simulations, particularly, sea surface temperature (SST) and heat content (681).

Experiments are carried out to study the ocean model performance using atmospheric forcing from observed data. The observed forcing was derived from the NMC twice daily 1000 mb analysis for winds, temperature, and relative humidity for 1982 and 1983.

It was found that, in general, a realistic mixed layer structure was produced by these SGS parameterizations, and that 12-hour forcing improves the overall simulation over monthly mean forcing.

In Figure 3.2, the top panel shows the model SST simulation, and the lower panel is the observed SST analysis after R. W. Reynolds.

3.3.2 Application to 1982/83 El Niño Event

The ocean GCM described in 3.3.1 has been applied to the 1982/83 El Niño case, using the twice-daily atmospheric forcing of NMC 1000 mb analysis for 5 years from 1979 to 1983. The simulation of the ocean state is satisfactory to the same extent as the result of Philander and Seigel (681), though in our case, the vertical resolution of the GCM is somewhat insufficient for reproducing sharp thermoclines. The main interests in this study are the conditions for the onset of ENSO. The evolution of ocean heat content in the equatorial Pacific is being investigated together with the atmospheric variations in the trade winds.

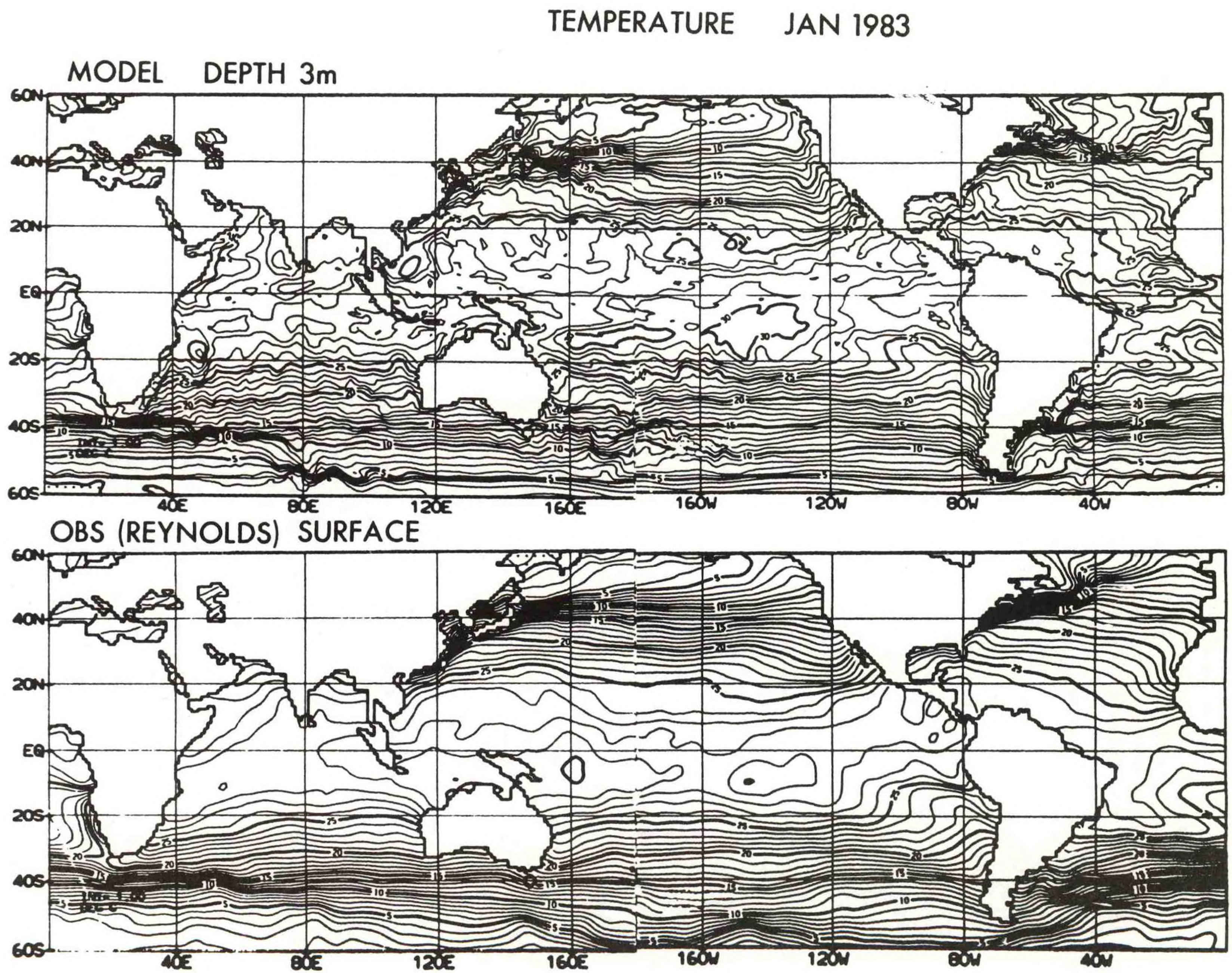

Fig. 3.2 - Distribution of the sea surface temperature in January 1983, as simulated by the Upper Ocean GCM (upper panel) and as analyzed by R. W. Reynolds based on observational data (lower panel). Contour interval 1°C.

3.3.3 Air-Sea Coupled GCM

The models of the atmosphere (R21L9-E) and the ocean (see in 3.3.1) are linked through the exchange fluxes of stress, heat, and moisture. The schemes of fluxes are specified in the so-called E-physics of the atmosphere (627), which are based on the Monin-Obukhov similarity scheme (587). The salinity at the ocean surface is, however, determined by the climatological seasonal variations. The first version thus incorporates full interaction between the atmosphere and ocean, with the exception of the prescribed salinity.

PLANS FY87

The vertical levels of ocean GCM will be increased from 12 to 15. Cloudiness of both climatology and satellite observations will be included in the radiation scheme. The ENSO onset will be pursued. A 10 year run from 1976 to 1986 will be started.

3.4 FOUR-DIMENSIONAL DATA ASSIMILATION

J. J. Ploshay   J. Derber
A. Rosati   W. F. Stern

ACTIVITIES FY86

3.4.1 Improvement of the Atmospheric Four-Dimensional Analysis Scheme

Two outstanding deficiencies in the GFDL data assimilation technique, noticed in the first FGGE analyses (552), were the noisiness of the analyzed fields and the underestimation of the central pressure in cyclones (568, 632, dy). In order to ameliorate these drawbacks, an improved scheme has been developed and tested successfully. The data assimilation scheme is still continuous data injection (649, dy), as opposed to an intermittent scheme. The improvements include (i) linear normal mode at every time-step for the incremental components, only applied to normal modes with periods shorter than 6 hours (652), (ii) a 6 hour forecast as the initial guess, (iii) 500 km data collection range for the local optimum interpolation, (iv) a higher resolution and more elaborate physics in the GCM, i.e., R42L18-EM, (v) a tightened toss-out criterion, (vi) > 1.5 hour data window, (vii) an improved quality control for moisture data, (viii) using observed SST, (ix) allowing data insertion to extend through the top two levels of the GCM, and (x) an improved vertical extrapolation scheme.

3.4.2 Development of a Oceanic Four-Dimensional Data Assimilation Scheme

A continuous four-dimensional data assimilation system for the Upper Ocean GCM has been developed and is currently being tested. The observational information is inserted into the forecast model through the use of an optimal interpolation analysis scheme applied at every timestep of the Upper Ocean GCM. In the optimal interpolation analysis scheme, data are used in a thirty-day window centered around the current model timestep. The corrections to the forecast fields are then calculated through the use of an iterative solution to the optimal interpolation analysis problem.

An examination of three aspects of the four-dimensional assimilation system are underway: 1) definition of the proper first guess error covariances; 2) the relative importance of the initial conditions, as specified through the data assimilation and the atmospheric boundary conditions; and 3) the necessity of initialization. The first aspect is being examined through the use of FGGE IIIc data sets. The second aspect will be examined using identical twin experiments while the initialization question will be examined using both data sets.

3.4.3 Application of Ocean Assimilation System to FGGE data

The FGGE IIIc ocean data is being obtained from NODC in order to produce analyses of the oceanic fields during the FGGE year. Due to the enhanced observing network, this period provides a good data base for the examination and testing of the oceanic assimilation system. Also, the improved analyses produced by the assimilation system can be used to improve the definition of the lower boundary conditions in atmospheric studies of the FGGE year. This work represents the first attempt to produce global oceanic analyses through the use of a four-dimensional data assimilation system.

3.4.4 Re-analysis of Atmospheric FGGE Data

A revised analysis of the FGGE Level IIb data for the special observing periods is being tested, using the new data assimilation technique (see 3.4.1). A careful comparison has been made for the cases of the Presidents' Day Storm, 16-20 February, pre-Monsoon period (Luo and Yanai, 1984),[1] 23-25 May, and Monsoon period 10-30 June. The results of the preliminary studies are overall satisfactory.

Level II satellite moisture data and temperature sounding data have been examined, and as a result, the incorporation of these data is being postponed. In the re-analyses of Special Observing Periods, heat and moisture sources/sinks are derived and archived. Note that this time, the archiving of the Level III data will be made at sigma-levels.

3.4.5 Initialization of the Tropical Atmosphere

It appears essential to reproduce the 40-50 day oscillation properly in forecasts in order to simulate the tropical heating effect due to cumulus convection and thereby, to forecast the teleconnection patterns correctly (f1).

A study is being carried out to develop an initialization scheme, by which the equatorial 40-50 day oscillations are maintained in the transition from the initial time to the forecasting phase. In order to achieve this, the continuous four-dimensional data assimilation is performed (see 3.4.1), and the matching calculation is switched to the forecasting phase without any particular change except stopping the injection of data. This process is being tested, using the 10-30 June 1979 case.

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[1]Luo, H., and M. Yanai, 1984: The Large-Scale Circulation and Heat Sources Over the Tibetan Plateau and Surrounding Areas During the Early Summer of 1979. Part II: Heat and Moisture Budgets. Mon. Wea. Rev., 112, 966-989.

PLANS FY87

Efforts will continue in order to achieve the maintenance of 40-50 day waves in the transition from the initial time to the forecast phase. The FGGE re-analysis will be carried out. The study of oceanic data assimilation will be pursued.

3.5 LONG RANGE FORECASTING

K. Miyakoda
W. F. Stern
R. Reynolds*
Y. Hayashi
R. T. Pierrehumbert
J. J. Ploshay
J. Sirutis
B. Wyman

*CAC/NMC

ACTIVITIES FY86

3.5.1 Effect of Sea Surface Temperature (SST)

The effect of SST on the forecasts of the January 1983 El Niño case has been studied, using observed SST analyses. One of the conclusions reported in FY86 is that the specification of SST in the equatorial Pacific is so delicate as to considerably affect the mid-latitude teleconnection patterns. In the meantime, it also has been found that the equatorial cumulus convection is dominantly associated with the 40-50 day oscillation (f1), and that the vertical motion in the tropics is intensified in the region of positive anomalies of SST.

These 40-50 day waves are the basic modes of velocity divergence for zonal wavenumbers 1 and 2, and the anomalous SST contributes to the increase in perturbation of divergence superposed on the basic mode (see 3.2.2, and 3.4.5). In other words, in order to simulate accurately the effect of SST on the equatorial heating, it is a prerequisite to reproduce the 40-50 day oscillation reasonably (see 3.4.5).

3.5.2 Interpretation of Ensemble-Time Mean Forecasts

Statistical interpretations of ensemble-time mean forecasts by the use of a dynamical model with unchanging external conditions are discussed (732). For this purpose, three kinds of variances are defined and their interrelations are clarified. It is proposed to define the predictability limit of the ensemble-time mean forecasts as the period when their error variance surpasses that of the climate-time mean forecasts. It is shown that, for a large ensemble of forecasts, this limit is close to the limit of individual time mean forecasts. The latter limit is defined as the period when the variance of time mean forecasts with slightly different initial perturbations approaches that of the time mean forecasts from widely different basic initial conditions. The statistical significance of ensemble-time mean predictability is also discussed and the interpretation of the analysis of variance is clarified. It is emphasized that a null hypothesis of unpredictability should not be readily accepted unless the confidence intervals are sufficiently small.

3.5.3 Intercomparison of the Forecasts for the Case of 15, 16 and 17 December, 1982

Using the three ECMWF analyses as the initial conditions, 45 day forecasts are being carried out in response to the proposal of the TOGA committee. Forecasts include the observed and climatological SST as the lower boundary conditions.

The forecast results will be compared with experiments of other groups such as the U.K. Meteorological Office, ECMWF, and University of Maryland, so that the deficiencies in the forecast systems, if any, will be detected.

PLANS FY87

The experiment on the maintenance of the 40-50 day waves will be continued, particularly with respect to the case of 1982/83. The intercomparison study based on the ECMWF initial conditions will be extended.

3.6 COLLABORATION WITH THE NATIONAL METEOROLOGICAL CENTER (NMC)

K. Miyakoda	S. B. Fels
J. Sirutis	J. Gerrity*
W. F. Stern	M. D. Schwarzkopf

*NMC

ACTIVITIES FY86

The second phase has involved collaboration in a number of areas which should result in improved model performance. These include: correcting a low-level summertime warm bias, the improvement of efficiency in the radiation calculation, the inclusion of orographic gravity wave drag, the incorporation of Tiedtke's shallow convection, and the application of new roughness parameters. All these targets have been reached or are currently being implemented.

The Fels-Schwarzkopf radiation scheme has been completely re-coded for the Cyber 205, resulting in a great increase in computational speed. The new 18 level model requires 3.5 ms/grid point, less than half that needed by the older code. A version of this model has been delivered to NMC, and will be used to replace the one presently used in their Medium Range Forecast GCM.

Comparisons of the operational radiation codes with the GFDL line-by-line calculations (cf. Sec. 1.8.1) have revealed cooling rate errors of up to 0.4°/day in the troposphere, due to inaccuracies in the emmisivities used in the operational models, and in their treatment of the e-type continuum. Preliminary results suggest that these errors can be largely corrected by a suitable application of the "simplified exchange approximation" of Fels and Schwarzkopf.

Tests after April 1986 have revealed that the performance of the NMC operational model (MRF-Medium Range Forecast) has been appreciably advanced with the additional improvements such as the better treatment of the effect of spectrally truncated mountains, a more adequate cumulus parameterization, and lateral diffusion of heat and moisture on pressure surfaces.

Note, however, that the original plan to implement the turbulence closure scheme (E4 physics) has been postponed temporarily.

PLANS FY87

The third phase of the cooperative effort will be pursued. This phase includes implementation of cloud-radiation interaction.

Work will continue on removal of the inaccuracies in the operational radiation codes.

4. OCEANIC CIRCULATION

GOALS

* To study the large-scale response of the ocean to atmospheric forcing over a range of time scales from a few weeks to decades.

* To perform oceanic observational studies by systematically processing the large data base available for the density structure and the fields of various tracers.

* To develop detailed, three-dimensional models of the World Ocean and its regional components and interpret these in terms of a coherent hydrodynamical framework.

* To develop a capability to predict the large-scale behavior of the World Ocean in response to changing atmospheric conditions.

* To identify practical applications of oceanic models to man's marine activities.

* To formulate and to test against observations a coastal ocean model which has a detailed surface layer and bottom boundary layer.

4.1 OCEANIC RESPONSE STUDIES

S. G. H. Philander
W. J. Hurlin
P. Chang
R. C. Pacanowski
R. Gardiner-Garden

ACTIVITIES FY86

4.1.1 Air-Sea Interactions in the Tropics

A general circulation model of the tropical Pacific has been transferred to NMC where it is being run operationally. Research to improve the model continues. A study of the necessary initial conditions shows that knowledge of the thermal structure of the ocean is essential while information about the currents is not critical (fe).

The oceanic GCM is being coupled with the atmospheric GCM that was used to simulate the Southern Oscillation over a 15 year period (702). In the first calculations being attempted, the forcing (incoming solar radiation) is steady. The purpose is to determine whether the oceanic-atmospheric response will be steady or whether there will be a Southern Oscillation, as in certain simple models.

An assessment of the predictability of El Niño, motivated by much publicized predictions of an El Niño for 1986 by colleagues at other institutions, indicates that the amplifications of perturbations into an El Niño by unstable air-sea interactions may be predictable if the ocean is in a state of non-equilibrium so that it is predisposed towards certain developments. Predictability, however, is very limited when the ocean is in a state of equilibrium as was the case in early 1986 (gg).

Interannual variability in the tropical Atlantic has intriguing differences and similarities with El Niño episodes in the Pacific. During 1986, conditions in the Atlantic resembled those in the Pacific during El Niño except that anomalous conditions in the Atlantic were uniform in longitude. In the Pacific, variations in the east and west are of the opposite sign. Apparently, Atlantic variability involves north-south movements of the ITCZ; Pacific variability has an additional aspect, i.e., the east-west movements of convergence zones (fn).

4.1.2 Simulation of Variability in the Tropical Atlantic Ocean

Bands of eastward and westward flowing currents characterize the oceanic circulation in the tropics. A model of the tropical Atlantic reveals that equatorial upwelling, and downwelling in adjacent regions, play a central role in closing the oceanic circulation. The eastward North Equatorial Countercurrent, between 3°N and 10°N approximately, loses mass because there is downwelling of fluid into the thermocline where it flows equatorward to feed the eastward Equatorial Undercurrent. The transport of the latter current decreases in a downstream direction because of equatorial upwelling and poleward Ekman drift into the westward South Equatorial Current, which feeds the Brazilian Coastal Current. The latter current in turn loses fluid to the two eastward currents (Fig. 4.1). The heat budget of the tropical Atlantic has also been analyzed.

