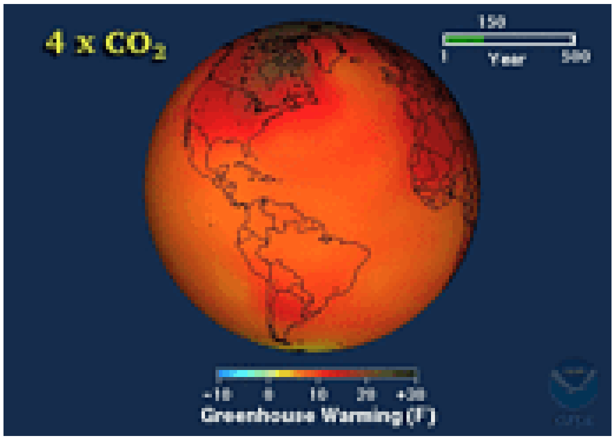
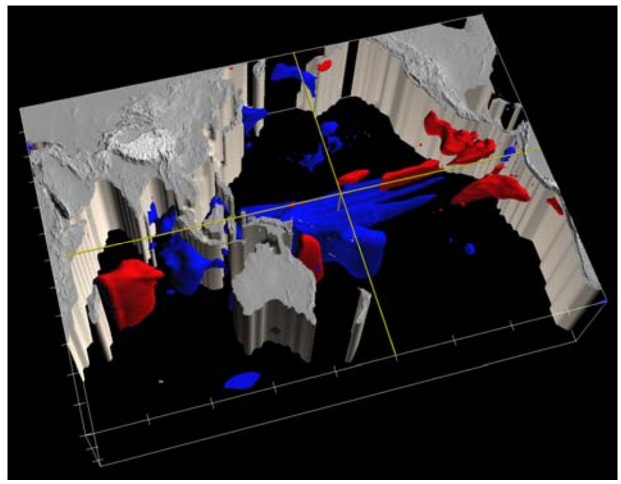
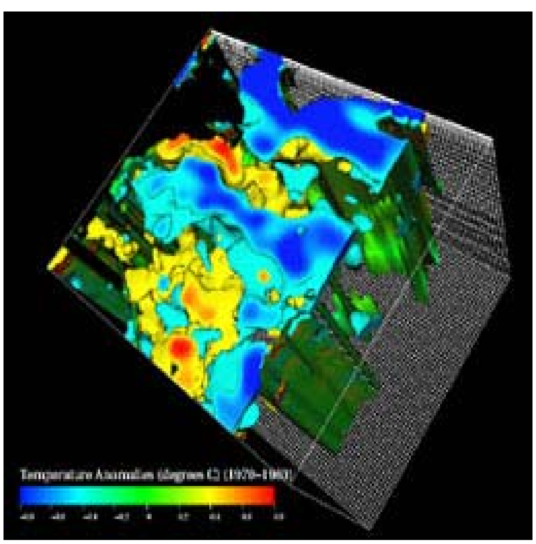


Annual Progress Report
July 1, 2003 – June 30, 2004
Cooperative Institute for Climate Science
at Princeton University



CICS



Jorge L. Sarmiento, Professor of Geosciences and Director
Cooperative Institute for Climate Science
Princeton University Forrestal Campus
300 Forrestal Road, Box CN 710
Princeton, New Jersey 08544-0710

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Cooperative Institute for Climate Science
Princeton University

Annual Report of Research Progress under Cooperative Agreement NA17RJ2612
During July 1, 2003 – June 30, 2004

Jorge L. Sarmiento, Director

Introduction

The Cooperative Institute for Climate Sciences (CICS) was founded in 2003 to foster research collaboration between Princeton University and the Geophysical Fluid Dynamics Laboratory (GFDL) of the National Oceanographic and Atmospheric Administration (NOAA). Its vision is

> *to be a world leader in understanding and predicting climate and the co-evolution of society and the environment – integrating physical, chemical, biological, technological, economical, social, and ethical dimensions, and in educating the next generations to deal with the increasing complexity of these issues.*