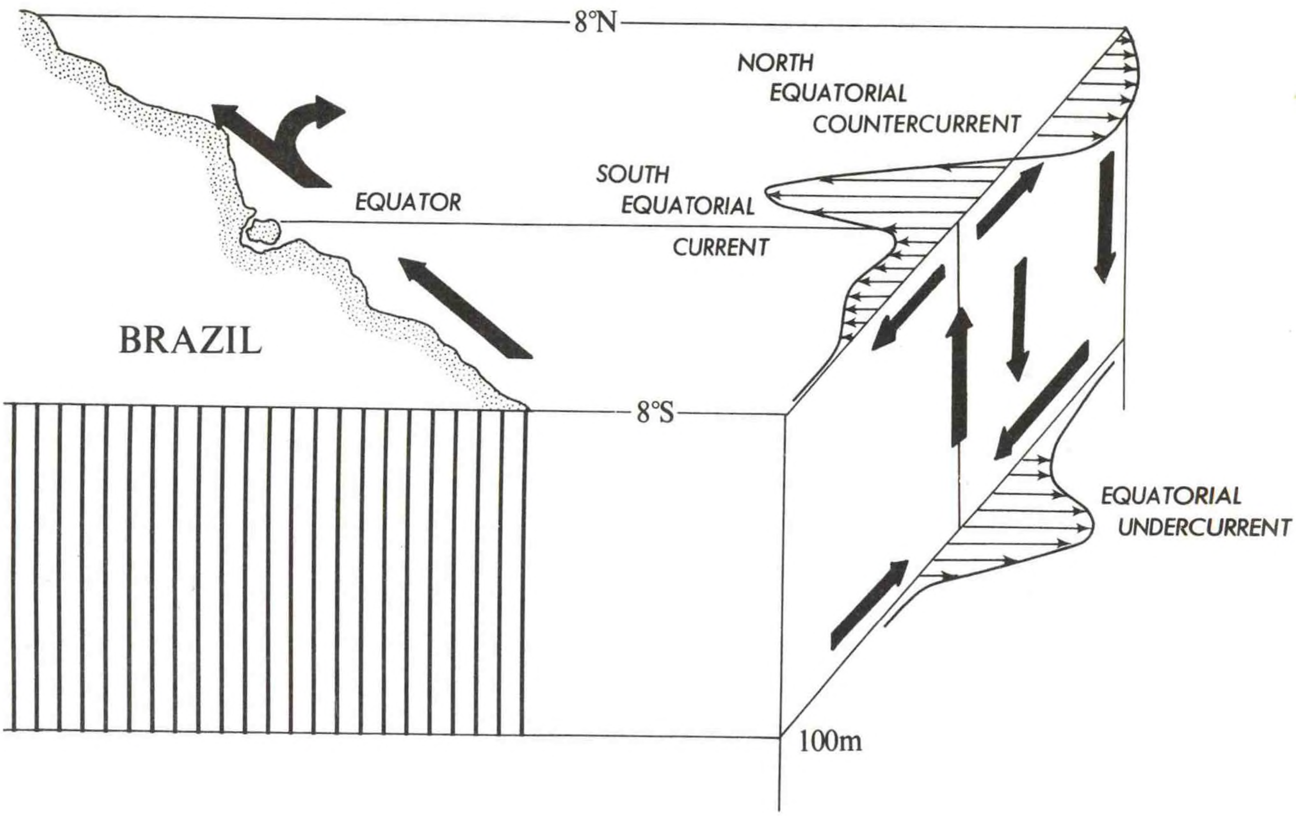

Fig. 4.1. A perspective diagram showing the circulation of the upper waters of the Equatorial Atlantic in early summer. The best data sets for verifying models of tropical ocean circulation are available in this region.

A comparison of measured and simulated surface currents in the tropical Atlantic indicates that mixing processes in the surface layer of the model are too weak. The use of monthly mean winds, rather than daily winds, to force the model contributes to the weak mixing (gj).

4.1.3 Seasonal Cycle of the Tropical Pacific Ocean

A simulation of the seasonal cycle in the tropical Pacific Ocean indicates that the movements of the ITCZ, and the associated changes in the curl of the wind, have a strong influence on the North Equatorial Countercurrent which disappears from the surface layer of the ocean during the Northern Hemisphere spring. The relatively weak southeast tradewinds at the equator at this time causes an eastward acceleration of the equatorial currents so that the westward surface flow disappears while the Equatorial Undercurrent attains its maximum speed.

PLANS FY87

Development of the coupled ocean-atmosphere general circulation models will continue. Specific integrations will attempt to determine whether the coupled system has an intrinsic 3 to 4 year time-scale comparable to that of the Southern Oscillation. The tropical Atlantic model will be forced with winds for the period 1982 to 1984 when extensive oceanographic measurements were made in the Atlantic. This test for the model should identify the needed improvements. Simulation of the tropical Pacific Ocean will concentrate on the heat budget during a regular seasonal cycle and during El Nino.

4.2 MARINE GEOCHEMISTRY

C. Broccoli
F. Bryan
S. Hellerman
M. Jackson
M. Kawase
R. Key
R. Najjar
D. Papademetriou
R. Rotter
J. L. Sarmiento
R. D. Slater
J. R. Toggweiler
L.-S. Yan

ACTIVITIES FY86

4.2.1 Carbon Cycle Modeling

A rudimentary ocean ecosystem model has been developed which will be incorporated into GFDL ocean circulation models to describe the downward flux of particulate carbon from the surface to the deep sea. The model consists of a limiting nutrient, and idealized populations of plants and small and large grazers. The most important feature of the ecosystem model in terms of global carbon cycle studies is its ability to predict the concentration of the limiting nutrient in surface water as a function of the latitude and the upward flux of nutrients from below. It has been shown that the maintenance of high surface nutrient levels in regions where deep water forms is critical to understanding how CO_2 is partitioned between the ocean and the atmosphere.

The basic approach that is being taken in developing the three-dimensional carbon cycle model is described in (725). A first set of experiments to test the sensitivity of atmospheric carbon dioxide to changes in ocean circulation with a simplified parameterization of biological processes will be completed in the near future. The ocean circulation models needed for this study have been constructed and the carbon cycle model has been tested and is ready to be run. The effect of changes of ocean circulation and surface productivity on the oxygen content of the deep ocean is being studied in the context of the considerable evidence for episodes of anoxia during the Cretaceous.

4.2.2 Modeling and Analysis of Quasi-Conserved Quantities

A study of the interaction between the surface salinity balance and deep water formation and its relevance to the global thermohaline circulation has been completed (gb). It was shown that a sector ocean general circulation model forced symmetrically about the equator has multiple equilibria involving inter-hemispheric circulations and model generated asymmetries in high surface salinities. A description of the heat balance in a seasonally driven model of the North Atlantic circulation has been completed (dq). This model and other simpler one- and two-dimensional models are being used in a study of how multiple tracer distributions can be used to yield information about physical processes. For details on boundary conditions for one of these tracers, Sr-90, see (ej). A review of tracer modeling has been prepared (fr).

Two analyses of measurements of temperature, salinity, oxygen, nitrate, and silica obtained in the North and Tropical Atlantic during the Transient Tracers in the Oceans (TTO) program have been completed (687, eh). Tritium measurements obtained in the Western Boundary Current help to elucidate the structure of this current (704).

4.2.3 Radionuclide Measurements

The Radium-228 laboratory continues to measure samples collected during the TTO cruises. A preliminary data compilation from the first set of results has been completed. These measurements have been used for a study of the rate of thermocline ventilation and oxygen utilization in the North Atlantic. The Amazon contribution to the surface waters of the eastern Tropical Atlantic has been estimated using radium and salinity measurements. Bottom profiles of radon-222 obtained in the Hatteras Abyssal Plain in a separate study aid in identifying the structure of the benthic mixed layer (704). Two cruises were carried out, one to do an inter-laboratory comparison of radium measurement techniques, the other to use tracers to study cross-Gulf Stream exchange in the North Atlantic.

PLANS FY87

The integration of the biological cycling formulations into the three-dimensional ocean circulation models and development of trace metal cycling models will continue to be a high priority. The multiple tracer study that was initiated during FY86 will be continued, using a hierarchy of models. The dynamics of the seasonal North Atlantic model will be described for publication. Field studies of tracer dynamics in the South Atlantic, Northeast Pacific, and Indonesian Passages have been proposed for the following year and are being reviewed at the present time.

4.3 WORLD OCEAN STUDIES

K. Bryan M. D. Cox
K. Dixon C. Boning
R.-X. Huang J. R. Toggweiler

ACTIVITIES FY86

The eddy-resolving model (694) provides a proxy data set for testing ideas on the role of mesoscale eddies in the ocean circulation. The role of mesoscale eddies in poleward buoyancy flux based on the model is reported in (dn). A detailed study of the time-dependent behavior of large scale waves in the eddy-resolving model has been completed (go). From the velocity structure of the model, it is possible to calculate the effective diffusion by mesoscale eddies. A comparison with diffusion coefficients calculated from Lagrangian float data for the North Atlantic indicates the same relationship between diffusivities and rms velocity as obtained in the model. A study of vertical profiles indicates that eddy diffusivities diminish more slowly with depth than the time-averaged velocity. Thus, diffusion can play a dominant role relative to advection by the time-averaged flow at the base of the thermocline. This result from the model which appears to be consistent with float data has very important implications for the structure of the thermocline. Most theories of the thermocline assume that the flow is nearly "ideal"; that is, potential vorticity and density are conserved along trajectories of geostrophic flow. The model results suggest that the reason for the nearly uniform potential vorticity field among density surfaces in the observed lower thermocline is simply that diffusion by mesoscale eddies dominates mean advection.

One of the best data sets for testing general circulation models are the GEOSECS measurements of carbon-14. These measurements are global and not only allow for a verification of the deep sea circulation in the natural carbon-14 field, but also provide a measure of vertical pathways near the surface through the recent invasion of anthropogenic carbon-14 produced by the bomb tests in the late fifties and early sixties. Several numerical experiments have been carried out using different circulation models based on the robust diagnostic method developed earlier (485). Verification of the predicted carbon-14 fields permit an evaluation and comparison of the models, which have slightly different parameterizations of vertical mixing. The model results show some deficiencies in the vertical exchange of the circulation models, but the global simulation of bomb-produced carbon-14 vertical inventories is very satisfactory and demonstrates that the main downward pathways are present in the three-dimensional model (see Fig. 4.2).

The testing of a 100km by 100km model of the World Ocean with 44 levels has been successfully carried out. The model provides an excellent simulation of intermediate water formation in the Southern Ocean, and the predicted strength of the thermohaline circulation in the North Atlantic is about 18-20 million tons/sec at 25N, in agreement with recent measurements.

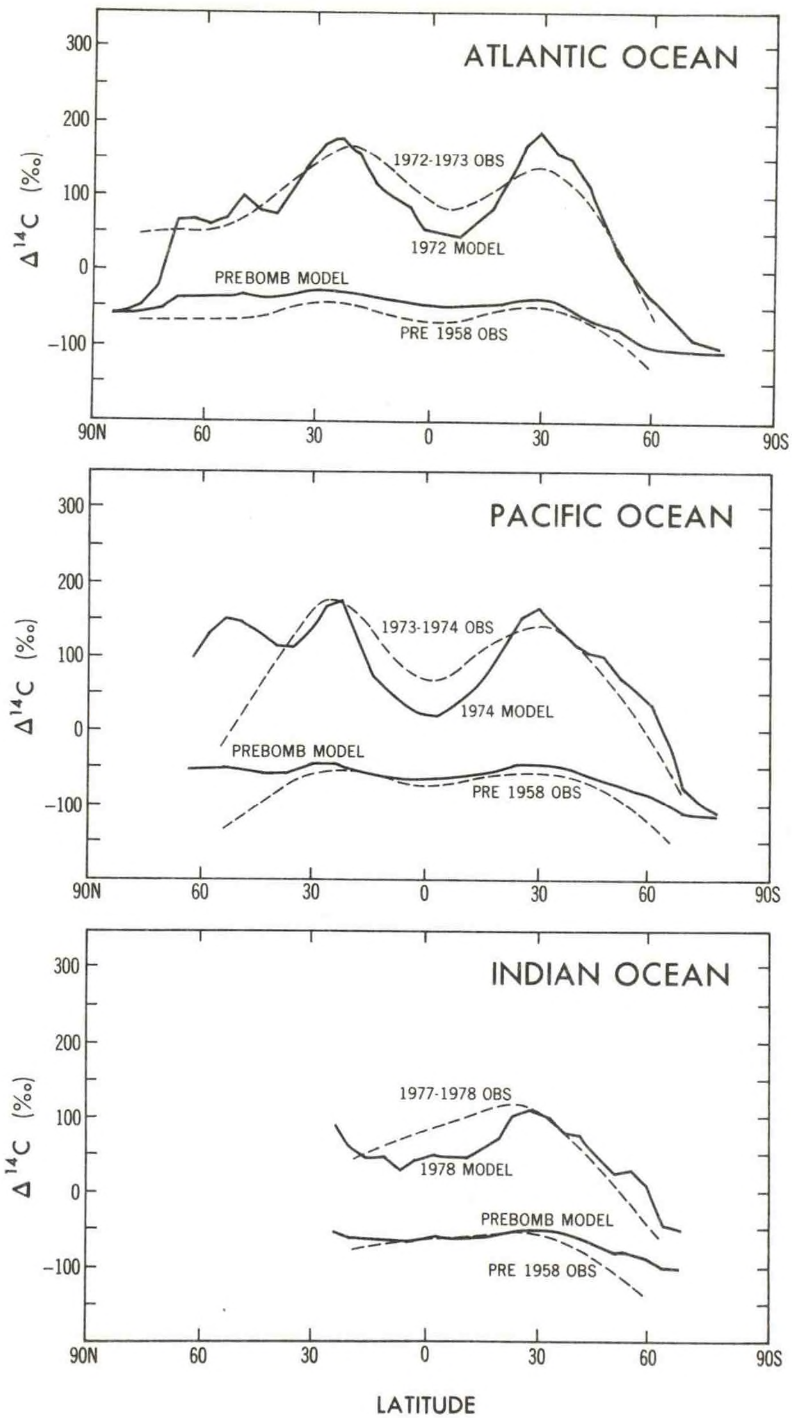

Fig. 4.2 - Carbon-14 in the upper ocean has been greatly increased by bomb tests taking place in the late fifties and early sixties. A three dimension model of the World Ocean is used to first predict the augmentation at the surface due to the bomb tests. Dashed lines indicate observations from Broecker, Peng, Ostlund, and Stuner (JGR, 90, C4, 6953-6970, 1985). Solid lines are zonal averages predicted by the ocean climate model (top) Atlantic, (middle) Pacific, and (bottom) the Indian Ocean.

PLANS FY87

Eddy-resolving calculations will be continued, using the same idealized geometry as in (694), but bottom topography will be introduced to determine the effect on the vertical profiles of eddy kinetic energy, the mean flow and the effective diffusivity by mesoscale eddies. The same model will also be set up for the geometry of the North Atlantic. Research will continue with a high resolution World Ocean model, including detailed verification of the simulated seasonal cycle in the upper thermocline against observations.

4.4 OCEAN MODEL DEVELOPMENT

K. Bryan M. Cox
R.-X. Huang R. D. Slater

ACTIVITIES FY86

There is abundant evidence that water mass properties tend to be conserved along trajectories and that much of the mixing of water mass properties by mesoscale eddies is parallel to isopycnal surfaces rather than across them. Subgrid-scale mixing along horizontal coordinate surfaces in models produces an undesirable cross-isopycnal component. Two approaches to eliminate this effect have been pursued. One approach has been to develop a model based on isopycnal coordinates. This has been done in a systematic way, starting with simple purely wind-driven models (cv, el, fx) and finally, a model which includes wind and buoyancy driving. The model reproduces the major features of much more complex models and provides a great deal of insight into the potential vorticity balance. Another approach to minimize cross isopycnal mixing is to rotate the mixing tensor so that it is parallel to isopycnal surfaces (555). Successful tests have been carried out with this parameterization in cooperation with the ocean geochemistry group on the World Ocean model with 100 km by 100 km resolution, resulting in a marked improvement in the simulation of water mass distributions with respect to density surfaces.

PLANS FY87

The performance of the bulk parameterization of the mixed layer in the model will be examined in the context of seasonal simulations of the high resolution World Ocean model. Testing of the rotated mixing tensor will continue, including tests in ocean-atmosphere coupled models.

4.5 COASTAL AND ESTUARINE OCEANOGRAPHY

G. L. Mellor
B. Galperin

ACTIVITIES FY86

The 2-D and 3-D models of Delaware Bay and River and the adjacent continental shelf were modified by introducing barotropic and baroclinic mass flux variables; this saves computational time and improves the numerical procedure of matching the shelf and the Bay and incorporating fresh water inflows. The bottom topography was improved. Daily averaged fresh water runoff data for 17 different locations around the Delaware Bay and River were obtained from the U. S. Geological Survey (USGS) and were incorporated into the numerical model.

Comparison of the barotropic model has been made with data from the National Ocean Service (NOS) 1984 circulatory study. For this purpose, the shelf has been decoupled from the Bay and the circulation in the Bay was driven by applying tidal and residual signals at the mouth. The wind field was obtained from meteorological data at Dover Air Force Base. The calculations are in good agreement with data in the lower Bay and up the river to Trenton. More numerical experiments were done with the wind-driven residual circulation at the mouth of the Bay and different formulation for the open boundary conditions at the shelf were used. Climatological temperature and salinity data for the shelf were obtained for future consumption by the 3-D model.

PLANS FY87

The main effort will be devoted to further improvement at the 3-D model and to a fifteen-month simulation of Delaware Bay, river and the adjacent continental shelf. The results will be analyzed and extensively compared with the measurements supplied by NOS. Predictions of 2-D and 3-D models will be compared as well.

4.6 COUPLED ICE-OCEAN MODEL FOR MARGINAL ICE ZONE

G. L. Mellor
L. H. Kantha
M. Steel

ACTIVITIES FY86

Work on a one-dimensional coupled ice-ocean model has been completed. This model has applications to marginal ice zone problems involving ice melting and freezing (fo). The model utilizes second moment closure to parameterize turbulent mixing and simulates quite well the melting and freezing processes occurring at the edge of the ice in marginal ice zones by treating the somewhat equivalent problem of time-dependent melting and freezing at the sea surface of the 1-D model. The model successfully simulates the rapid melting that takes place when ice first comes into contact with warm water; subsequently, the melting rate drops drastically. The melt water stabilizes the mixed layer and causes a reduction in the stress at the ice-sea interface. These results are consistent with observations in the marginal ice zone (MIZ).

Since the 1-D model cannot simulate certain processes related to the ice edge, such as ice edge fronts and the associated phenomena such as ice edge jets and upwelling/downwelling, work was begun on the development of a two-dimensional (x-z) model of the ocean in the marginal ice zone. This model specifically attempts to simulate the winter conditions in the Bering Sea MIZ. Here, the ice is advected by off-ice wind towards the shelf break where contact with warmer North Pacific waters melts the ice. It appears that the advection of warm waters below and past the ice edge constitutes the major source of heat to melt the ice and maintain the ice edge.[1] A two-dimensional model has been set up to simulate these conditions. However, even though double-diffusive convection is a strong source of mixing in the mixed layer under the ice in the MIZ, mechanical mixing brought about by ice motion at the surface and tidal stirring at the bottom cannot be ignored (fq).

A model of ice dynamics, incorporating the influence of internal ice stresses, has been formulated and tested against an available model.[2] The agreement appears to be good. The thermodynamics of ice has been incorporated into an ice model so that the heat balance at the air-ice interface can be properly dealt with in the coupled ice-ocean model. When decoupled from the ocean, comparisons with an earlier model[3] are favorable.

PLANS FY87

The ultimate goal of this project is to formulate a comprehensive, three-dimensional, coupled ice-ocean model suitable for application to the MIZ's around the Arctic. The model, in addition to including ice rheology, and dynamical and thermodynamical interactions between the ice and the ocean, will be fully three-dimensional with turbulent mixing parameterized by second moment closure. During the next fiscal year, the various subcomponents of the model will be combined, and the model will be tested with Greenland Sea MIZ as the test case.

4.7 TURBULENCE MODELING

G. Mellor
B. Galperin
L. H. Kantha

ACTIVITIES FY86

A turbulent energy model close to the level 2.5 model of Mellor and Yamada has been extended to include the effects of a solid wall on the components of the turbulent kinetic energy. This modified model has been applied to the simulation of turbulent diffusion from elevated and ground point sources in neutral boundary layers.

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[1] Hendricks, Muench and Stegan, A Heat Balance for the Bering Sea Ice Edge, J. Phys. Oceanogr., 15, 1747-1758, 1985.

[2] Leparanta and Hibler, The Role of Plastic Ice Interaction in Marginal Ice Zone Dynamics, J. Geophys. Res., 90, 11899-11909, 1985.

[3] Maykut and Untersteiner, Some Results from a Time-Dependent Thermodynamic Model of Sea Ice, J. Geophys. Res., 76, 1550-1575, 1971.

PLANS FY87

An effort will be made to incorporate the Coriolis terms in Reynolds stress and heat flux equations and to assess their impact on boundary layer simulations.

5. PLANETARY CIRCULATIONS

GOALS

* To understand the fundamental processes controlling global circulations.

* To develop numerical models capable of simulating any global circulations.

5.1 PLANETARY CIRCULATIONS

G. P. Williams R. J. Wilson

ACTIVITIES FY86

5.1.1 Planetary Vortices

The study of the dynamics of barotropic planetary vortices has been completed. Stable vortices were found to occur readily in midlatitudes and at the equator, but were dependent on the presence of zonal jets in low latitudes. Vortex dynamics, analyzed using the general geostrophic equation (654), was found to depend on balances among the steepening, dispersion, twisting, and advection processes. Advection is the main preserver of vortices. Stable vortices can have a variety of sizes and balances.

The generation of vortices by barotropically unstable currents most often resulted in a single vortex when zonal jets are wide and in multiple vortices when jets are narrow. Single vortex states were also generated by the merging of stochastically-forced eddies. A movie simulating the genesis of Jupiter's Great Red Spot shows that such a vortex thrives in a turbulent environment. Overall, the solutions provide an explanation for the origin, uniqueness and longevity of the Great Red Spot.

5.1.2 Global Circulations

The study of the dynamics and parametric variability of global circulations has been completed (gq). Solutions were examined to a standard GCM for which the external parameters (rotation rate, obliquity, diurnal period) were varied. The atmospheres were moist, dry, and axisymmetric and had regular, drag-free and interior-heated surfaces.

Despite their variety and complexity, circulations are made up of only a few elementary forms - five were identified - whose mix varies as the parameters change. Circulations vary from multi-jet, multi-element forms at high rotation rates to single-jet, single-element forms at low rotation rates.

Analogues exist between the planets and some GCM solutions (670): the Jovian planets correspond to high rotation rates, Mars to medium rotation, Titan to low rotation, and Venus lies in the singular range where the rotation rate nearly vanishes and circulations become sensitive to thermodynamical details. The recent Voyager encounter with Uranus revealed a circulation that corresponds to a low-obliquity GCM solution, suggesting that deep atmospheres, like the ocean, reduce the seasonal variation.

PLANS FY87

Model development for the atmospheric circulations of Jupiter and Venus will now be advanced as the major activity and will be used initially to examine the nature of coherent vortices in baroclinic fluids.

5.2 VENUS ATMOSPHERIC TIDES

S. B. Fels
P. Valdes*
A. Hou*
*Other Institutions

ACTIVITIES FY86

Studies of the tide-induced Eliassen-Palm flux divergence in the Venus upper atmosphere (db) were continued with the results presented in an expanded version. The tidal deceleration of the zonal mean wind from 70 to 90 km agrees very well with the deceleration deduced from purely radiative considerations, as is seen in Figs. 5.1a and 5.1b.

Comparison between tidal fields calculated using the approximate model and a two-dimensional numerical model designed by P. Valdes of Oxford University are made. The agreement is generally good, but there remain surprisingly large discrepancies in the horizontal structure of the predicted tides.

An efficient version of the tidal calculation algorithm was developed for use in conjunction with the axisymmetric Venus model constructed by A. Hou at Harvard. This is currently being used to carry out self-consistent tidal-mean flow calculations of the circulation of the Venus atmosphere, in which the mean flow seen by the tidal computations is precisely that driven by the tidal Eliassen-Palm flux divergence working against the radiatively induced zonal mean flow.

PLANS FY87

Work on the self-consistent tidal-mean flow model will continue in collaboration with A. Hou. If feasible, joint work with P. Valdes (now at Reading University, United Kingdom) will be started to discover the causes of the differences between the numerical and WKB tidal calculations.

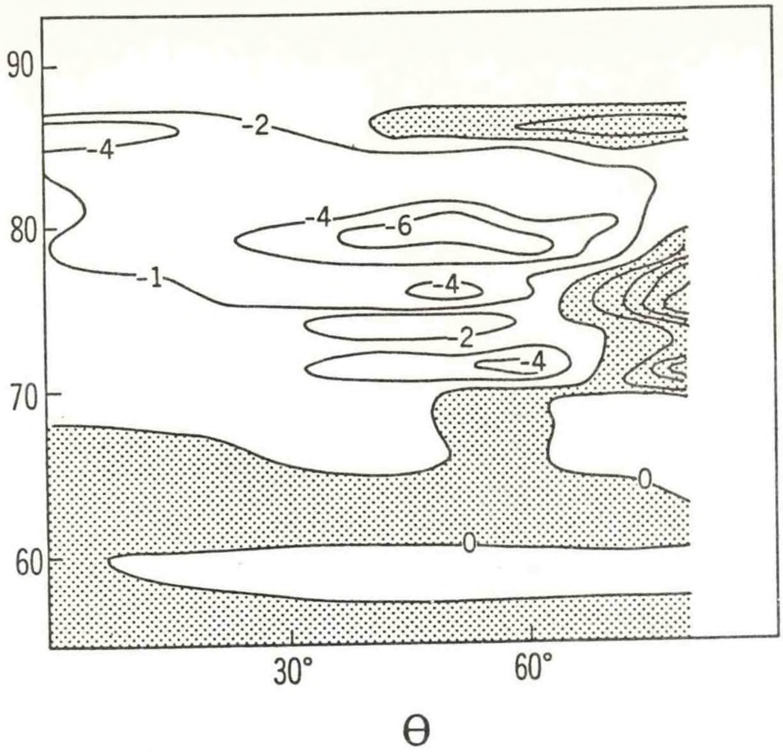

Fig. 5.1.a The zonal acceleration (in m/sec/day) deduced by Crisp (Ph.D. thesis, Princeton University, 1985) on the basis of the mean residual circulation required to balance the calculated radiative inbalance in the Venus upper atmosphere.

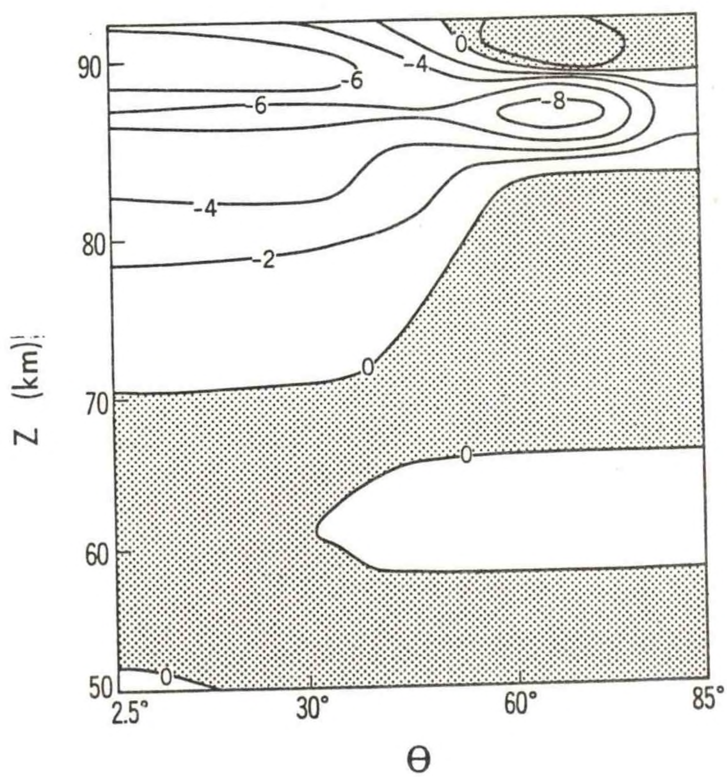

Fig. 5.1.b The same quantity as calculated from the EP flux divergence in the WKB tidal model.

6. OBSERVATIONAL STUDIES

Goals

* To determine and evaluate the physical processes by which the atmospheric and oceanic circulations are maintained, using all available observations.

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

6.1 CLIMATE OF THE ATMOSPHERE

N. C. Lau
N. Nakamura
M. J. Nath
A. H. Oort
M. Rosenstein
H. Savijärvi
A. Sotomayor
J. P. Peixóto*

* Visiting Scientist from University of Lisbon, Portugal

ACTIVITIES FY86

6.1.1 Data Processing and Comparisons Between Various Analyses

With the aid of J. Welsh from the Computer Systems Support Group, the objective analysis scheme for the monthly rawinsonde statistics was tested for different grid resolutions. Through various experiments in which 10% of the data was withheld, the analysis error could be established for the different parameters, levels and seasons. This enables us to choose the optimum resolution, smoothing, and data rejection criteria consistent with the data distribution. The improved schemes will be used to analyze global atmospheric circulation statistics for each month beginning May 1973.

In cooperation with Prof. David Karoly of Monash University, Australia, extensive comparisons have been completed between the Australian routine upper air analyses in the Southern Hemisphere and those created at GFDL (599).

6.1.2 Regional Budgets of Moisture and Energy

A comparison of the energy budgets of the Arctic and Antarctic regions poleward of 60° latitude is in progress. The earth-atmosphere exchange is computed as a residual. It shows a clear annual cycle of an upward flux of energy in winter and a downward flux in summer with an annual cycle of about 50 W m^{-2} amplitude. Most of this exchange of energy appears to be connected with the latent heat stored in the ocean, and only a small fraction with the melting and freezing of snow and ice.

A comparison between local energy budgets based on FGGE IIIb ECMWF analyses and those based on the GFDL station data analyses was carried out over some land and sea areas. The results were reasonably similar and may be interpreted to show the net effects of subgrid scale processes, such as gravity wave drag and cumulus convection (gu).

The GFDL station data analyses for the period 1963-1973 were used for global energy and moisture budget calculations. The originally noisy mean midlatitude divergent winds were replaced by dynamically constrained divergent winds, which satisfy both the vorticity and mass balances. This improved the energy budgets markedly. The results are comparable to various budget calculations based on FGGE IIIb analyses. In the tropics, the data void areas over the oceans are problematic in the station analysis scheme. The sparsity of observations in these regions result in various artificial features in the energy budgets.

6.1.3 Diagnosis of Transient Eddy Behavior in Observed and Simulated Atmospheres

The frequency dependence of the three-dimensional structure and propagation characteristics of transient disturbances appearing in observed and simulated atmospheres have been compared in detail (fz). Extensive use has been made of teleconnection and cross-spectral techniques. It is demonstrated that good agreement exists between model simulation and observations. In particular, the transition from north-south dipole-like oscillations in the 40-60 day band, to the Rossby dispersive waves in the 10-20 day band, and the eastward propagating baroclinic disturbances in the 4-day band, are all evident in the NMC analyses and in the model data. The diagnosis of near-surface disturbances in the vicinity of sloping terrain reveals a clear tendency for the eddies to propagate in a direction parallel to the local topographic contours. These strongly baroclinic disturbances are associated with severe cold air outbreaks on the leeward side of the Himalayas and the Rockies.

6.1.4 Observational Studies of the East Asian Circulation

The mean, variance and covariance statistics derived from the Royal Observatory of Hong Kong (ROHK) analyses for the 1976-1984 period have been compared extensively with corresponding quantities from other data sets. The ROHK results are seen to be of high quality and exhibit most of the known climatological features and their seasonal dependence in this region. Spectral and Extended Empirical Orthogonal Function analyses of the ROHK data set have revealed several phenomena with well-defined periodicities. Particularly noteworthy are the enhanced variances within the 40-50 day, 20-25 day and 14-day bands in selected regions. There also exists substantial evidence on the close relationship between the summer monsoon over the Indian subcontinent and the Mei-yu (Plum Rain) circulation systems over China and Japan.

6.1.5 Intraseasonal Oscillations in GCM Atmospheres

A detailed documentation of the 25-40 day oscillations appearing in a model atmosphere with realistic orography as well as land-sea contrast and subjected to climatological oceanic forcing has been completed (ek,er). It is demonstrated that the three-dimensional structure and propagation characteristics of these simulated phenomena bear a strong resemblance to observational results (Fig. 6.1). Similar oscillations are also detectable in other GCM experiments performed by the Climate Dynamics group, including one with variable oceanic conditions, and another one with no land-sea contrast and no orography (see section 1.6.1). Diagnosis of the latter simplified system has yielded new information on phase relationships between various hydrological parameters and the dynamical fields associated with such oscillations.

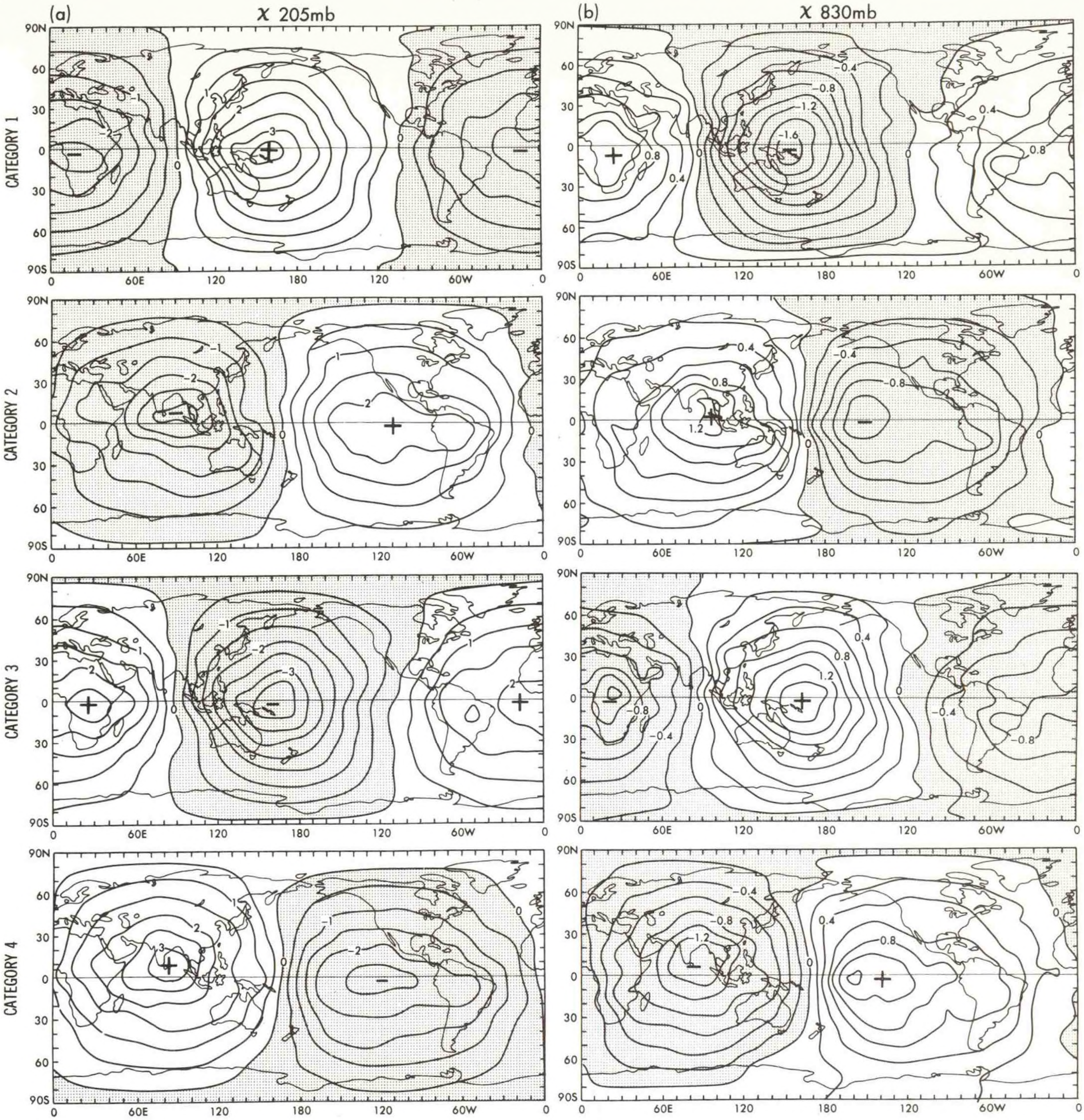

Fig. 6.1. Distributions of the anomalous velocity potential at (a) 205 mb and (b) 830 mb during the typical life-cycle of GCM-simulated 25-40 day oscillations. The categories 1, 2, 3 and 4 represent the four successive stages in the life-cycle, with the time interval between consecutive categories being approximately 6-10 days. The divergent component of the circulation is directed perpendicular to the velocity potential contours from low to high values. Note the eastward migration of the maxima and minima with the passage of time, and the out-of-phase relationship between the features in the upper and lower troposphere. Contour interval is $5 \times 10^5 m^2 s^{-1}$ for 205 mb data, and $2 \times 10^5 m^2 s^{-1}$ for 830 mb data.

PLANS FY87

Processing and analysis of the post-1973 rawinsonde data will continue, and global monthly anomaly fields will be generated with a 300 km grid resolution. Estimates will be made of the analysis errors due to spatial data gaps.

Research on the energy and water budgets of the Arctic and Antarctic polar caps will be completed. Other regional budget studies will be initiated.

The spatial relationships between different parameters of interest as the 25-40 day oscillation evolves through a complete life-cycle will be further delineated. In collaboration with the Climate Dynamics group, experiments with a simplified linear model will be conducted in order to determine the extent to which this oscillation might be forced by a moving tropical latent heat source. Other contemporary theories on the dynamical origin of this phenomenon will be tested using GCM data.

The myriad of interesting circulation features observed over the East Asian sector in both the winter and summer monsoon seasons will be examined in detail using the ROHK data set. Of particular concern are the apparent time lag of the Mei-yu fronts over China and Japan relative to the active phase of the summer monsoon over India, extratropical signals of the 40-50 day oscillation in the Asian sector, and the role of the Tibetan Plateau in steering the near-surface disturbances during the winter season.

6.2 AIR-SEA INTERACTIONS

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

* On two-year visit June 1985 - May 1987 from Academia Sinica, Beijing, China supported by grant from EPOCS Council.

ACTIVITIES FY86

6.2.1 Data Processing and Preparation of a Long-Term Climatology

Using an objective analysis scheme developed by Levitus (528), monthly 1°x1° analyses of the sea surface temperature were generated for each month of the 110 year period, 1870 through 1979, based on the Comprehensive Ocean-Atmosphere Data Set (COADS). A reliable climatology was created using the recent 1950-79 data. The SST anomaly analyses for each month since January 1870 show the general similarity between the different ENSO events during the last 110 years (ei). Similar analyses are being run for the atmospheric surface temperature, the wind components and the surface pressure.

A climatological atlas showing the normal annual cycle of most of the parameters available in the COADS is in preparation.