CICS is built upon the strengths of Princeton University in biogeochemistry, physical oceanography, paleoclimate, hydrology, ecosystem ecology, climate change mitigation technology, economics, and policy; and GFDL in modeling the atmosphere, oceans, weather and climate. It plans to enhance these strengths by incorporating interactions between these activities and the coastal ocean. CICS is an outgrowth of a highly successful forty-year collaboration between Princeton University scientists and GFDL under Princeton University's Atmospheric and Oceanic Sciences (AOS) Program that contributed to the development of oceanic and atmospheric models, performed research on climate and biogeochemical cycling, and educated several generations of graduate students. CICS was founded by expanding the existing AOS cooperative agreement into a Joint Institute.

Research Themes Overview

CICS has four research themes:

(1) **Earth System Studies**. Earth System modeling at GFDL and Princeton is now emerging from an intense period of model development during which we have produced fundamentally new atmospheric, oceanic and land models, coupled models, chemistry-radiative forcing models, cloud resolving models with new microphysics, and a non-hydrostatic limited area model. Although these models are already producing useful products, new and more sophisticated tools are required for increasingly realistic representations of the processes and interactions in the Earth's climate system.

CICS is also pursuing a number of fundamental issues in climate modeling, including parameterization of cloud-radiation-convection interactions and land surface heterogeneity; and investigations of regional climate changes in response to natural and anthropogenic forcings, detection-attribution of climate variations and change, hydrologic cycle-climate feedbacks, anthropogenic influence on modes of climate including changes in stratospheric circulation that may have influenced 20^{th} century Arctic warming, Gulf Stream and gyre dynamics, and the regulation, stability and variability of Atlantic overturning circulation.

In addition, CICS is pursuing new approaches to confronting models with observations to diagnose problems and judge reliability. The ability to simulate observed climate variability, both natural and externally forced is a central focus in the development of a sound climate modeling system. ENSO, the climatic response to volcanic eruptions, verification of the changes in the radiatively-active short-lived species and their climate forcing, clouds and the hydrologic cycle, soil moisture, interdecadal oceanic variability, and the glacial-interglacial cycles of the Pleistocene, for example, all present distinct challenges that must ultimately be addressed simultaneously by a successful Earth System model.

CICS also sponsors a limited number of symposia and workshops that explore the relationship among natural science, social science, economics and policy options for dealing with climate change. For example, in November 2004, a workshop entitled Global Warming: The Psychology of Long Term Risk will explore how new findings in psychology bear on the way people incorporate scientific information about climate and how this influences their views on policy options.

(2) **Biogeochemistry**. CICS is contributing to the development of the land and ocean biogeochemistry components of the Earth System model, and to the ongoing efforts to add aerosol chemistry to the existing tropospheric chemistry model. The new model components are being used to study the causes and variability of land and oceanic carbon sinks, to develop a data assimilation system for carbon that will provide improved estimates of the spatial distribution of carbon fluxes, and to investigate a wide range of additional issues including the air quality impacts of biogenic volatile organic compounds and the relationships between air quality and the carbon cycle.

The new dynamic land model that has been developed simulates carbon, but still lacks nitrogen or phosphorus dynamics that are likely to limit the growth of the land carbon sink caused by CO_2

fertilization. CICS is developing a global model for nitrogen and phosphorus in natural and agricultural ecosystems. In addition to improving predictions of the future land sink, this model will predict nutrient inputs into coastal waters. CICS is also performing a series of modeling experiments to investigate the causes of the current terrestrial sink (e.g., CO_2 fertilization vs. land use) and the large inter-annual variability in its size. The development of a new fully predictive ocean biogeochemistry model of carbon, nitrogen and phosphorus, is nearing completion in a close collaboration between CICS and GFDL. The model includes critical processes such as iron limitation and the formation of organic matter in the surface of the ocean and its export to the abyss. CICS will perform a series of modeling experiments to examine variability of air-sea CO_2 fluxes on seasonal, interannual, and decadal time scales and its response to global warming, and study the impact of global warming on marine biology. CICS is also building a data assimilation capability for our models of the carbon cycle that integrates data from flask stations, tall towers, eddy correlation towers, shipboard ocean transects, and forest inventories. This effort will add diagnostic capability to our prognostic models.