A study of the entire historical record of the sea surface temperature shows that the long-term changes in various 10°-latitude wide belts have been similar, except during the 1960's and 1970's when the Southern Hemisphere midlatitudes showed a heating and the Northern Hemisphere midlatitudes a cooling tendency. There is no obvious explanation at this point for the differences in the two trends (fu).

6.2.2 Diagnosis of Simulated Meteorological Phenomena Associated with the El Niño-Southern Oscillation (ENSO)

The spatial structure of the Northern Hemisphere midlatitude response to sea surface temperature anomalies in the tropical Pacific has been separated from the mode of variability associated with natural fluctuations of the zonally averaged flow (eq,ev). This distinction between the internal and external causes of atmospheric variability has enhanced our understanding of the origin of circulation anomalies appearing in GCM experiments with and without perturbations in the oceanic forcing (475, 572, 679, 702).

Detailed local balances of heat, water vapor and moist static energy have been constructed over the globe for both the 30-year climatology and the anomalous ENSO episodes simulated in an extended GCM run (702). Energy fluxes and wind stress fields at the air-sea interface have also been computed.

PLANS FY87

The analyses of historical ENSO events based on the COADS will continue, with principal emphasis on ocean-atmosphere feedback processes.

An atlas of climatological mean values of surface marine parameters is in preparation. Estimates of interannual variability of monthly mean fields will also be presented.

In collaboration with the Ocean Circulation and Climate Dynamics Groups, the feasibility of simulating meteorological and oceanographic phenomena using an air-sea coupled general circulation model will be critically examined. The impact of sea surface temperature anomalies located outside of the equatorial Pacific Basin on the atmospheric circulation will be studied by initiating further GCM experiments with prescribed oceanic forcing.

Budget studies based on history tapes for completed GCM runs will continue, with specific emphasis on the relative importance of fluxes of energy in various forms across the air-sea interface during a typical ENSO episode.

6.3 CLIMATE OF THE OCEAN

S. Ascher* S. Levitus
M. Jackson A. H. Oort

* Student in GFD Program's Undergraduate Summer Research Program during summer 1986.

ACTIVITIES FY86

6.3.1 Data Processing and Comparisons Between Various Analyses

Because of great demand a set of 1000 copies of the Climatological Atlas of the World Ocean (528) was reprinted by the U.S. Government Printing Office. The objectively analyzed fields and five-degree square statistics presented in the Atlas have been made available to the research community on magnetic tape via the National Oceanographic Data Center.

A thorough comparison was made between two distinct sets of monthly sea surface temperature climatologies for the world ocean. The first set was based on 1.5 million vertical temperature soundings archived by the National Oceanographic Data Center (NODC) and the second set on 70 million historical merchant ship reports from COADS. Excellent agreement was found in the annual and semiannual components (ft).

6.3.2 Heat and Salinity Balances

The annual cycle of salinity in the upper 500 m of the world ocean was examined. Major features of interest included the relatively large annual cycles in the tropical Pacific and off the coast of Labrador (719).

A comprehensive analysis was made of the annual variation of the heat storage in the world ocean. The amplitude of the annual cycle shows maxima exceeding 300 W m^{-2} along 40°N in the Pacific and Atlantic Oceans and in midlatitudes of the Southern Hemisphere. Values exceeding 200 W m^{-2} are found in the tropics (gc).

Global computations of Ekman horizontal and vertical volume transport as well as meridional heat transports have been completed(Fig. 6.2). Large seasonal variations were found in the Ekman heat transport in the tropical ocean (cu).

6.3.3 Long-Term Variations in the Ocean Heat Storage

A study of the variability of the North Alantic Ocean temperature at intermediate and deep depths on decadal and pentadal time scales is underway. A comparison with the results of Roemmich and Wunsch (1984)[1] at 24°N and 36°N shows good agreement in both the sign and magnitude of differences between the IGY period and the 1970-74 period.

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[1]Roemmich and Wunsch 1984: Apparent Changes in the Climatic State of the Deep North Atlantic Ocean, Nature, 307, 447-450.

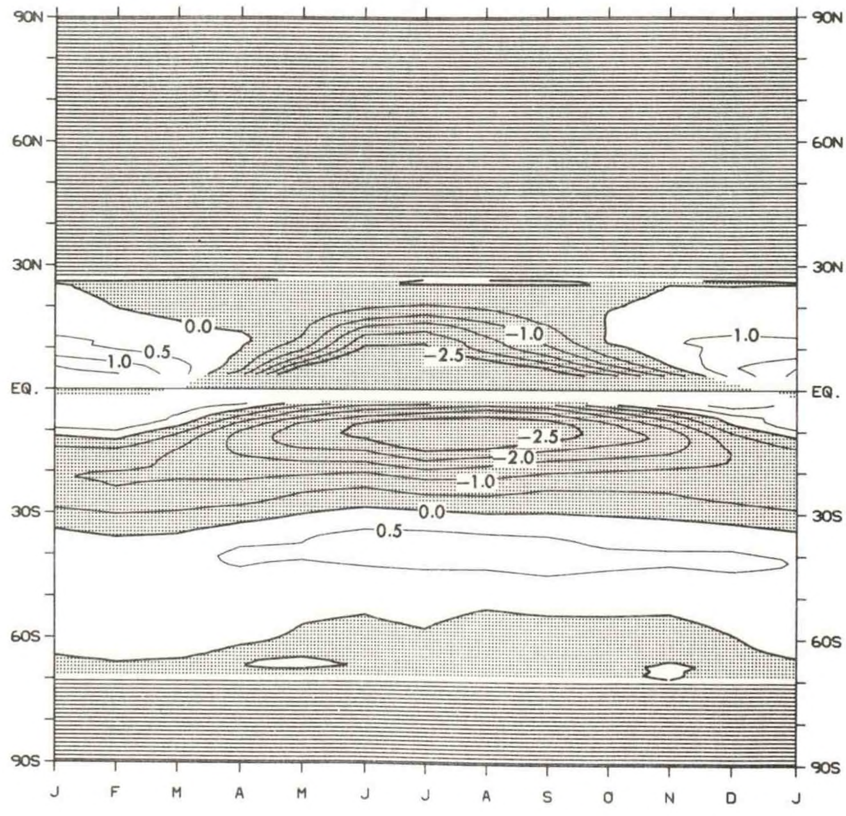


Fig. 6.2 - Zonal integral of meridional Ekman heat flux (petawatts = 10^{15}W) in the Indian Ocean as a function of month and latitude. Shading indicates southward flux. Contouring not performed within 3.5° of the Equator. The strongest southward fluxes occur during the summer monsoon. The annual mean shows a net southward heat flux in qualitative agreement with the net annual mean total heat flux estimated using surface heat balance considerations (Hastenrath and Lamb, 1980 On the heat budget of hydrosphere and atmosphere in the Indian Ocean. J. Phys. Ocean. 10, 694-708).

shows good agreement in both the sign and magnitude of differences between the IGY period and the 1970-74 period.

PLANS FY87

A thorough study of inter-pentadal and inter-decadal variability of the North Atlantic Ocean will be made.

Estimates of the observed available potential and kinetic energy will be made for the world oceans. The results will be compared with those for the atmosphere.

The series of studies describing the annual cycle of the world ocean will continue. Future manuscripts will describe the annual cycle of mixed-layer depth, dynamic topography, and Ekman heat and volume transports.

An investigation of satellite SST data from the viewpoint of interannual variability of large scale features is being initiated.

Unpacking of the MOODS (Master Oceanographic Observations Data Sets) data base from Fleet Numerical Oceanography Central will take place.

7. HURRICANE DYNAMICS

GOALS

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

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

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

7.1 GENESIS AND DECAY OF TROPICAL CYCLONES

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

ACTIVITIES FY86

7.1.1 Effects of Mountainous Islands

Investigation of the effect of mountainous islands on the behavior of tropical cyclones has continued. The numerical results from the triply-nested movable mesh model with the finest resolution of 1/6 degree longitude and latitude were obtained for the case of the Caribbean Islands, Taiwan and the island of Luzon in the Philippines. The results have been analyzed and summarized (fg). It was found that island mountain ranges can influence both the mean flow and the wind field associated with the storm itself to cause significant storm track deflection. Displacement of a storm due to such an effect can be comparable to the position errors of current operational hurricane forecasting. The storm intensity was affected by the advection of dry air from near and above the mountain tops as well as by the forced structural changes. The storm's central pressure generally started to fill before landfall and the storm weakened rapidly after making landfall and encountering the high mountain ranges. Structural change in the Taiwan case with a 10 m/s easterly steering flow was characterized by the formation of secondary low pressure systems in lee of the mountains, while the original system decayed on the upstream side. In case of the island of Luzon, the vertical structure of the storm system was distorted and the surface pressure center, the upper and lower circulation centers and the location of the warm core or area of intense precipitation were displaced from one another by more than 100 km. (See Fig. 7.1.) Since the storm structure often becomes altered or disorganized during and after crossing the island terrain, care must be taken in the determination of the storm position.

Simulation experiments were also carried out for the mountainous regions of Japan. The steering flow was obtained from a stationary Haurwitz wave. The process of storm decay after landfall was quite sensitive to the landing position.

7.1.2 Genesis of Real Tropical Storms

An extensive study on the genesis phase of real tropical storms has continued. A model of 1/4 degree longitude and latitude grid resolution was initialized with either ECMWF or GFDL, original or revised, FGGE data sets. Evolution of storms from various pre-storm conditions were investigated and simulations of some cases are in progress. The disturbances being treated are (1) Hurricane David, which developed from an easterly wave over the Atlantic, (2) a non-developing wave disturbance over the Atlantic, (3) Supertyphoon Tip over the Northwestern Pacific and (4) a North Indian Ocean storm which appeared to have interacted with another tropical disturbance located over the South Indian Ocean. In general, the simulation of intensity change and movement of the abovementioned pre-storm disturbances was at a satisfactory level, though not perfect. In some cases, the distribution of

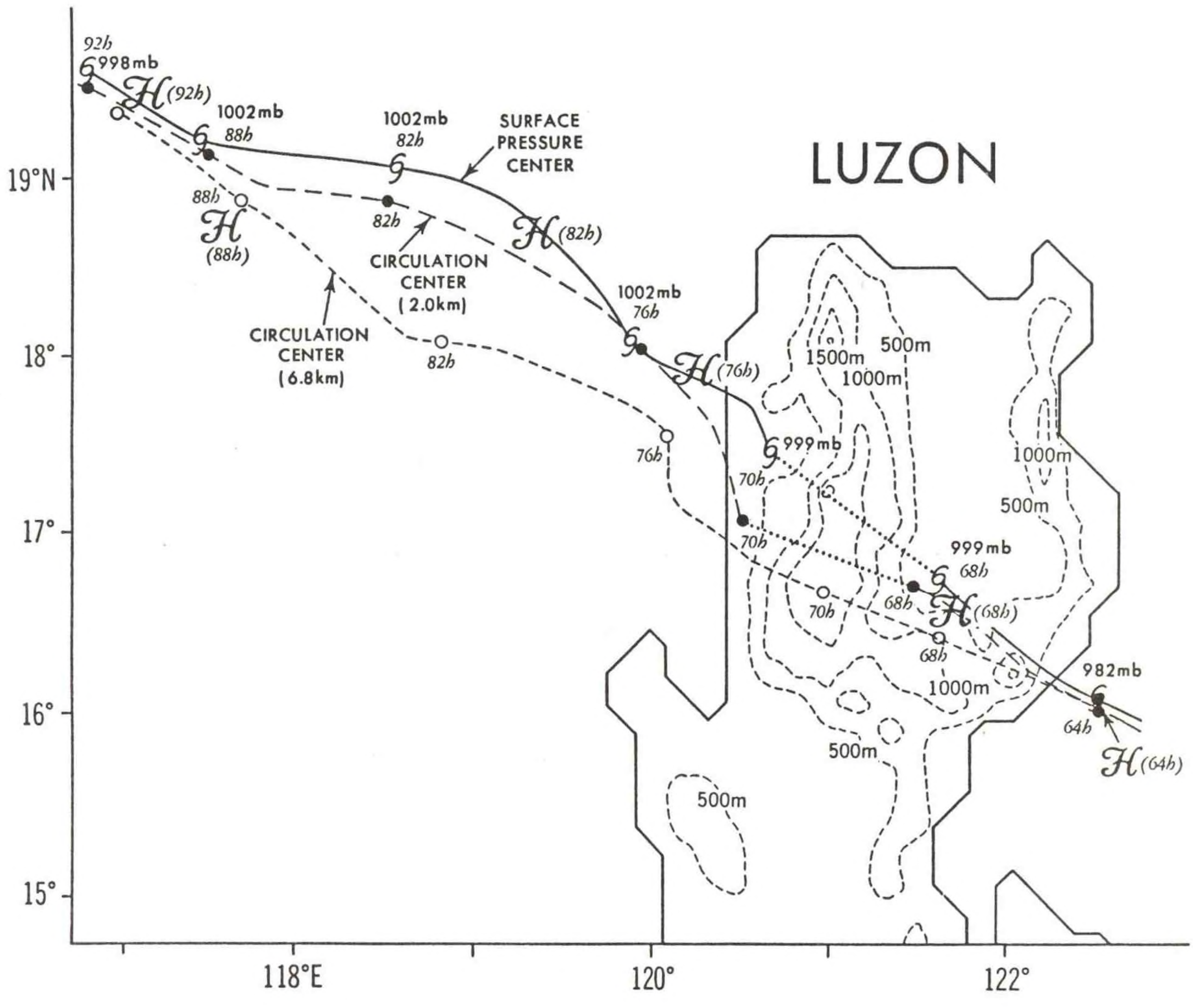


Fig. 7.1 Tracks and positions of the storm's sea level pressure (solid line and tropical cyclone symbol), and the center of circulation of the wind field at the 2 km (long dashed line and closed circle) and 6.8 km (short dashed line and open circle) heights for the simulation experiment with a 5 m/s easterly steering flow. Positions of the 8.1 km warm core (letter H) are given. The coastline of northern Luzon is indicated by a thick solid line with the topographical height contoured (thin dashed line). When the tracks were not continuous the positions are connected by a dotted line.

precipitation in the model after about one day corresponded very well with satellite imagery. These results indicate that some of the real pre-storm disturbances are significantly controlled by the synoptic scale environmental conditions. This inference gives an important and encouraging view for the predictability of the evolution of pre-storm disturbances.

The meteorological fields in the interior of the integration domain are affected when the lateral boundary condition is altered from a simulation mode, i.e., specified condition obtained from analysis, to a prediction mode. An investigation on this subject is underway.

PLANS FY87

Results of the simulation experiments of the tropical cyclone landfall onto the mountainous islands of Japan will be analyzed.

Further experiments to study the influence of realistic orography on tropical storms will be planned and performed for other areas, including the east coast of the United States.

Study on the genesis of real tropical storms will continue with attention to the interaction of storms with their large scale environment.

7.2 EXPERIMENTAL HURRICANE PREDICTION

M. A. Bender
C. Kerr
Y. Kurihara
R. E. Tuleya
M. DiPaola

ACTIVITIES FY86

7.2.1 Model Improvement

When a movable nested mesh model is used, quantities over mountain regions have to be redefined as the grid resolution changes. Schemes to treat this issue were examined. Also, problems associated with the lateral boundary conditions of a regional model have been addressed, in particular, for the case in which the mountainous terrain exists at an inflow boundary.

An effort is being made to improve the readability of the coding of our hurricane model. New analysis programs have been formulated in order to obtain analysis results at a level of high quality.

7.2.2 Initialization Scheme

Formulation of a scheme of diabatic initialization for the model of the tropical atmosphere has continued. A test, using a simple vertical slab version of an easterly wave, is almost complete. Application of the reverse divergence equation in mass diagnosis produced a result which agreed fairly well with an observed field of composite African waves. A diagnostic formula, which was derived from a combination of the time derivative of the divergence equation and the thermodynamical equation, yielded a reasonable estimate of the heating rate. Extension of such a scheme to a three-dimensional model is in progress.

7.2.3 Cooperation with the National Meteorological Center

Collaboration with NMC was established for promoting a joint project to construct a hurricane model which may eventually become an NMC hurricane prediction model after the introduction of the next generation computer.

PLANS FY87

Effort will continue to increase the efficiency of the integration of the hurricane models and to improve the open lateral boundary conditions.

Progress will be made in programming of the three-dimensional version of the initialization scheme which was tested in the previous year with a slab symmetric model.

Work will start, in cooperation with the National Meteorological Center, to develop a candidate model for future operational hurricane prediction.

8. MESOSCALE DYNAMICS

GOALS

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

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

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

8.1 THE GENERATION OF MESO-CYCLONES

L. Orlanski N. Nakamura
L. Polinsky

ACTIVITIES FY86

8.1.1 Local Baroclinicity

A study has been completed (ee) using a two-dimensional numerical model to investigate the evolution of mesoscale disturbances on a mean baroclinic state. Three main problems were considered: the effect of static stability on meso-baroclinic waves in a periodic domain; downstream instability in an open domain, including the effect of surface sensible heat; and the effect of moisture on these unstable waves.

It was found that a flow can be unstable to mesoscale baroclinic waves. The instability condition that wavelengths be less than 1000 km is similar to that for the planetary, quasi-geostrophic baroclinic waves. These unstable waves will only be sensitive to the baroclinicity of the atmosphere in a layer with a depth which is the order of the Rossby penetration height. Characteristics of the finite-amplitude unstable waves suggest that the limiting amplitude for the baroclinic waves is achieved by an energy cascade to frontal scales. The most significant finding of this study has been to demonstrate the importance of localized surface heating in producing the more intense development of short baroclinic waves. It was also found that waves in the presence of surface heating grew twice as fast as those without. These waves, which have a depth on the order of the boundary layer and horizontal scales of a few hundred kilometers, can organize convergence of surface moisture on these scales. With the addition of moisture, the waves will explosively develop into an intense meso-cyclone (Section 8.1.3).

8.1.2 Mesoscale Baroclinic Instability

The classical linear stability problems of baroclinic flow considered by Charney and Eady were successful in explaining the preferred synoptic scale and the growth rate of the disturbances commonly observed in the atmosphere. While these analyses have been widely accepted, baroclinic cyclogenesis does not always seem to occur as a synoptic-scale (greater than 1000 km) disturbance.

A simple two-dimensional linear stability analysis is being done to study the characteristics of mesoscale baroclinic cyclogenesis. The effect of a more realistic vertical thermal structure and of related nongeostrophy is being investigated in detail. Both short (mesoscale) waves trapped in the mixed layer and long waves extending throughout the column were found to be unstable. Nongeostrophic effects become important as the Richardson number decreases; the scale of the most unstable Eady wave becomes sensitive to changes in the shear, in contrast to the geostrophic case.

8.1.3 Polar Lows

A study has been made (615) of cold air cyclones, known as polar lows, which develop over extratropical oceans in the unstable air mass behind a major frontal cloud band. A 48-hour numerical simulation was made of one such observed polar low (occurring on 11-12 January 1979) which exhibited explosive cyclogenesis. In order to clarify the importance of latent heating versus surface sensible heat flux for the cyclone's development, sensitivity tests were performed with three different cases: one without moisture, one with observed moisture, and one with enhanced moisture. The case without moisture (and hence without latent heating) produced a weak low-pressure system which did not grow in time. However, with the inclusion of moisture, and particularly with enhanced moisture, both the polar low and the frontal system showed an intensifying surface vorticity, while the comma cloud associated with the polar low and the frontal cloud band tended to merge in the case with enhanced moisture. These results indicate that latent heating is crucial to the explosive cyclogenesis of the polar low, whereas surface sensible heat flux provides the triggering mechanism (Section 8.1.1) which causes the initial disturbance to develop.

PLANS FY87

Further investigation of mesoscale baroclinic instability will be carried out in connection with three-dimensional numerical experiments to better understand the physical mechanisms involved.

8.2 COASTAL CYCLOGENESIS

I. Orlanski
J. Katzfey

ACTIVITIES FY86

A study of the Presidents' Day cyclone of 18-19 February 1979 was completed (gd) using the Limited-Area HIBU Model (LAHM). The model accurately predicted the development of the surface low in this case, both with respect to position and intensity. Some discrepancies were noted for upper air features between the analyses and the model solution during the first 24 hours.

The impact of the initial conditions on the model solution was tested by using four different analyses. In general, the variability of the solutions was less than the variability of the analyses. Varying the horizontal diffusion in the model produced stronger development with weaker diffusion, but the character of the development did not change significantly. The sensitivity of the simulation to latent heat was tested by running the model without latent heating. A low did develop in this model solution, although it was much weaker and did not develop vertically as in the cases with latent heating. The most significant improvement in accuracy occurred when the horizontal resolution was increased. The position and intensity of the surface low were much closer to reality as indicated by comparison with a meso-analysis and with satellite imagery (Fig. 8.1).

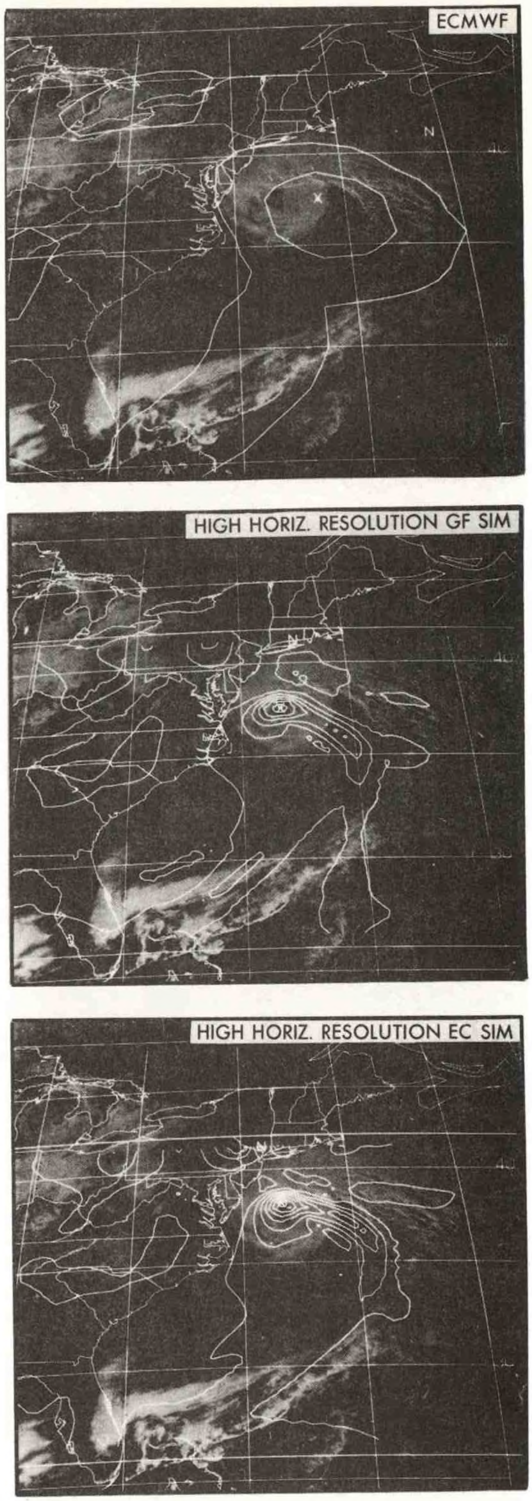


Fig. 8.1. Visible satellite cloud images at 1830 GMT 19 February 1979 are composited with contours of surface relative vorticity as taken from analysis of observations and LAHM simulations at 1800 GMT (Contour interval is $1 \times 10^{-4} s^{-1}$). Contours in the top panel are from the ECMWF FGGE analysis. The middle and lower panels show vorticity fields taken from LAHM simulations with 50-km horizontal resolution, using initial and lateral boundary data from the FGGE analyses of GFDL and ECMWF, respectively.

The nested model was also run in forecast mode with boundary conditions for the limited-area model supplied by the GFDL global spectral model. In general, the quality of the forecast compared very well with the simulations. The overall character and intensity of the development were similar.

The role of lateral boundary conditions was demonstrated by comparing forecasts and simulations with identical initial conditions. The results indicate an increasing importance of the boundary data with time in the forecast and show a high correlation between the errors in the limited-area forecast and the global forecast within the limited-area domain.

PLANS FY87

Study of the role of surface sensible and latent heat in the explosive nature of coastal cyclogenesis will continue.

8.3 OROGRAPHIC EFFECTS ON MESOSCALE SYSTEMS

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

ACTIVITIES FY86

8.3.1 Heavy Rainfall Vortex in the Lee of the Tibetan Plateau

A case involving a heavy rainfall vortex that occurred during the period 14 - 15 July 1979 is being studied using a limited-area mesoscale numerical model. This vortex is a representative example of warm southwest vortices that form over the eastern flank of the Tibetan Plateau after the onset of the summer Indian monsoon.

Some common features in the dynamic structure between simulation and observation are noted. The vortex originated and rapidly developed in a stagnation region on the lee side of the plateau. The presence of the stagnation region not only removes local energy sources from the environmental flow but also diminishes topographic destablization through reduced vortex stretching for the component flowing over the plateau and reduced convergence for the component flowing around the plateau. Without latent heating, dynamic instability and/or forcing of the large scale flow interacting with the Tibetan Plateau are not sufficient to generate the observed disturbance.

On the other hand, the plateau blocking effect favors the establishment of a conditionally unstable environment. The simulation indicates that a sudden onset of vigorous deep convection followed by a rapid vorticity intensification at 700 mb took place once the dynamic forcing associated with a mesoscale plateau disturbance was positioned over the moist stagnation region. The principal result of this study is that the warm heavy rainfall vortex is apparently driven primarily by cumulus convective heating. The thermal influence of the elevated plateau topography may appreciably affect the vortex initiation through changing the intensity of the forcing associated with the triggering mechanism.

8.3.2 Cyclogenesis in the Lee of the Andes Mountains

Cyclogenesis in the lee of the Andes Mountains is under investigation using the Limited-Area HIBU Model. Development of mesoscale lee cyclones forced by the high, narrow mountain chain has not been studied extensively and is inaccurately predicted in global models. However, these cyclones have important implications for the weather and climate of the region. The role of the mountains in upstream blocking also needs to be investigated.

Simulations are being carried out using observations taken from the 1979 FGGE analysis. Model results show a realistic development of the cyclogenesis that occurred on August 30, 1979. Comparison of the evolution of the surface front over the 48-hour prediction period with surface observations indicates very good agreement. However, similar agreement is not found between modeled and observed precipitation patterns on the lee of the Andes Mountains. Preliminary analysis indicates deficiencies in the initial moisture field derived from the FGGE analysis. Experiments are currently being performed to determine the sensitivity of model results to an improved surface moisture analysis obtained from an objective analysis of Argentine surface observations.

PLANS FY87

Studies of the dynamics of lee cyclogenesis associated with the Andes Mountains will continue.

8.4 MESOSCALE FORCING OF CONVECTIVE SYSTEMS

I. Orlanski B. Ross
A. Crook

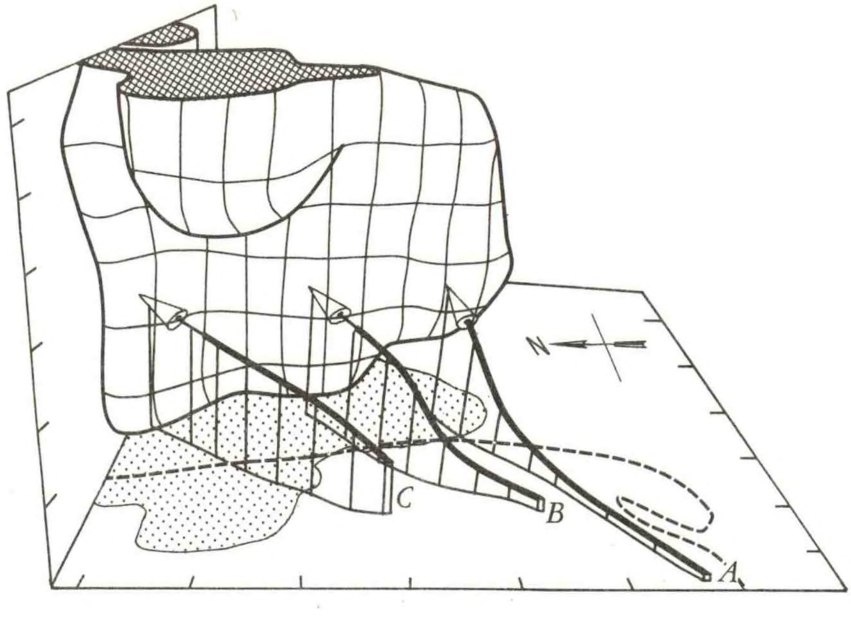
ACTIVITIES FY86

8.4.1 Squall Lines

The effect of mesoscale forcing and diabatic heating on the formation of convective systems has been investigated (ex) using a simplified numerical simulation of the pre-squall line and squall line convective systems occurring over Texas and Oklahoma on 10-11 April 1979. A simulation run without latent heat showed both systems to be initiated and maintained by convergence produced by larger-scale forcing. The earlier pre-squall line cloud system formed downwind of the convergence zone that was produced by the confluence of air streams along the dryline. As a cold front approached from the west, this convergence zone rotated to align itself lengthwise with the southwesterly, low-level flow, thereby leading to the formation of the actual squall line.

When latent heat was included, the continuous cloud in the pre-squall line system broke into convective cells (Fig. 8.2) which moved downstream from the convergence zone. In the squall line itself, latent heat release produced a deeper cloud system while intensifying and maintaining the low-level convergence. However, unlike the earlier system, the squall line did not break into convective cells when latent heat was included in the simulation.

NO LATENT HEAT



LATENT HEAT INCLUDED

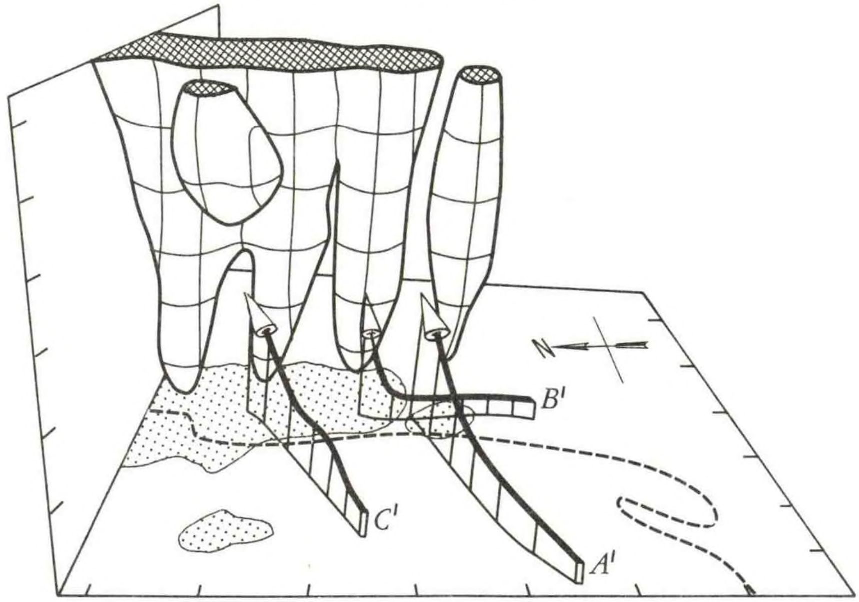


Fig. 8.2. Three-dimensional cloud fields and parcel trajectories are compared for simulations of the 11 April 1979 case without and with latent heat included in the model. Dashed contours indicate the position of the dryline at the surface, with moist air to the east and drier air to the west. Without latent heating, air parcels are advected into the cloud from the southwest (trajectories A, B, and C) with vertical diffusion supplying moisture to the cloud. When latent heat is included, convective cells develop, with moisture supplied to the cells by vertical advection (B′) and drier air moving between the cells from the west (A′ and C′). The spacing between tick marks along the borders is one kilometer in the vertical and 100 kilometers in the horizontal.

8.4.2 Frontal Rainbands

The generation of squall lines at a surface cold front has been studied using both hydrostatic and non-hydrostatic models. This work essentially extends that of Ross and Orlanski (296). With the hydrostatic model (horizontal resolution 14 km), it is shown that successive convective lines can be generated at a front. The time period between line generation is found to be on the order of 20-30 hours.

The periodicity in convection is explained as resulting from an inertial gravity oscillation in the low-level convergence. The natural period of this oscillation for a dry front is about 13 hours; the difference between this period and that of line generation is apparently caused by the coarse representation of convection in the hydrostatic model. The non-hydrostatic model of Lipps and Hemler (with a horizontal resolution of 2.7 km) is applied to the same case; a periodicity in convection at the front is again found, this time with a period very close to 13 hours. Observations of fronts in convective environments also show that there is an oscillation in convective activity with a similar time-scale.

PLANS FY87

Observational data, which have been obtained for several observing days during the "Oklahoma-Kansas PRE-STORM" experiment of June 1985, will be used to produce further simulations of the development of meso-convective systems.

The investigation of the generation of frontal rainbands will be completed.

8.5 MODEL DEVELOPMENT

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

ACTIVITIES FY86

The Limited-Area HIBU Model has been enhanced through increased vectorization, the saving of various equation terms during integration for more detailed analysis, and an increase in the number of model levels to 18. A dry, no-physics version of the model was compared to a model with the new horizontal advection scheme and new vertical coordinate. Streamlines and 3-D trajectories have been added to the analysis package. A more efficient spectral model (used to provide boundary conditions for the limited-area model) was implemented.

The MAC/BES (Meso-Alpha Scale/Beta Scale) model code has been converted to Fortran 77 and streamlined in order to facilitate planned improvements in the model's formulation. The model equations are being reformulated from anelastic equations to the full primitive equations with the inclusion of a terrain-following vertical coordinate.

A Barnes objective analysis routine has been adapted for use both to produce a verification analysis for model results and to provide gridded initial/boundary data for either the MAC/BES model or the LAHM. Routines have also been developed to display the pre-analysis data and to contour the objective analysis results.

The interactive analysis system for the MAC/BES model has been enhanced to provide a means to display fields and parcel trajectories in three dimensions (e.g., Fig. 8.2). Also, a capability has been developed to composite contour maps of model fields with satellite imagery (e.g., Fig. 8.1).

PLANS FY87

The new horizontal advection and vertical coordinate schemes of the LAHM will be tested in collaboration with the National Meteorological Center. Also, the model will be further vectorized. Alternatives to the moist convective adjustment scheme will be investigated. An R42L18 spectral model will be tested to obtain boundary conditions for the limited-area model. The LAHM analysis package will be further improved.

Conversion of the MAC/BES model to a primitive equation set with a terrain-following vertical coordinate will be completed. The associated analysis programs will also need to be modified to reflect changes in the model formulation.

Methods will continue to be developed to objectively analyze observational data. Also, an investigation will be made of possible techniques for assimilating both standard and nonstandard observational data into mesoscale models.

9. CONVECTION AND TURBULENCE

GOALS

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

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

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

9.1 MODEL IMPROVEMENTS

R. S. Hemler F. B. Lipps

ACTIVITIES FY86

In the past year, mixing due to subgrid-scale condensation effects has been incorporated into the moist convection model in a more consistent manner following an earlier approach (Lipps, 1977).[1] This has been made possible by solving a prognostic equation for the sum of water vapor and cloud water. The cloud water mixing ratio is then obtained diagnostically using the condition of saturation in cloud. This scheme produces subgrid-scale condensation just below cloud base with resultant latent heat release. For both shallow and deep convection, this low level heating produces a more uniform vertical velocity maximum with time and maintains the cloud over a longer lifetime. For shallow convection, rain reaching the ground is increased significantly.

The second major change in the numerical model has been to incorporate variable grid spacing in the vertical. The model now has more vertical levels in the boundary layer and lower cloud layers. The lowest grid level is at approximately 65 m so that the lower boundary conditions derived for the constant flux layer are reasonably valid. Comparison of simulations for this model and the corresponding model with constant grid spacing are now underway. An immediate result is that surface cooling in gust front outflows is significantly larger for the variable grid model with its higher boundary layer resolution.

PLANS FY87

The comparison of simulations with the variable grid and constant grid spacing models will be completed. This comparison is being made for an observed case of deep moist convection in the Central United States.

A joint project with the Experimental Prediction Group will be initiated with the long term goal of incorporating a form of moist turbulent closure in the general circulation model. The initial phase of this project requires the development of a prognostic subgrid-scale energy equation in the cloud model. Such an equation will be developed and tested in the coming year.

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[1] Lipps, F. B., 1977: A Study of Turbulence Parameterization in a Cloud Model. J. Atmos. Sci., 34, 1751-1772.

9.2 SIMULATION OF CONTINENTAL CONVECTION

R. S. Hemler B. B. Ross
F. B. Lipps

ACTIVITIES FY86

A cooperative effort is being carried out with the Mesoscale Dynamics Group to simulate the observed deep moist convection on April 11, 1979 in the Central United States. Their meso-β scale model has been used to supply the initial large-scale flow and side boundary conditions for the present model. Preliminary calculations have been carried out with the horizontal grid length of 5 km and the constant vertical grid spacing of approximately 0.5 km. The total rectangular domain size is 240 km in the east-west direction and 320 km in the north-south direction. These calculations show isolated cells of convection developing toward the northeastern side of the domain, but not the line of convection as obtained in (ex) and seen in the observations. Calculations carried out using both the mesoscale model and the present model indicate that our domain size is too small for an accurate simulation. An investigation is underway to determine the more precise requirements for an accurate simulation.

PLANS FY87

The investigation of the more precise requirements for an accurate simulation will be completed. It is anticipated that calculations will be carried out on a larger horizontal domain with higher horizontal grid resolution.

9.3 PASSIVE TRACER STUDY

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

ACTIVITIES FY86

The model improvements described in Section (9.1) have been applied to model simulations with different forms of passive tracer. In each case, the initial conditions have a boundary layer with constant mixing ratio of tracer up to 1.80 km and no tracer above that level. The vertical transport of tracer due to the deep moist convection is then examined. Three types of passive tracers are considered: i) Insoluble tracer, ii) Fully soluble tracer and (iii) Partially soluble tracer. Calculations for the partially soluble tracer have been carried out assuming that the gaseous tracer in the air is in thermodynamic equilibrium with the tracer in the condensed cloud water.