(3) **Coastal Processes.** The coastal oceans are being severely impacted by human activities and climate change and these impacts will grow with time. Traditionally, the main models used for climate prediction at GFDL have not included processes like tides and bottom boundary layers that play a dominant role in the dynamics of the coastal zone. CICS has proposed to develop a collaboration with a coastal modeling group that will enable the development of tools that link climate change to coastal circulation so as to provide tools for decision makers. While this goal has not yet been achieved, the first steps have been taken. The goal of the collaboration would be to develop the capability to predict the physical and biogeochemical response of the coastal system to the full range of human impacts from climate change to pollution runoff (as simulated by the models under development at Princeton), as well as the interaction of these stresses. This presents an exciting and potentially critical research opportunity which we hope to be able to explore in the future.

(4) **Paleoclimate.** The most valuable observational constraints that we have to test our understanding of the response of the Earth System to changes in forcing come from the geological and ice core record. GFDL has a long history of important contributions to our understanding of climate change through the application of climate models. In recent years, Princeton University has attracted several new faculty with active research programs in the empirical and theoretical analyses of paleoclimate. CICS is supporting research on critical issues that Princeton has particular expertise in that are likely to be of importance in determining future climate response. These include the changing response of the climate to solar insolation forcing, the cause of glacial/interglacial carbon dioxide changes, and significant climate trends that have occurred within the Holocene. These studies will be integrated with climate model development described above.

CICS research is closely aligned with the U.S. Climate Change Science Plan (US-CCSP) that was issued in July 2003 and with NOAA's Strategic Plan for FY 2003-2008. The US-CCSP identified five goals: (1) to increase understanding of the past and present climate, including variability and change, (2) to improve the quantification of the forces causing climate change and related changes, (3) to reduce uncertainty in predictions about future climate and related changes, (4) to understand ecosystem responses to climate change, and (5) to develop resources to support policies, planning and adaptive management (decision support). The research that is being carried out under CICS is obviously central to the first, second, and third of these goals. In addition, our research on improved estimation of carbon source and sinks is directly called for in the US-CCSP document under goal 2. The coastal work and the global ecosystem modeling required in the biogeochemistry section contribute to goal 4, and all of the modeling work supplies tools that aid in decision support (goal 5).

NOAA's Strategic Plan identified four mission goals: (1) protect, restore and manage the use of coastal and ocean resources through ecosystem-based management, (2) understand climate variability and change to enhance society's ability to plan and respond, (3) serve society's needs for weather and water information, and (4) support the nation's commerce with information for safe, efficient and environmentally sound transportation. The research being carried out by CICS is highly relevant to the first three of these goals, particularly the second one. The Research Reports provided in Section 5 list which of the mission goals is addressed by each research project.

A key aspect of all 4 themes of CICS is the synergistic effect of each on the others. This leveraging effect across components enhances the prospect that this research will prove of critical importance to the community of scientists and decisions makers concerned with impacts between Earth systems and human systems.

Structure of the Joint Institute

Princeton University and GFDL have a successful 40-year history of collaboration that has been carried out within the context of the Atmospheric and Oceanic Sciences Program. The new Cooperative Institute for Climate Science (CICS) builds on this existing structure. The CICS research and education activities are organized around the four themes discussed above. The following basic types of tasks and organizational structure have been established to achieve its objectives:

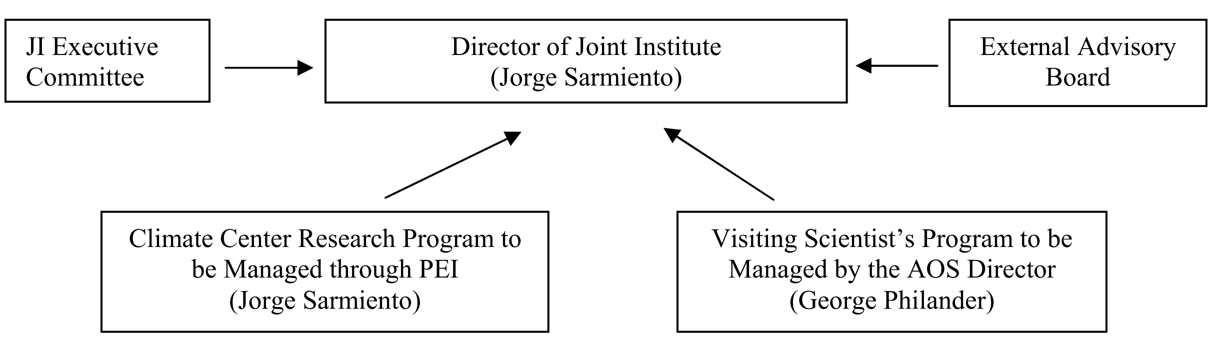
(1) Administrative Activities are carried out jointly by the AOS Program and PEI (Princeton Environmental Institute).

(2) Cooperative Research Projects and Education to be carried out jointly between Princeton University and GFDL. These will continue to be accomplished through the Atmospheric and Oceanic Sciences (AOS) Program of Princeton University. They include a post-doctoral and visiting scientist program and related activities supporting external staff working at GFDL and graduate students working with GFDL staff. Selections of Post Doctoral Scientists, Visiting Scholars, and Graduate Students are made by the AOS Program, within which most of the senior scientists at GFDL hold Princeton University faculty appointments. The AOS Program is an autonomous academic program within the Geosciences Department, with a Director appointed by the Dean of Faculty. Other graduate students supported under Principal Investigator led research projects are housed in various departments within Princeton University and the institutions with which we have subcontracts.

(3) Principal Investigator led research projects supported by grants from NOAA that comply with the themes of CICS. These all fall within the newly formed Princeton Climate Center (PCC) of PEI and may also include subcontracts to research groups at other institutions on an as needed basis.

The CICS has a Director (currently Jorge Sarmiento) recognized by the Provost as the lead for the interactions between NOAA and GFDL. The Director is the principal investigator for the CICS proposal. The Director is advised by an Executive Committee consisting of the Directors of the AOS Program and PCC, and three faculty members each from the AOS Program and the PCC. The Director is also advised by an External Advisory Board consisting of representatives from NOAA and three senior scientists independent of NOAA and Princeton University.

STRUCTURE FOR THE PRINCETON/GFDL JOINT INSTITUTE
COOPERATIVE INSTITUTE FOR CLIMATE SCIENCES (CICS)



CICS Committees and Members

<u>PEI's Princeton Climate Center (PCC) Advisory Committee</u>
Jorge L. Sarmiento – Director of Joint Institute and Professor of Geosciences
Stephen W. Pacala – Professor of Ecology and Evolutionary Biology
Michael Oppenheimer - Professor Geosciences and International Affairs
Ignacio Rodriguez-Iturbe – Professor Civil and Environmental Engineering

<u>Executive Committee</u>
S. George H. Philander – Director of AOS and Professor of Geosciences
Issac Held – GFDL Senior Research Scientist
Hiram Levy – GFDL Senior Research Scientist
V. Ramaswamy – GFDL Senior Research Scientist
Plus PCC Advisory Committee
Jorge L. Sarmiento – Director of Joint Institute and Professor of Geosciences
Stephen W. Pacala – Professor of Ecology and Evolutionary Biology
Michael Oppenheimer - Professor Geosciences and International Affairs
Ignacio Rodriguez-Iturbe – Professor Civil and Environmental Engineering

<u>Administrative Committee</u>
S. George H. Philander – Director of AOS and Professor of Geosciences
Francois Morel - Director of PEI and Professor of Geosciences
Anthony F. Dahlen - Chair and Professor of Geosciences
Stephen W. Pacala – Professor of Ecology and Evolutionary Biology
Ants Leetmaa - Director of GFDL

Research Highlights

The following highlights ongoing research and plans for the near future in the major research and education themes we identified in Section 2. The CICS has considerable ongoing research in Earth Systems Studies and Biogeochemistry areas growing out of the pre-existing AOS Program that is described here along with new research that has recently been initiated. The Coastal Oceanography area has not been initiated as yet, and the Paleoclimate area is a new initiative and has only modest activities.