Calculations for a partially soluble tracer have been carried out using SO_3. At present, these calculations are being compared with calculations for the insoluble tracer and the fully soluble tracer. Preliminary results indicate that the vertical mixing of SO_3 due to deep convection has more in common with the vertical mixing of the insoluble tracer than with the fully soluble tracer.

<u>PLANS FY87</u>

The comparison between the vertical mixing of SO_3 and that of the insoluble and fully soluble tracers will be completed. A comparison of the results from the constant and variable vertical grid resolution models will be carried out.

Calculations will be carried out for other atmospheric tracers.

APPENDIX A

GFDL Staff Members

and

Affiliated Personnel

during

Fiscal Year 1986

Jerry D. Mahlman, Director	FTP
Betty M. Williams, Secretary	FTP
Douglas G. Hahn, Assistant Director	FTP
Joyce C. Jarvis, Actg. Admin. Assistant	PTP*
Joan M. Pege, Actg. Admin. Assistant	FTP

CENTRALIZED SUPPORT SERVICES

Administrative and Technical Support

Baker, Philip	Computer Programmer Analyst	FTP
Fraulino, Philip	Library Technician	PTP
Prettyman, William	Programmer	FTT
Urbani, Elaine	Travel Clerk	FTP
Uveges, Frank	Actg. Computer Specialist	FTP
Amend, Beatrice	Clerk Typist	PTT
Bennett, Lois	Management Support Clerk	FTP*
Byrne, James	Jr. Technician	FTP
Chandler, Annette	Secretary	WAE*
Conner, John	Photographer	FTP
Kennedy, Joyce	Editorial Assistant	FTP
Marshall, Wendy	Clerk Typist	FTT
Tunison, Philip	Supv. Scientific Illustrator	FTP
Miller, Almore III	Jr. Office Draftsman	WAE*
Raphael, Catherine	Office Draftsman	PTP
Varanyak, Jeffrey	Jr. Office Draftsman	FTP
Zadworney, Michael	Jr. Office Draftsman	FTP

*Affiliation Terminated Prior to September 30, 1986

Computer Systems Support

Welsh, James	Sr. Computer Sys. Analyst	FTP
Lewis, Lawrence	Computer Sys. Analyst	FTP*
Shaginaw, Richard	Computer Sys. Programmer	FTP
White, Robert	Computer Sys. Programmer	FTP
Yeager, William	Computer Sys. Programmer	FTP

Computer Operational Support

Shearn, William	Supv. Computer Operator	FTP
Davis, Manuel	Peripheral Equip. Opr.	FTT
Deuringer, James	Peripheral Equip. Opr.	FTT
Fox, James E.	Peripheral Equip. Opr.	FTT*
Henne, Ronald	Computer Operator	FTP
Hopps, Frank	Computer Operator	FTP
Kravitz, Michael	Peripheral Equip. Opr.	FTT*
Lenox, Kevin P.	Peripheral Equip. Opr.	FTT*
Mitman, Mark	Peripheral Equip. Opr.	FTP*
Smith, Robert	Computer Operator	FTP
Taylor, Thomas	Computer Operator	FTP
Hand, Joseph	Computer Operator	FTP
King, John	Computer Operator	FTP
Brandbergh, Gerald	Computer Operator	FTP
Cordwell, Clara	Computer Operator	FTP
Haught, Darrell	Peripheral Equip. Opr.	PTT
Weltmann, Richard	Peripheral Equip. Opr.	FTP*
Heinbuch, Ernest	Supv. Computer Operator	FTP
Conover, Leonard	Computer Operator	FTP
Miller, Almore	Computer Operator	FTP
Deuringer, Howard	Computer Operator	FTP*
Kreuger, Mark	Computer Operator	FTP*

*Affiliation Terminated Prior to September 30, 1986

CLIMATE DYNAMICS

Manabe, Syukuro	Sr. Research Scientist	FTP
Broccoli, Anthony	Research Associate	FTP
Brooks, Kevin	Junior Fellow	FTP
Delworth, Thomas	Research Associate	FTP
Fels, Stephen	Sr. Research Scientist	FTP
Davis, Kenneth	Student	PU*
Ma, Chung-Chun	Student	PU
Ramaswamy, V.	Program Scientist	PU
Saravanen, R.	Student	PU
Schwarzkopf, M. Daniel	Sr. Research Associate	FTP
Hayashi, Yoshikazu	Research Scientist	FTP
Golder, Donald	Sr. Research Associate	FTP
Held, Isaac	Sr. Research Scientist	FTP
Cook, Kerry	Research Associate	FTP
Feldstein, Steven	Program Scientist	PU
Huot, J.-P.	Student	PU
Kang, In-Sik	Program Scientist	PU*
Neelin, J. David	Student	PU
Phillipps, Peter	Research Associate	FTP
Ting, Mingfang	Student	PU
Spelman, Michael	Sr. Research Associate	FTP
Daniel, Donahue	Research Associate	FTP
Penik, Stephen	Junior Fellow	FTP
Stouffer, Ronald	Sr. Research Associate	FTP
Wetherald, Richard	Sr. Research Associate	FTP

MIDDLE ATMOSPHERE DYNAMICS AND CHEMISTRY

Mahlman, Jerry D.	Sr. Research Scientist	FTP
Graves, Denise S.	Student	PU*
Kida, Hideji	Program Scientist	PU
Levy, Hiram II	Research Scientist	FTP
Black, Charles	Junior Fellow	FTP
Moxim, Walter J.	Sr. Research Associate	FTP
Tao, Xin	Student	PU
Umscheid, Ludwig J.	Sr. Research Associate	FTP
Kranz, Christopher	Junior Fellow	FTP*

*Affiliation Terminated Prior to September 30, 1986

EXPERIMENTAL PREDICTION

Miyakoda, Kikuro	Sr. Research Scientist	FTP
Chao, Yi	Student	PU
Derber, John	Program Scientist	PU
Gordon, Charles	Research Scientist	FTP
Gudgel, Richard G.	Research Associate	FTT
Navarra, Antonio	Student	PU*
Pierrehumbert, Raymond	Research Scientist	PTP
Anderson, J.	Student	PU
Bacmeister, Julio T.	Student	PU
Carissimo, B.	Student	PU
Knutson, Thomas	Research Associate	FTP
Lin, Shian-Jiann	Student	PU
Wyman, Bruce	Research Associate	FTP
Ploshay, Jeffrey	Research Associate	FTP
Rosati, Anthony	Sr. Research Associate	FTP
Sirutis, Joseph	Sr. Research Associate	FTP
Fork, David	Junior Fellow	FTP*
Stern, William	Sr. Research Associate	FTP
Fine, Benjamin	Junior Fellow	FTP*

OCEANIC CIRCULATION

Bryan, Kirk	Sr. Research Scientist	FTP
Boning, Claus	Program Scientist	PU
Cox, Michael	Sr. Research Associate	FTP
Dixon, Keith	Research Associate	FTP
Huang, Rui-Xin	Program Scientist	PU*
Reed, Kimberly	Junior Fellow	FTP*
Philander, Samuel G.H.	Sr. Research Scientist	FTP
Gardiner-Garden, Robert S.	Student	PU
Chang, Ping	Student	PU
Hurlin, William	Research Associate	FTP
Pacanowski, Ronald	Sr. Research Associate	FTP

PLANETARY CIRCULATIONS

Williams, Gareth	Sr. Research Scientist	FTP
Wilson, Robert	Research Associate	FTP

*Affiliation Terminated Prior to September 30, 1986

OBSERVATIONAL STUDIES

Oort, Abraham	Sr. Research Scientist	FTP
Ascher, Stephen	Student	PU*
Forman, Mark	Junior Fellow	FTP*
Lau, Ngar-Cheung	Research Scientist	FTP
Lau, A.K.	Student	PU
Nath, Mary J.	Research Assistant	FTP
Levitus, Sydney	Sr. Research Associate	FTP
Jackson, Martha	Sr. Technician	FTP
Pan, Yi Hong	US-TOGA Visiting Scientist	
Rosenstein, Melvin	Sr. Technician	FTP
Savijarvi, Hannu	Program Scientist	PU
Sotomayer, Anibal	Junior Fellow	FTP

HURRICANE DYNAMICS

Kurihara, Yoshio	Sr. Research Scientist	FTP
Bender, Morris A.	Sr. Research Associate	FTP
Kerr, Christopher L.	Research Associate	FTT
Tuleya, Robert E.	Sr. Research Associate	FTP
DiPaola, Michael	Junior Fellow	FTP

MESOSCALE DYNAMICS

Orlanski, Isidoro	Sr. Research Scientist	FTP
Crook, Norman	Program Scientist	PU
Matano, R.	Student	PU
Nakamura, Noburo	Student	PU
Katzfey, Jack	Research Associate	FTP
Perkins, Thomas	Physical Science Aid	FTT*
Polinsky, Larry	Research Associate	FTP
Ross, Bruce	Sr. Research Associate	FTP
Baum, John	Junior Fellow	FTP
Wang, Bin	Program Scientist	PU

CONVECTION AND TURBULENCE

Lipps, Frank	Research Scientist	FTP
Hemler, Richard	Research Associate	FTP
Mellor, George	Professor	PU
Galperin, Boris	Research Staff	PU
Kantha, Lakshmi	Program Scientist	PU
Rajkovic, Borivoje	Student	PU*
Steele, Michael	Student	PU
Xue, H.-J.	Student	PU

*Affiliation Terminated Prior to September 30, 1986

GFD PROGRAM

Sarmiento, Jorge	Associate Professor	PU
Amend, Beatrice	Clerk/Typist	PU
Broccoli, Carol	Technical Specialist	PU
Bryan, Frank	Student	PU*
Callan, Johann	Secretary	PU
Hellerman, Solomon	Computer Programmer PT	PU*
Kawase, Mitsuhiro	Student	PU*
Key, Robert	Research Staff	PU
Levy, Adam	Laboratory Aid	PU*
Najjar, Raymond	Student	PU
Olsen, Esther	Administrative Assistant	PU
Papademetriou, Demetra	Student	PU
Park, Jeffrey	Program Scientist	PU*
Simon, Clegg	Research Staff	PU
Slater, Richard	Computer Programmer	PU
Thiele, Gerhard, P.J.	Program Scientist	PU
Toggweiler, John	Research Staff	PU

CONTROL DATA CORPORATION

B. Kazawic, Sales Representative

Stringer, John	Analyst in Charge	CDC
Siebers, Bernard	Senior Analyst	CDC*
Hess-Hughes, Julie	Analyst	CDC
Reiss, Israel	Systems Analyst	CDC
Helster, Paul	Senior Eng. in Chg.	CDC
Armbrister, Richard	Senior Customer Eng.	CDC
Csapo, Michael	Customer Engineer	CDC
Dorado, Manual	Senior Customer Eng.	CDC
Johnson, Eric	Senior Customer Eng.	CDC*
Smith, Alain	Senior Customer Eng.	CDC
Thompson, Robert	Senior Customer Eng.	CDC
Valin, Chris	Customer Engineer	CDC
Weiss, Edward	Senior Customer Eng.	CDC

*Affiliation Terminated Prior to September 30, 1986

PERSONNEL SUMMARY

September 30, 1986

FTP - Full Time Permanent (GFDL)	77
PTP - Part Time Permanent (GFDL)	3
FTT - Full Time Temporary	6
PTT - Part Time Tempory	2
Junior Fellows (GFDL)	6
Program Scientists (Princeton University)	10
US-TOGA Visiting Scientist	1
Students (Princeton University)	20
Professors (Princeton University)	2
Research Staff (Princeton University)	4
Support Staff (Princeton University)	4
Control Data Corporation Computer System Program Support Staff	11
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APPENDIX B

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1981-1986

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Princeton University - Post Office Box 308
Princeton, New Jersey 08542

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*In collaboration with other organizations

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(go) Cox, Michael D., A Numerical Model of the Ventilated Thermocline: Time Dependence, (Submitted to the Journal of Physical Oceanography, August 1986).

(gp) Mahlman, J. D., and S. B. Fels, Antarctic Ozone Decreases: A Dynamical Cause?" (Submitted to Geophysical Research Letters, August 1986).

(gq) Williams, Gareth P., Global Atmospheric Circulations, (Submitted to Climate Dynamics, August 1986).

(gr) Bryan, Kirk, Man's Great Geophysical Experiment: Can We Model the Outcome? (Submitted to Oceanus, September 1986).

(gs) Huang, Rui-Xin and Kirk Bryan, A Multi-Layer Model of the Thermohaline and Wind Driven Ocean Circulation: Model Development and Initial Test, (Submitted to Journal of Physical Oceanography, September 1986).

(gt) Wang, Bin and Isidoro Orlanski, Study of a Heavy Rainfall Vortex Formed over the Eastern Flank of the Tibetan Plateau, (Submitted to Monthly Weather Review, September 1986).

(gu) Savijarvi, H. I., Atmospheric Energy Budgets from FGGE and Station Data, (Submitted to Journal of the Atmospheric Sciences, September 1986).

(gv) Karoly, David J., and Abraham H. Oort, A Comparison of Southern Hemisphere Circulation Statistics Based on GFDL and Australian Analyses, (Submitted to Monthly Weather Review, September 1986).

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1981-1986

CROSS-REFERENCE BY AUTHOR

APPENDIX C

Computational Support

APPENDIX C

Computational Support

The computational support at GFDL comprises three Control Data CYBER computers:

CY1, a 170/720 with 256K words of memory;
CY2, a 205 supercomputer, with 2 million words of memory; and
CY4, another 205, with 4 million words of memory.

The outstanding event of FY86 was the purchase by the government of the entire CYBER computer system in December, 1985. The purchase retained guarantees of system availability made by Control Data in the original GFDL contract.

No augmentation or alteration of the system hardware was accomplished during FY86. New operating software, VSOS 2.1.6, was installed on the CYBER 205's. New operating software for the CYBER 170, NOS 2.4, is expected to be installed by the end of FY86.

Plans to increase the number of terminals attached to the CYBER system during FY86 were suspended due to budget cuts required by the Gramm-Rudman-Hollings legislation. This goal will be revisited during FY87.

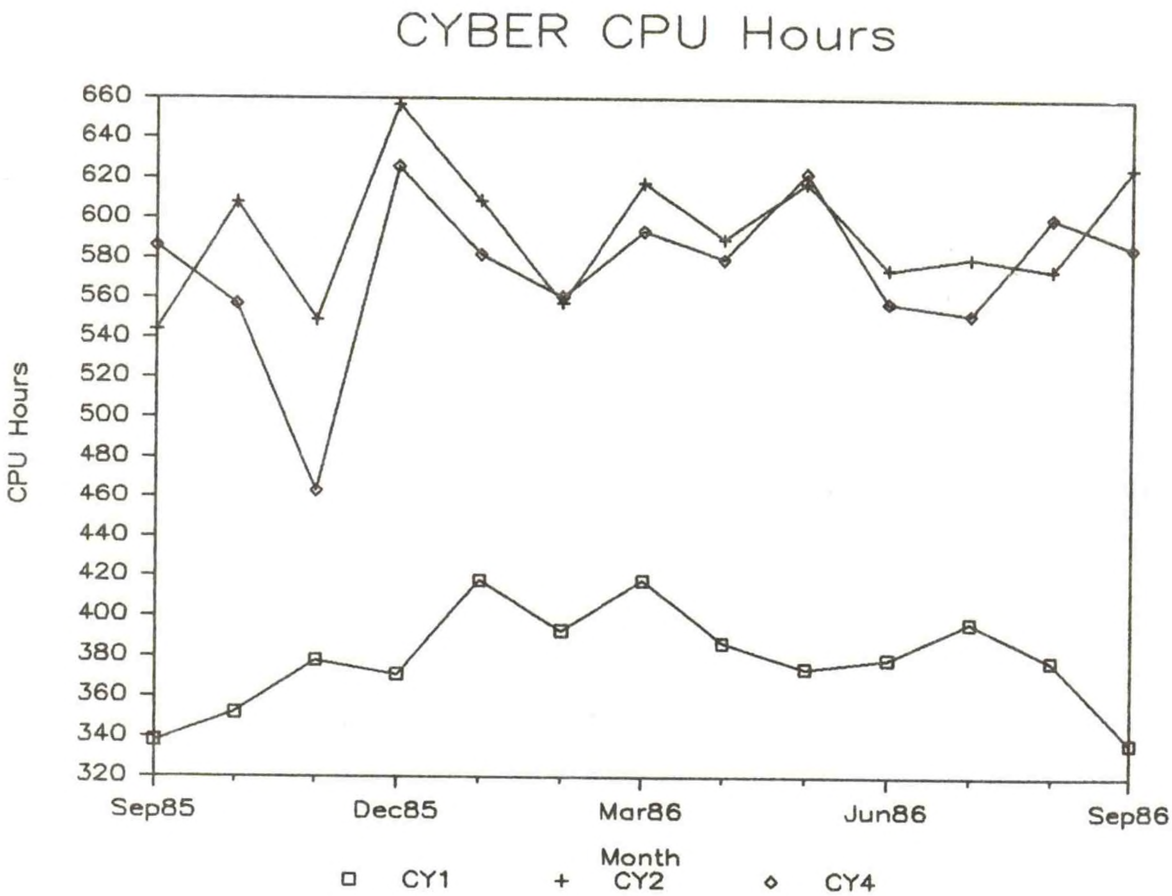
During FY87, we will be completing specifications for GFDL's next computer system, to be delivered in FY89 or FY90.

The following table and figure show the number of CPU hours achieved on each machine during the period of this report.

Table C-1. Achieved CPU Hours for GFDL Machines

Month	CY1	CY2	CY4	CY2+CY4
Sep 85	338*	544*	586*	1130*
Oct 85	352	608	557	1165
Nov 85	378	549	463	1012
Dec 85	371	657	626	1283
Jan 86	418	609	582	1191
Feb 86	393	558	561	1119
Mar 86	418	618	594	1212
Apr 86	387	590	580	1170
May 86	374	618	623	1241
Jun 86	379	575	558	1133
Jul 86	397	581	552	1133
Aug 86	378	575	601	1176
Sep 86	337	626	586	1212

* Not reported in the FY85 Annual Report


CYBER CPU Hours
CPU Hours
660
640
620
600
580
560
540
520
500
480
460
440
420
400
380
360
340
320
Sep85
Dec85
Mar86
Jun86
Sep86
Month
CY1
CY2
CY4

APPENDIX D

Seminars Given at GFDL

During Fiscal Year 1986

8 October 1985	"Neutral Surfaces Versus Potential Density Surfaces in the Ocean" by Dr. Trevor McDougall, CSIRO, Division of Meteorology, Hobart, Australia
8 October 1985	"Numerical Modeling of a Line of Towering Cumulus on Day 226 of GATE" by Dr. Frank Lipps and Mr. Richard Hemler, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
10 October 1985	"Vacillations of an Ocean-Atmosphere Model" by Dr. Max Suarez, NASA, Goddard Space Flight Center, Greenbelt, MD
11 October 1985	"Convection in Shear Flow - A Numerical Study" by Dr. Andre Domaradski, Flow Research, Inc., Seattle, WA
17 October 1985	"Three-Dimensional Modeling of the Carbon Cycle" by Dr. Inez Fung, Atmospheric & Planetary Sciences Div., NASA Goddard Inst. for Space Studies, New York
24 October 1985	"Experiments in Data Assimilation using the Adjoint Model Technique" by Drs. Olivier Talagrand and P. Courtier, Laboratoire de Meteorologie Dynamique, Paris, France
24 October 1985	"Radiative Perturbations Due to Carbonaceous Aerosols" by Dr. V. Ramaswamy, Geophysical Fluid Dynamics Program, Princeton University, Princeton, NJ
29 October 1985	"Gravity Waves" by Dr. Susan Friedlander, Princeton University, Princeton, NJ
4 November 1985	"Numerical Results of Quasi-Lagrangian Hurricane Model" by Dr. Mukut Mather, National Meteorological Center Washington, DC
5 November 1985	"Thermally Forced Stationary Waves" by Dr. Isaac Held, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
5 November 1985	"Development of a 2-D Zonally Averaged Statistical-Dynamical Model: The Parameterization of Moist Convection and its Role in the General Circulation" by Prof. Peter Stone, Department of Meteorology, Massachusetts Institute of Technology, Cambridge, MA
6 November 1985	"Data Constraints Applied to Models of the Ocean General Circulation. Part I: The Steady Case" by Dr. Paola Rizzoli, Dept. of Earth, Atmospheric & Planetary Sciences, M.I.T., Cambridge, MA.

8 November 1985	"Coherent Structures in a Baroclinic Atmosphere as Models for Blocking Events" by Dr. Paola Rizzoli, Dept. of Earth, Atmospheric & Planetary Sciences, M.I.T., Cambridge, MA
12 November 1985	"Modeling and Barotropic Eddy-Resolving Oceans" by Dr. C. Boning, Geophysical Fluid Dynamics Program, Princeton University, Princeton, NJ
14 November 1985	"Interannual Variability of Coastal and Slope Water Mass Along the Western North Atlantic" by Dr. Vincent Lyne, Physical Oceanography, Woods Hole Oceanographic Inst. Woods Hole, MA
15 November 1985	"The 40-50 Day Oscillation in the Tropics" by Dr. Roland Madden, NCAR, Dept. of Atmospheric Analysis, Boulder, CO
26 November 1985	"Principal Modes of Atmospheric Variability in Model Atmospheres With and Without Anomalous Sea Surface Temperature Forcing in the Tropical Pacific" by Dr. In-Sik Kang, Geophysical Fluid Dynamics Program, Princeton University, Princeton, NJ
3 December 1985	"Verification of Inverse Methods for Determining Ocean Circulation" by Dr. Grant Bigg, Hooke Institute, Oxford University, Oxford, England
3 December 1985	"Acid Rain Research at GFDL" by Dr. Hiram Levy II, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
10 December 1985	"Observed Air-Sea Interactions (ENSO) and Climatic Change during the Last Ten Decades" by Y.-H. Pan and A. H. Oort, Geophysical Fluid Dynamics Program, Princeton University, Princeton, NJ
12 December 1985	"Climatic Fluctuations over the Northern Hemisphere since the Mid-19th Century" by Prof. Raymond Bradley, University of Massachusetts, Amherst, MA
16 December 1985	"TOGA Modelling at Oxford" by Christopher Gordon, Oxford University, England
17 December 1985	"A Comparison of the Annual Cycle of Two Sea Surface Temperature Climatologies" by Sydney Levitus, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
6 January 1986	"Unstable Equatorial Modes in Coupled Ocean-Atmosphere Models" by Anthony Hirst, Department of Meteorology, University of Wisconsin, Madison, WI

7 January 1986	"Composite View of 30-60 Day Atmospheric Oscillations" by Tom Knutson, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
14 January 1986	"Linear and Nonlinear Diagnostic Models of Stationary Eddies in the Upper Troposphere and their Anomalies" by Dr. In-Sik Kang, Geophysical Fluid Dynamics Program, Princeton, NJ
21 January 1986	"A Numerical Study of the Tides in the Bight of Abaco using a Frequency Domain Finite Element Model" by Joannes Westerink, Princeton, NJ
23 January 1986	"Experimental Forecasts of El Nino" by Dr. Mark Cane, Lamont-Doherty Geological Observatory, Palisades, NY
27 January 1986	"Energetics Calculations at ECMWF" by Prof. K. Arpe, ECMWF, Shinfield Park, Reading, Berkshire, England
28 January 1986	"Numerical Simulation of Gravity Waves and Mesospheric - Lower Thermospheric General Circulation" by Dr. H. Kida, Geophysical Fluid Dynamics Program, Princeton, NJ
4 February 1986	"African Drought" by Dr. S. G. H. Philander, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
12 February 1986	"The Antarctic Ozone Catastrophe?" by Dr. Susan Solomon, Aeronomy Laboratory, ERL/NOAA, Boulder, CO
13 February 1986	"Initial Results from Earth Radiation Budget Experiment (ERBE)" by Dr. Bruce Barkstom, Langley Research Center/NASA, Mail Stop 420, Hampton, VA
18 February 1986	"Transient Tracer Fields in the Canary-Cape-Verde Basin" by Dr. G. Thiele, Geophysical Fluid Dynamics Program, Princeton, NJ
20 February 1986	"Helium Isotopic and Noble Gas Dynamics in the Upper Ocean: Implications for Gas Exchange and Biological Productivity" by Dr. William Jenkins, Woods Hole Oceanographic Inst., Woods Hole, MA
25 February 1986	"Some Observational and Mesoscale Modelling Studies Made in ECMWF and Finland" by Dr. Hannu Savijarvi, Geophysical Fluid Dynamics Program, Princeton, NJ
27 February 1986	"Ventilated Mid-Depth Circulation Model for the Eastern North Atlantic" by Dr. Richard Schopp, Woods Hole Oceanographic Inst. Woods Hole, MA

4 March 1986	"The Tropical 40-50 and 25-30 Day Oscillations Appearing In General Circulation Models Mid FGGE Data" by Dr. Y. Hayashi and Mr. D. Golder, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
6 March 1986	"Climate Diagnostics from Outgoing Longwave Radiation" by Dr. William K. Lau, Climate and Radiation Branch, NASA Goddard Space Flight Center, Greenbelt, MD 20771
10 March 1986	"Atmospheric Normal Modes: The Untold Story" by Dr. Kevin Hamilton, McGill University, Montreal, Canada
18 March 1986	"Simulation of '82 and 83' El Nino with an Oceanic GCM" by A. Rosati, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
25 March 1986	"A Thinking Toward a New Analysis of Motions and Transports in the Middle Atmosphere" by H. Kida, Geophysical Fluid Dynamics Program, Princeton University, NJ
25 March 1986	"Nonlinear Stability of Stationary and Travelling Baroclinic Rossby Waves" by Dr. Steven B. Feldstein, Dept. of Meteorology, The Pennsylvania State University, University Park, PA
3 April 1986	"Modelling Cloud-Capped Boundary Layers" by Dr. David Randall, Global Modelling & Simulation Branch, NASA Goddard Space Flight Center, Greenbelt, MD
8 April 1986	"Lagrangian Eddy Statistics in the North Atlantic" by C. Boning, Geophysical Fluid Dynamics Program, Princeton University, Princeton, NJ
10 April 1986	"Recent Results of Numerical Experiments and Observational Analyses of Mesoscale Convective Systems" by Prof. William Cotton, Dept. of Atmospheric Sciences, Colorado State University, Fort Collins, CO
15 April 1986	"Cirrus Cloud Microphysics and the Influence on Upper Tropospheric Climate" by Dr. V. Ramaswamy, Geophysical Fluid Dynamics Program, Princeton University, Princeton, NJ
16 April 1986	"Spatial and Temporal Characteristics of Global Cloud Cover as Observed from the NIMBUS-7 Satellite" by Dr. Larry Stowe, Atmospheric Science Branch, NESDIS/NOAA, Washington, DC
17 April 1986	"Recent Research at Kiel Institute fur Meereskunde" by Dr. Rolf Kase, Institute fur Meereskunde, Kiel, Germany

22 April 1986	"Strange Attractors" by Dr. R. T. Pierrehumbert, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
24 April 1986	"The Three-Dimensional Structure of Synoptic-Scale Disturbances over the Tropical Atlantic" by Dr. Lloyd J. Shapiro, Hurricane Research Div., ERL/NOAA, Miami, Fl
2 May 1986	"Some Ideas on Internal Hydraulics and Severe Downslope Winds" by Prof. Ronald B. Smith, Dept. of Geology and Geophysics, Kline Geology Laboratory, New Haven, CONN
6 May 1986	"Potential Vorticity and Ocean Circulation" by Dr. Kirk Bryan, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
6 May 1986	"Physical, Optical, and Biochemical Variability in the Upper Ocean" by Dr. T. Dickey, Princeton University, Princeton, NJ
7 May 1986	"Dynamics of Ultra-High Reynolds Number 2-D Flows" by Dr. David Dritschel, Dept. of Applied Math. & Theoretical Physics, Cambridge University, Cambridge, England
8 May 1986	"Cloud Prediction and Cloud Radiation Interaction in General Circulation Models" by Dr. Julia Slingo, National Center for Atmospheric Research, Boulder, CO
9 May 1986	"Stratocumulus and Climate" by Dr. Anthony Slingo, National Center for Atmospheric Research, Boulder, CO
12 May 1986	"Planetary Waves in Preconditioned Flows" by Dr. Walter Robinson, Department of Atmospheric Sciences, University of Washington, Settle, WA
13 May 1986	"Milankovitch Rhythms and Mid-Cretaceous Climate Dynamics" by Dr. Tim Herbert, Geophysical Fluid Dynamics Program, Princeton University, Princeton, NJ
13 May 1986	"Return of the Strange Attractors" by Dr. R. T. Pierrehumbert, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
19 May 1986	"A Study of the Radiative Balance of the Stratosphere" Dr. Jeffrey T. Kiehl, Cloud Climate Interactions Group, National Center for Atmospheric Research, Boulder, CO
20 May 1986	"Parameter Sensitivity Study of Ecosystem Model" by Dr. J. R. Toggweiler, Geophysical Fluid Dynamics Program, Princeton University, Princeton, NJ

27 May 1986	"3-D Transport by Quasi-Geostrophic Transient Eddies" by Dr. Alan Plumb, CSIRO, Division of Atmospheric Physics Aspendale, Victoria, Australia
29 May 1986	"The Eulerian Equations on a Sphere: Implications for Numerical Weather Prediction" by Dr. Roger Daley, Canadian Climate Centre/CCRN, Downsview, Ontario, Canada
4 June 1986	"Spectral Methods with a Change of Coordinates" by Dr. John Boyd, Department of Atmospheric & Oceanic Science, University of Michigan, Ann Arbor, MI
6 June 1986	"Development and Application of a Nested Grid, Second Moment Turbulence Closure Model" by Dr. Tetsuji Yamada, Los Alamos National Laboratory, Los Alamos, NM
10 June 1986	"Response of a Coupled Ocean Atmosphere to an Abrupt Increase of Atmospheric Carbon Dioxide" by Dr. S. Manabe, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
10 June 1986	"The Extratropical Response to El Nino" by Dr. Isaac Held, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
17 June 1986	"Radiocarbon in a 3-D Global Ocean Model" by K. Dixon and R. Toggweiler, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
17 June 1986	"Atmospheric Heat Budget of Polar Regions" by Dr. N. Nakamura, Geophysical Fluid Dynamics Program, Princeton, NJ
24 June 1986	"The 40-50 Day Oscillation: A Simple Theory for the Time Scale" by Dr. Duane Stevens, National Meteorological Center, Colorado State University, CO
24 June 1986	"A comparison of IGY and TTO Data in the North Atlantic" by S. Hellerman, Geophysical Fluid Dynamics Program, Princeton University, Princeton, NJ
1 July 1986	"Development of a North Atlantic Model with Isopycnal Mixing" by R. Slater, Geophysical Fluid Dynamics Program, Princeton University, Princeton, NJ
8 July 1986	"An Isopycnal Mixing Model" by M. Cox, Geophysical Fluid Dynamics Program, Princeton University, Princeton, NJ
8 July 1986	"The Extratropical Response to El-Nino" (cont.) by Dr. Isaac Held, Geophysical Fluid Dynamics Laboratory, Princeton, NJ

15 July 1986	"Renewal Rates of East Atlantic Deep Water Estimated by Inversion of Carbon 14 Data" by R. Schlitzer, Geophysical Fluid Dynamics Program, Princeton University, Princeton, NJ
22 July 1986	"Oceanic Data Assimilation System" by J. Derber, Geophysical Fluid Dynamics Program, Princeton University, Princeton, NJ
29 July 1986	"Simulation of the Ocean Circulation with a Layer Model" by R. X. Huang, Geophysical Fluid Dynamics Program, Princeton University, Princeton, NJ
31 July 1986	"EEO Within ERL/NOAA" by Anthony Tafoya, NOAA/ERL, Boulder, CO
12 August 1986	"On the Use of Multiple Tracers for Inferring Ocean Circulation and Mixing" by G. Thiele, Princeton University, Princeton, NJ
12 August 1986	"The Semi-Annual Oscillation" by Kevin Hamilton, McGill University, Montreal, Canada
22 August 1986	"Artificial Intelligence Activities in ERL, An Overview" by William Moninger, ERL/NOAA, Boulder, CO
26 August 1986	"Computations of Available Potential Energy in the World Ocean" by A. Oort, S. Ascher, and S. Levitus, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
27 August 1986	"Dynamic Normal-Mode Initialization" by Dr. Masato Sugi, Florida State University, Tallahassee, FL
2 September 1986	"The Inertial Recirculation of a Gyre" by Dr. Richard Greatbach, London, England
9 September 1986	"Apologia Pro Vita Mia in Princeton" by Dr. R. X. Huang, Geophysical Fluid Dynamics Program, Princeton University, Princeton, NJ
12 September 1986	"Blocking, Flow Reversal and Strong Jets Induced by a Rotating Stratified Fluid" by Prof. Lee-Or Merkine, Dept. of Mathematics, Technion - Israel Inst. Technology, Haifa, Israel
19 September 1986	"The Case for SGS-Compensation in Numerical Cloud Models" by F. B. Lipps and R. S. Hemler, Geophysical Fluid Dynamics Program, Princeton University, Princeton, NJ

22 September 1986	"Networking For Scientists" by I. Fuchs, Princeton University, Princeton, NJ
23 September 1986	"Multiple Equilibria in a Coupled Atmosphere-Ocean GCM" by R. J. Stouffer, Geophysical Fluid Dynamics Laboratory, Princeton, NJ
30 September 1986	"Improvement of High Resolution Model Climate Simulation Using Gravity Wave Drag" by A. J. Broccoli, Geophysical Fluid Dynamics Laboratory, Princeton, NJ

APPENDIX E

Talks, Seminars, and Papers Presented Outside GFDL

During Fiscal Year 1986

Seminars not included in FY 85 Report

July 2-August 8, 1985	Dr. Isidoro Orlanski "Recent Advancements in Dynamical Meteorology" (12 Lectures), Universidad De Buenos Aires, Dept. of Meteorology, Buenos Aires, Argentina

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11 September 1985	Dr. Isidoro Orlanski "The Use of Super Computers in Numerical Weather Prediction" Universidad De Buenos Aires, Center of Science and Technology, Buenos Aires, Argentina
2 October 1985	Dr. Kikuro Miyakoda "Experimental Extended Range Forecasting at GFDL" Workshop on Dynamical Extended Range Forecasting, National Meteorological Center, Washington, DC
11 October 1985	Dr. J. R. Toggweiler "Oceanic Dissolved Organic Carbon and Implications for Glacial to Interglacial Changes in Atmospheric CO_2" Lamont-Doherty Geological Institute, NY
18 October 1985	Dr. Raymond T. Pierrehumbert "High Resolution Calculations of the Stuart Vortex Instability" Schlumberger Research Center, Ridgefield, Connecticut
23 October 1985	Dr. J. R. Toggweiler "Chemical Cycling in Ocean General Circulation Models" Paleooceanography Panel of SCOR/CCCO in Ville, Franche, France
28 October 1985	Dr. Raymond T. Pierrehumbert 1. "Nonlinear Rotating Flow over Mountains 2. "Lee Cyclogenesis on March 4/5" 3. "Frontal Passage" ALPEX Conference, Venice, Italy
28 October 1985	Mr. Anthony J. Broccoli "Characteristics of Seasonal Snow Cover as Simulated by GFDL Climate Models" SNOWWATCH 1985: Workshop on CO_2/ Snow Interaction, College Park, Maryland
29 October 1985	Dr. Frank B. Lipps "Numerical Modelling of a Midlatitude Squall Line" Fourteenth Conference on Severe Local Storms of the American Meteorological Society, Indianapolis, IN

29 October 1985	Dr. Kirk Bryan "Modeling Seasonal Variations in the North Atlantic" World Ocean Circulation Experiment/Numerical Experimentation Group Meeting, London, England
29 October 1985	Dr. J. R. Toggweiler "Chemical Cycling in Ocean General Circulation Models" Global Ocean Flux Study Pacific Planning Meeting, San Francisco, CA
18 November 1985	Dr. Isidoro Orlanski "Localized Baroclinicity: A Source of Mesocyclones" UCLA, Los Angeles, CA
20 November 1985	Dr. Jorge L. Sarmiento "Oceanic Control of Atmospheric pCO_2; an Important Climate Feedback Mechanism?" Yale University, New Haven, CONN
25 November 1985	Dr. Yoshio Kurihara "Numerical Models of Cyclone Formation and Structure" International Workshop on Tropical Cyclones, Bankok, Thailand
26 November 1985	Dr. Hiram Levy II "Acid Rain vs. Acid Deposition: A General Circulation/Transport Model Study" University of Rhode Island, Kingston, Rhode Island
2 December 1985	Dr. Charles T. Gordon "Parameterization of Land Surface Processes and PBL Parameterizations in the GFDL GCM's" International Satellite Land Surface Climatology Project Conference on Parameterization of Land Surface Characteristics, Frascati, Italy
3 December 1985	Dr. Jorge L. Sarmiento "Ra-226 and Ra-228 as Tracers of Ocean Circulation" University of Washington, Seattle, WA
4 December 1985	Dr. Jorge L. Sarmiento "Isopycnal Analysis of Atlantic TTO Nutrient and Hydrographic Observations" University of Washington, Seattle, WA
6 December 1985	Dr. Raymond T. Pierrehumbert "Spatial Baroclinic Instability" University of Chicago, Chicago, Ill