Earth Systems Studies

We focus specifically in the following paragraphs on ongoing research on Land Dynamics; Ocean Dynamics, Large-Scale Atmospheric Dynamics; Short-lived species and Radiative Forcing; and Clouds and Moist Convection. See Section 5 for a more comprehensive report of ongoing research. Except for the Land Dynamics component, ongoing research in this area involves principally cooperative research activities, i.e., post-docs and graduate students in the AOS Program working directly with GFDL staff.

Land Dynamics

The PCC component of CICS has taken the lead in developing the physical as well as biological components of a new land model for GFDL's climate modeling system. On both the physical side, discussed here, and the biological side discussed in Section 4.2, the importance of land dynamics for climate requires that we continue to strengthen this connection through CICS. Two AOS post-doctoral scientists are currently engaged in model development activities in hydrology, one on a study of the relative importance of land and oceanic boundary conditions for interannual variability in the new GFDL atmospheric model (AM2), and another on the building of a prototype National Stream Flow Information System. In addition, Rodriguez-Iturbe and Wood were recently funded with support for two research staff members to study the scaling of hydrologic fluxes in space and time. The heterogeneity of the land surface, in its soil moisture, vegetation characteristics, and topography make for distinct reductive and integrated modeling problems. We need to better understand which aspects of the climate system are influenced by land heterogeneity and how best to model this effect. CICS will focus on the impact of land surface processes on climate prediction on time scales from months to centuries, the dynamics and simulation of drought, and research on sources of nonlinearity relevant to the modeling of the effects of heterogeneity. This component is important as an element of climate modeling as well as for predicting impacts that result from changes in runoff and nutrient flows.

Ocean dynamics

As examples of our efforts in oceanic dynamics of relevance to climate, several post-docs are working on topics closely related to the stability and variability of the Atlantic overturning circulation, one of the central uncertainties in the ocean's role in shaping the climatic response to changes in greenhouse gas concentrations. One is studying how decadal-time scale variability in the North Atlantic is controlled by events such as the Great Salinity Anomaly of the 1970's and its relationship with the North Atlantic Oscillation. Others are analyzing relatively low-resolution ocean models that can be integrated for millennia. One is testing the control exerted by Southern Hemisphere winds for the Atlantic overturning, while another is focusing on new ideas that the effects on density of enhancement/reduction of salinity due to the nonlinear equation of state is a key to paleoclimatic and future changes in this circulation. A recently arrived post-doc will be working on connections between polar oceanic changes, equatorial ocean dynamics, and ENSO that are potentially relevant for global warming predictions and paleoclimatic studies.

Accurate simulation of the separation of the Gulf Stream from the coast remains a difficult challenge for ocean models; in fact, improper Gulf Stream path results in some of the largest local surface temperature biases in the GFDL coupled model currently under development. Two current post-docs are studying Gulf Stream and gyre dynamics, by looking at factors that influence separation in coarse-resolution models, and by examining the effects of meso-scale eddy dynamics on separation.

Chemistry-Radiation-Climate interactions

Enhancements in the modeling of climate variations and change require continuous advances in our knowledge of atmospheric physics and chemistry, the component modules and the accuracy with which these represent the complexity found in the Earth's system in climate models. In recent years, the radiation component of atmospheric models has been carefully calibrated against 'benchmark' calculations. An IPCC-coordinated intercomparison exercise with NCAR and other institutions in the US and around the world is helping to identify differences in forcing computations among various GCMs. Improved treatment of cloud-radiation interactions including the formulation of generalized vertical overlap schemes have been implemented, guided by observations.

The new GFDL atmospheric chemistry-transport model includes all the known aerosol species. These concentrations are being extensively tested against diverse sets of observations. Together with explicit treatment of the optical properties, this allows for a comprehensive determination of the climate forcing by short-lived greenhouse gases and aerosols. A graduate student has underscored the importance of black carbon aerosols on chemical processes, while another student has established organic carbon aerosols as important species in climate forcing. Another student and a post-doctoral fellow will be augmenting these activities soon. The chemical-dynamical interactions in the stratosphere and their effects on climate will also soon be investigated with the 3D model, with the impacts on stratospheric ozone recovery being a principal feature. Further refinements in our models include the representation of clouds in terms of natural and anthropogenic aerosol concentrations with more detailed microphysical considerations, making the cloud processes inherently more realistic. A post-doctoral fellow has formulated the aerosol-cloud linkages in climate based on fundamental understanding. An important feature of the model developments and simulations is the application of the growing observational datasets, including satellite, towards verification of climate processes, an essential step in establishing the reliability of the simulated climate and climate change.

All these research activities contribute towards our pursuit of the causal explanation of the observed climate record in terms of natural and anthropogenic factors. In addition, these will also enable projections of future climate change in response to specified emission scenarios. The ongoing and future modeling developments address the CCSP goals and will play an important role in the fourth IPCC Assessment Report (2007) context.

Large-scale Atmospheric Dynamics

A set of key dynamical issues relevant to climate change that have recently come to the fore involve stratospheric-tropospheric coupling, and specifically the extent to which change in stratospheric circulation, caused by ozone or greenhouse gas changes, or volcanoes, can influence tropospheric circulation. A poorly understood trend in Arctic and North Atlantic surface pressures (the North Atlantic Oscillation) has played a significant role in the observed late 20th century warming of the Arctic, and it has been suggested this trend is intimately connected to stratospheric changes. Two post-docs and a graduate student have research foci that are in large part motivated by this problem. An idealized general circulation model has been designed to isolate the influence of changes in the stratospheric polar vortex on the troposphere, a simple stochastic model of the Arctic Oscillation that helps explain its preferred location and structure has been developed, and a high resolution study has been initiated of the Atlantic storm track and the extent to which its strength is controlled by the characteristics of the waves propagating over North America from the Pacific.

Several students are approaching related issues from the perspective of theories of the large-scale atmospheric circulation as a whole. One graduate student is studying how the surface westerlies and storm tracks are displaced north-south by changing atmospheric parameters, focusing initially on explaining why the westerlies move poleward as the strength of the surface friction decreases. Another is focusing on how the rotation rate of the Earth influences the scale of midlatitude eddies and the location of the jet stream and surface winds. A problem of special difficulty is to construct idealized moist general circulation models that retain enough simplicity that the effects of moisture on the model's circulation can be understood. One post-doc and a graduate student have taken on this challenge, and have constructed a series of such models with which they are examining the effects of increasing water vapor content on the general circulation, and the ways in which alternative idealizations of moist convection affect the organization of precipitation in the tropics. Comparing these results with global warming simulations using more comprehensive models should be especially instructive.

Clouds and Convection

It is generally recognized that the Earth's cloud field is one of the most difficult climate variables to simulate, and that our difficulties in this regard have a profound effect on our ability to simulate climate sensitivity from first principles. Five post-docs are pursuing research in clouds and convection motivated in large part by the need for improvements in this aspect of our climate models. One research project includes a study of diurnal cycle of clouds, convection, and upper tropospheric water from satellite data and a comparison with model simulations. The diurnal cycle presents a relatively straightforward test of the models. Also, the cloud prediction scheme in use in the newly developed atmospheric model at GFDL is being tested against the recently collected data from the ARM program. CICS is also funding a scientist to act as liaison with the newly formed Climate Process Team, who will work on Low-Latitude Cloud Modeling and Cloud Feedbacks. In addition, a version of GFDL's new non-hydrostatic model has been developed for simulating deep tropical convection, and is being used to examine the behavior of convection and clouds in the model in various settings, from horizontally homogeneous radiative-convective equilibrium, to idealized Walker and Hadley circulations, to simulations of TOGA-COARE data. This effort will prepare the way for the future possibility of cloud-resolving simulations in global models.

Work is also underway in evaluating a variety of convective closure schemes against various observational data sets. In particular, a new convection scheme that incorporates mesoscale hydrologic aspects of ice cloud systems is being readied for the atmospheric model. This scheme resolves some persistent biases present in older convection schemes when compared against observations. The scheme demonstrates the importance of tracer transport in deep convective systems, a crucial consideration for chemistry-transport modeling. The microphysics schemes employed in the GCM and nonhydrostatic model will be further refined based on advances in fundamental cloud physics and recent observations.