9 December 1985	Dr. Ngar-Cheung Lau "Diagnosis of GCM Simulations of ENSO Phenomena at GFDL" Workshop on the Modeling of Ocean-Atmosphere Interaction, National Center for Atmospheric Research, Boulder, CO
9 December 1985	Mr. Joseph Sirutis "Simulation of the 82/83 El Nino Event: Atmospheric Response to Observed SST Tracing" SST Model Intercomparison Workshop, National Center for Atmospheric Research, Boulder, CO
9 December 1985	Dr. Kikuro Miyakoda "Status of Experimental Monthly Predictions and Proposals for Specific Initiatives" "Anomaly GCM's" SST Model Intercomparison Workshop, National Center for Atmospheric Research, Boulder, CO
9 December 1985	Dr. Hiram Levy II "Acid Rain vs. Acid Deposition: Long-Range Transport vs. Local Emission" Fall American Geophysical Union Meeting, San Francisco, CA
9 December 1985	Mr. Anthony J. Rosati "Assimilation of 1982-1983 El Nino using an Ocean GCM: SST Model Intercomparison Workshop, National Center for Atmospheric Research, Boulder, CO
10 December 1985	Mr. Julio Bacmeister "Transient Flow over Mountains" AGU Meeting, San Francisco, CA
10 December 1985	Dr. Syukuro Manabe "Climate Warming due to Greenhouse Gases" Testimony presented to U.S. Senate Subcommittee on Toxic Substances and Environmental Oversights, U.S. Capital Building, Washington, DC
10 December 1985	Dr. Yoshio Kurihara "Orographic Effects on the Tropical Cyclone Behavior" Meteorological Research Institute, Tsukuba, Japan
10 December 1985	Dr. In-Sik Kang "Principal Modes of Atmospheric Variability in Model Atmospheres with and without Anomalous SST Forcing in the Tropical Pacific" NCAR Workshop, Boulder, CO
10 December 1985	Dr. N. Andrew Crook "Energy Trapping in Atmospheric Undular Bores" AGU Meeting, San Francisco, CA

10 December 1985	Mr. Michael Steele "Sea-Ice Boundary Layer Dynamics and Thermodynamics - The Freezing Process" AGU Meeting, San Francisco, CA
11 December 1985	Dr. Jeffrey Park "The Asymptotic Behavior of Coupled-Mode Seismic Spectra on an Aspherical Earth" AGU Meeting, San Francisco, CA
11 December 1985	Dr. Yoshio Kurihara "Response of Tropical Cyclones to Orography" Tokyo University, Tokyo, Japan
12 December 1985	Dr. Yoshio Kurihara "Effects of Mountainous Islands on Tropical Cyclones" Japan Meteorological Agency, Tokyo, Japan
16 December 1985	Mr. Julio Bacmeister "Transient Flow over Mountains" Naval Postgraduate School, Monterey, CA
16 December 1985	Mr. Michael Steele "A One Dimensional Numerical Model of the Oceanic Boundary Layer Under Sea-Ice, the Melting and Freezing Processes" Naval Postgraduate School, Monterey, CA
18 December 1985	Dr. N. Andrew Crook "Generation and Long Term Behavior of Low Level Internal Gravity Waves" Naval Postgraduate School, Monterey, CA
7 January 1986	Mr. Ronald Pacanowski "Mass and Heat Budget of the Tropical Atlantic" SEQUAL Meeting, Palisades, NY
7 January 1986	Dr. George Philander "Mass and Heat Budget of the Tropical Atlantic" SEQUAL Meeting, Palisades , NY
7 January 1986	Dr. Jorge L. Sarmiento "Ocean Circulation and Deep Ocean Oxygen" Gordon Conference on Chemical Oceanography, Oxnard, CA
8 January 1986	Dr. Hiram Levy II "Atmospheric Chemistry" Public Television Station WHRO, Norfolk, VA
13 January 1986	Dr. Kerry H. Cook 1. "Report on Volunteers Program" 2. "Prospectus for Workshop on Scientists as Parents" American Meteorological Society Board on Women and Minorities, Miami, FL

14 January 1986	Dr. J. R. Toggweiler "Mathematical Formulation for a Hypothetical Deep-Dwelling Animal Responsible for Intercepting and Repackaging Sinking Particulate Material" and "Biological and Chemical Cycle Modeling in the Global Ocean Flux Study" AGU/ASLO Meeting, New Orleans, LA
14 January 1986	Mr. Robert E. Tuleya "The Simulation of the Genesis of Tropical Storms using the FGGE IIIB Data Set" American Meteorological Society Conference on the Scientific Results of the First GARP Global Experiment (FGGE) Miami, FL
14 January 1986	Mr. Jeffrey J. Ploshay "Assessment of Results from Different Data Assimilation Schemes" American Meteorological Society Conference on the Scientific Results of the First GARP Global Experiment (FGGE) Miami, FL
21 January 1986	Mr. Sydney Levitus "Fourier Analyses of Sea Surface Temperature Climatologies" "Interannual Variability of Marine Surface Fields" COADS Workshop, Boulder, CO
23 January 1986	Dr. Claus Boning "Lagrangian Properties of the Eddy Field in the North Atlantic" Ocean Circulation Workshop, Seattle, WA
23 January 1986	Dr. Rui-Xin Huang "Numerical Simulation of Subtropical/Subpolar Gyres with Outcropping" Ocean Circulation Workshop, Seattle, WA
24 January 1986	Mr. Sydney Levitus "Fourier Analyses of Sea Surface Temperature Climatologies" NCAR, Boulder, CO
29 January 1986	Dr. J. R. Toggweiler "Testing Concepts about Marine Productivity and Chemical Cycling with a Model" University of Washington, Seattle, WA
29 January 1986	Dr. J. D. Mahlman 1. "Forecasting Research at GFDL" 2. "Problems in Mesoscale Initialization" 3. "Ocean Modeling Research at GFDL" OAR Retreat, Gaithersburg, MD

30 January 1986	Dr. J. R. Toggweiler "Bacterial Populations and the Degradation of Organic Matter; A Theoretical Discussion on the Dark Side of the Biological Production Loop in the Ocean" University of Washington, Seattle, WA
3 February 1986	Prof. G. Mellor "Numerical Model Results of the Hudson-Raritan Estuary" Seminar - Harvard University, Cambridge, MA
7 February 1986	Mr. Anthony J. Broccoli "Climate Model Sensitivity to Ice Age Boundary Conditions" Dept. of Meteorology & Physical Oceanography, Rutgers University, New Brunswick, NJ
12 February 1986	Mr. Sydney Levitus "Climatological Averages of Historical Data" WOCE Oceanographic Data Subgroup Meeting, Rockville, MD
18 February 1986	Dr. Ngar-Cheung Lau "Modeling the Influence of the Tropics on Mid-Latitude Weather and Climate" Aeronomy Laboratory/ERL, Boulder, CO
28 February 1986	Dr. J. R. Toggweiler "On the Importance of the High Latitude Oceans in Controlling Ocean Chemistry and Atmospheric PCO_2" Climate Research Committee of the National Academy of Sciences, Washington, DC
4 March 1986	Dr. Jerry D. Mahlman "Stratospheric Temperature Trends: A Dynamical Perspective" Workshop on Early Detection of Stratospheric Changes, Boulder, CO
5 March 1986	Dr. Syukuro Manabe "CO_2 and Paleoclimate" Harvard Seminar on Ancient Climate, Cambridge, MA
17 March 1986	Dr. Kikuro Miyakoda "Experimental 30-Day Forecasting at GFDL" Workshop on Predictability on Medium and Extended-Range Forecasts, European Center for Medium Range Weather Forecasts, Reading, England
20 March 1986	Dr. J. R. Toggweiler "Building a Simple Ecosystem Model for Large Scale Studies of Ocean Chemistry" Working Group of Global Ocean Flux Program, Cambridge, MA

26 March 1986	Dr. George Philander "Mass and Heat Budgets of the Tropical Atlantic and Pacific Oceans" University of Miami, Miami, FL
31 March 1986	Dr. J. R. Toggweiler "Building a Simple Ecosystem Model for Large Scale Studies of Ocean Chemistry" Department of Applied Mathematics, New York University, NY
7 April 1986	Mr. Michael D. Cox "Tracer Release Experiments in a Numerical Eddy Resolving Model of the Thermocline" World Ocean Circulation Experiment Sector Meeting on Gyre Interactions, Boston, MA
17 April 1986	Dr. Rui Xin Huang "Simulating the Ocean Circulation with a Layered Model" Woods Hole Oceanographic Institute, MA
22 April 1986	Dr. Jerry D. Mahlman 1) "Antarctic Ozone: Dynamical Possibilities" 2) "Effects of Ozone Redistribution on Climate Change" Fluorocarbon Program Panel Meeting of the Worldwide Chemical Manufacturer's Association, Noordwijk, Holland
22 April 1986	Dr. Claus Boning "Lagrangian Eddy Statistics in the North Atlantic" Woods Hole Oceanographic Institute, MA
1 May 1986	Dr. Jerry D. Mahlman "GFDL Research in Medium Range Weather Forecasting" National Academy of Sciences Board on Atmospheric Sciences and Climate, NOAA Review Panel, Suitland, MD
12 May 1986	Dr. Stephen B. Fels "Review of Radiative Cooling Rate Accuracy" American Meteorological Society Radiation Meeting, Williamsburg, VA
12 May 1986	Dr. Abraham H. Oort "Climate Observations and Diagnostics" NATO Advanced Study Institute on "Physically-Based Modeling and Simulation of Climate and Climatic Change" Erice, Italy.
12 May 1986	Dr. Kirk Bryan 1. "Equilibrium Solution Methods for Coupled Ocean-Atmosphere Models" 2. "Ocean Circulation in Warm and Cold Climates" NATO Advanced Study Institute on "Physically-Based Modeling and Simulation of Climate and Climatic Change" Erice, Italy.

13 May 1986	Mr. Marcel D. Schwarzkopf "Aspects of Longwave Fluxes and Cooling Rates Computed with a Line-by-Line Model" Sixth Conference on Atmospheric Radiation, Williamsburg, VA
13 May 1986	Dr. V. Ramaswamy "Influence of Cirrus Shortwave Properties on Simulations of Climate" 6th Conference on Atmospheric Radiation, Williamsburg, VA
21 May 1986	Dr. Kirk Bryan "Modeling World Ocean Circulation" Royal Meteorological Society, London, England
26 May 1986	Dr. Abraham H. Oort "Balance Conditions in the Earth's Climate System" Academy of Sciences, Lisbon, Portugal
9 June 1986	Dr. Hiram Levy, II "Modeling Tropospheric Chemistry" Rocky Mountain ACS Symposium on Chemistry of the Atmosphere, Denver, CO
16 June 1986	Dr. V. Ramaswamy "Simulation of Cirrus Clouds in Climate Models" Oxford University, England
19 June 1986	Dr. Syukuro Manabe "Overview of Climate Change/Future Weather Report" Conference on the Health and Environmental Effects of Ozone Modification and Climate Change, Washington, DC
25 June 1986	Dr. Bin Wang "On the Nature of CISK and the Development of the Tibetan Plateau Warm Vortex" IAMAP/DMG Symposium on the Verification of Theories in Atmospheric Large/Medium Scale Dynamics, Munich, Germany
28 June 1986	Dr. Raymond T. Pierrehumbert "Formation and Destruction of Ordered Structures in Turbulence" Woods Hole Summer GFD Institute, Woods Hole, Mass.
3 July 1986	Dr. V. Ramaswamy "Aerosol Climate Effects" Seminar at Space Application Center, Indian Space Research Organization, Ahmedabad, India
4 July 1986	Dr. V. Ramaswamy "Satellite Retrieval Techniques for Sea-Surface Temperature" Seminar at Space Aplication Center, Indian Space Research Organization, Ahmedabad, India

9 July 1986	Dr. Bruce B. Ross "Mesoscale Modeling Activities at GFDL", NOAA Profiler Workshop, Boulder, CO
14 July 1986	Dr. Stephen B. Fels 1. "The Physics of Spectral Line Formation" 2. "Outstanding Problems in Radiative-Dynamical Interaction" NOAA/AMS Summer Course on Radiation and Climate, Boulder, CO
18 July 1986	Dr. Syukuro Manabe "The Interaction of Ocean Transport and Ice Albedo Feedback" Summer Course entitled "Radiation as it Relates to Climate" sponsored by the American Meteorological Society, Boulder, CO
21 July 1986	Dr. Isidoro Orlanski "Forecast Experiments of Winter Storms" World Meteorologicl Organization/American Meteorological Society, International Workshop on Rain Producing Systems in the Tropics and Extratropics, San Jose, Costa Rica
22 July 1986	Mr. Michael D. Cox "Isopycnal Mixing Applied to a Level Model" World Ocean Circulation Experiment Workshop on Process Dynamics in Large-Scale Ocean Circulation Monitoring, Sydney, British Columbia
30 July 1986	Dr. Kikuro Miyakoda 1. "Anomaly General Circulation Models" 2. "Results from GFDL SKYHI Model Experiments: An Exploration of Higher Resolution" Seminar on Studies of Large-Scale Atmospheric Processes by use of Models, Kyoto, Japan
30 July 1986	Dr. Raymond T. Pierrehumbert Workshop "Seminar on Studies of Large-Scale Atmospheric Processes by Use of Models" Kyoto, Japan
4 August 1986	Dr. Kikuro Miyakoda "Recent Developments in the GFDL Extended Range Forecasting System" International Symposium on Short and Medium Range Numerical Weather Prediction, Tokyo, Japan

4 August 1986	Dr. Yoshio Kurihara "A Diabatic Dynamic Initialization Scheme for Numerical Prediction Models" and "Effects of Mountainous Islands on the Behavior of Tropical Cyclones" WMO/IUGG International Symposium on Short and Medium-Range Numerical Weather Prediction, Tokyo, Japan
11 August 1986	Dr. Kikuro Miyakoda "Climate Drift" WMO Working Group on Numerical Experimentation, Japan Meteorological Agency, Tokyo, Japan
26 August 1986	Mr. Richard T. Wetherald "Interaction Between Clouds, Radiation, and Hydrology", International Radiation Symposium, Beijing, Peoples Republic of China
8 September 1986	Dr. Ngar-Cheung Lau "Simulation of Intraseasonal Oscillation by General Circulation Models at GFDL" Royal Meteorological Society/American Meteorological Society Conference on Variability of the Atmosphere and the Oceans on Time Scales of a Month to Several Years, London, England
8 September 1986	Dr. Isaac M. Held "Linear and Nonlinear Models of the Extratropical Response to El-Nino" Royal Meteorological Society/American Meteorological Society Conference on Variability of the Atmosphere and the Oceans on Time Scales of a Month to Several Years, London, England
8 September 1986	Mr. David Neelin "Simple Models of Tropical Atmospheric Circulation: Simulating a GCM" Royal Meteorological Society/American Meteorological Society Conference on Variability of the Atmosphere and the Oceans on Time Scales of a Month to Several Years, London, England
8 September 1986	Mr. Thomas R. Knutson "30-60 Day Atmospheric Oscillations: Composite Life Cycles of Convection and Circulation Anomalies" Royal Meteorological Society/American Meteorological Society Conference on Variability of the Atmosphere and the Oceans on Time Scales of a Month to Several Years, London, England
8 September 1986	Dr. George Philander "General Circulation Models of the Ocean" Royal Meteorological Society/American Meteorological Society Conference on Variability of the Atmosphere and the Oceans on Time Scales of a Month to Several Years, London, England

9 September 1986	Prof. G. Mellor "Turbulence Closure Methods in Geophysics" Seminar - SACLANT ASW Research Center, LaSpezia, Italy
10 September 1986	Prof. G. Mellor "Ice-Mixed Layer Interactions" Seminar - SACLANT ASW Research Center, LaSpezia, Italy
15 September 1986	Dr. Raymond T. Pierrehumbert 1. "Blocking Effects of Mountains 2. "Parameterization of Gravity Wave Drag" European Center for Medium-Range Weather Forecasts, Reading, England
16 September 1986	Mr. Bertrand Carissimo "Mountain Drag Associated with Frontal Passage During Alpex" ECMWF Seminar, Reading, England
18 September 1986	Dr. Jerry D. Mahlman "High Resolution Modeling of the Middle Atmosphere" University of Washington, Seattle, Washington
20 September 1986	Dr. Kirk Bryan "Ocean Models for Climate Studies" PMEL Review and ERL Meetings on Scientific Plans, Seattle, Washington
20 September 1986	Dr. Jerry D. Mahlman "Atmospheric Modeling Requirements for Climate Change Research" Workshop on "The Greenhouse Problem" Seattle, Washington
23 September 1986	Dr. Kikuro Miyakoda "ENSO", Pontifical Academy of Sciences sponsored Study Week on "Persistent Meteo-Oceanographic Anomalies and Teleconnections" Rome, Italy
29 September 1986	Dr. Kikuro Miyakoda 1. "The Tropical Initialization for Extended Range Forecasts" 2. "Dynamical Long-Range Forecasts" World Meteorological Organization Conference on Long-Range Forecasting: The Practical Problems and Future Prospects, Sofia, Bulgaria

APPENDIX F

List of Acronyms

APPENDIX F

ACRONYMS

ALPEX	ALPine EXperiment
ANMRC	Australian Numerical Meteorology Research Centre
A2,E2,E4, F,M	Five physical parameterization packages in use at GFDL, in increasing order of sophistication. E4 physics includes a high-order closure scheme for sub-grid turbulence, F physics includes Arakawa-Schubert convective parameterization, and M physics include envelope orography
CAC	Climate Analysis Center (NOAA)
CDC	Control Data Corporation
CLIMAP	Climate: Long Range Investigation, Mapping and Prediction
COADS	Comprehensive Ocean-Atmosphere Data Set
CODE	Coastal Ocean Dynamics Experiment
ECMWF	European Centre for Medium-Range Weather Forecast
ENSO	El Nino - Southern Oscillation
FGGE	First GARP Global Experiment- Dec.1978 - Nov.1979 IIIb - Data set analyzed on a spatial grid. 4D- Analysis system taking into account both space and time variation of the data. SOP1 - First Observing Period, Jan.5 - Mar.5,1979 SOP2 - Second Observing Period May 1 - June 30, 1979
GARP	Global Atmospheric Research Program
GATE	GARP Atlantic Tropical Experiment
GCM	General Circulation Model
GFDL	Geophysical Fluid Dynamics Laboratory
HIBU	Hydrological Institute, Belgrade University
ICRCCM	Intercomparison of Radiation Codes in Climate Models
ITCZ	Intertropical Convergence Zone
LAHM	Limited Area HIBU Model

LGM	Last Glacial Maximum
LIMS	Lim Infrared Modulated Sensor
MAC/BES	Meso-alpha coarse model/meso-Beta scale model
MCS	Mesoscale Convective System
Meso α, β, or γ	Three classes of mesoscale atmospheric motion, in descending order of spatial scale.
MIZ	Marginal Ice Zone
MOODS	Master Oceanographic Observations Data Set
MRF	Medium Range Forecast
NESDIS	National Environmental Satellite, Date Information Service
NODC	National Oceanographic Data Center
NOS	National Ocean Service
NMC	National Meteorological Center (USA)
PU	Princeton University
ROHK	Royal Observatory of Hong Kong
SESAME	Severe Storms & Mesoscale Experiment
SKYHI	The GFDL Troposphere-Stratosphere-Mesosphere GCM
SST	Sea Surface Temperature
TOGA	Tropical Ocean Global Atmosphere
TOVS	TIROS-N Operational Vertical Sounder
TTO	Transient Tracers in the Ocean
USGS	U. S. Geological Survey
WOCE	World Ocean Circulation Experiment

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