Biogeochemistry

The science of climate change is currently hobbled by our lack of understanding of the responses of natural ecosystems and human institutions to climate. Climate has dramatic effects on agricultural productivity, human land use, and the functioning of natural ecosystems; and, of course, these systems in turn affect climate through their impact on the cycle of carbon and other greenhouse gases and aerosols, the water cycle, the albedo, etc. Although not traditionally part of climatology, feedback loops involving both natural and human response may be as important as the purely physical feedbacks that dominate the current debate about global warming. Research in "Biogeochemistry" will explore the links between changes in the physical climate and the potential impacts on natural ecosystems and human institutions, and feedbacks from these back on to climate. We are focussed on developing ocean biogeochemistry, land processes, and atmospheric chemistry modules for an Earth System model (ESM) that will be used to understand the interactions and feedback of the Earth's biosphere with its climate and assess the impacts of future human activities.

Ocean Biogeochemistry

Currently GFDL's Biospheric Processes Group, with support from Jorge Sarmiento's Group at Princeton, is developing a fully prognostic Carbon-Nitrogen-Phosphorous ocean biogeochemistry module which is being tested in a reduced-resolution ocean general circulation model. These scientists are also: studying the role of the Southern Ocean in anthropogenic carbon uptake; developing inverse modeling and data assimilation of atmospheric, oceanic, and terrestrial carbon observations to determine the large scale distribution of carbon sources and sinks with an emphasis on the spatial and temporal distribution of the North American carbon sink; and implementing tracers in GFDL's Isopycnal Model (HIM), a potential long-term replacement or supplement to MOM4 for GFDL's coupled Earth System model.

Future research with the ocean biogeochemistry module [OBGCM] will focus on studies of ocean biogeochemistry under climate change, including: (1) changes in the size of the ocean carbon sink, (2) changes in the distribution of biomes and biological productivity, and (3) effects on human activities such as fisheries. The OBGCM will also be coupled to a climatologically driven ocean general circulation model [OGCM] to study a number of ocean driven properties: variability in air-sea fluxes of CO_2; partitioning of this CO_2 flux variability into physical and biological components; the observed decadal changes in oxygen concentrations in the thermocline; potential feedbacks between short-wave radiation penetration variability, the nutrient supply to the surface, meridional heat flux, and El Niño; the impact of natural seasonal and inter-annual variability on marine biological resources through variability in phytoplankton productivity and community structure; and connections between regional variability of temperature and productivity and recruitment variability in fisheries.

Land Processes

A global land surface model, which emphasizes terrestrial carbon sources and sinks and is suitable for an Earth System model (ESM), is being developed at GFDL by the Pacala Group of Princeton in collaboration with GFDL, a group at the University of New Hampshire which has been subcontracted, Wood's Princeton Group and the USGS Hydrology Group at GFDL. The model includes static or changing vegetation, plant physiology, a non-isothermal surface and a number of other extensions. Future versions will include a new soil model, static or dynamic land use, and numerous hydrology refinements currently under development. The initial development of a new land model, along with a new offline driver, is complete and it is now being coupled to the GFDL atmospheric GCM [AM2].

In subsequent years, Pacala's group will continue to develop, maintain and run the land models. They will also collaborate with GFDL in studies of the land surface under climate change, including: (1) changes in the sizes of terrestrial carbon sources and sinks, (2) changes in the distribution of biomes, (3) effects of vegetation and land use change on the hydrologic cycle, and (4) effects on human activities. Initially the land C model will be driven by GFDL's AGCM coupled to its mixed-layer ocean model. This will also be used to study the impacts of historic land use changes on vegetation cover and terrestrial carbon dynamics. Wood's Hydrology Group at Princeton will participate in a collaboration with GFDL and USGS to: evaluate and improve the hydrologic components of the land model; examine the role of land surface states in seasonal to annual prediction; determine the influence of Arctic river discharge variability on climate variability.

The Pacala, Hedin, and Oppenheimer Groups at Princeton are collaborating with GFDL on the development of a global nitrogen [N] and phosphorus [P] nutrient cycling model for natural and managed ecosystems to be coupled to the existing Carbon [C] cycle land model. Initially, existing agriculture and forest N and P nutrient cycling models will be adapted, though the development of a new forest model will be explored. The agriculture model will be used to develop simple representations for the crucial cropping systems around the globe (e.g., corn, soybean, wheat, rice) with the goal of simulating crop yields, soil N processes, carbon cycling and N leaching to the river system across the globe, based on fertilizer inputs and cropland distribution. The forest model will simulate global variations in forest growth and carbon balances in response to nutrients, water and climate variability. Of particular interest is the role of forest-to-agriculture conversion in the cycling and export of nitrogen in tropical landscapes. A third area of research will link the N leaching component of the model with a river network model being developed at GFDL in order to simulate export of N to coastal ecosystems. The land model will eventually be coupled to the coastal and ocean biogeochemistry models described elsewhere.

Atmospheric Chemistry

GFDL has incorporated a full gas phase tropospheric chemistry in its AGCM and is developing a complete aerosol chemistry. With these developments in the atmospheric chemistry now taking place at GFDL, and the prospect for a full atmospheric chemistry (trop+strat) interactive module in the GFDL GCMs in about 1-2 years, there will be the facility to couple emissions directly to chemistry, microphysics, clouds, radiation and climate, and allow for feedbacks to study past and future climates. Along with the modeling expertise, extensive data collection and analyses from a number of platforms (satellite, NCEP, surface concentrations, vertical profiles) are also going on which allows for rigorous testing and confidence-building measures with regards to the model simulations. GFDL, in collaboration with Pacala's group, is also studying air quality impacts of changes in biogenic volatile organic compounds (BVOC) emissions from the 1980s to 1990s in the eastern U.S.; examining future changes in biogenic versus anthropogenic VOC emissions in the eastern United States and their influence on surface ozone; incorporating the global MEGAN isoprene inventory of Alex Guenther (NCAR) into the C land model being developed at Princeton/GFDL for studies of global air quality.

Earth System model [ESM]

GFDL, in collaboration with Princeton, has already begun construction of the prototype ESM using a subset of the modules described above and GFDL's coupled atmosphere-ocean model [CM2] that has been developed for this round of IPCC studies. Once the prototype is complete, a large number of studies are planned. A few examples are given below:

- Simulations with a range of anthropogenic emission scenarios such as those produced by the IPCC will be run to examine the possible climate-ecology feedbacks and to assess the impact of climate change on both land and ocean carbon sinks and ecologies.
- The global iron cycle will be studied to determine the extent to which iron supply (from the atmosphere and the ocean interior) determines primary productivity and the biogeochemical cycling of the elements, particularly with respect to modulation of CO_2 in the atmosphere. Development of this type of globally dynamic model would make possible improved assessments of the feasibility of iron fertilization as a means of sequestering CO_2 and determining its environmental impact such as on global fisheries.
- The ESM model with C-N-P nutrient cycling will be used to assess the impact of humanity's doubling the input to the global nitrogen cycle, primarily due to the ubiquitous application of fertilizer for agriculture. There have already been drastic impacts locally through eutrophication of inland and coastal waterways. The regional impacts are beginning to be seen in changes to the Black Sea and the Mediterranean and the "Dead Zone" at the mouth of the Mississippi in the Gulf of Mexico. The impacts to open ocean primary productivity, community structure and interior oxygen are largely unknown. As an example of the integrated approach, CICS will examine how human perturbations of the nitrogen cycle interact with climate change to alter concentration of nitrous oxide, thereby feeding back on changes in climate and atmospheric chemistry.
- ESM modeling of Coastal/estuarine eutrophication and toxic blooms would probably require development of an isopycnal ocean model and would require close collaboration with the Coastal Zone Section. Impacts of nitrogen loading through human activities on water quality are both a social and political concern. Impacts include practical ones like collapse of fisheries due to hypoxia and ecological conditions favoring toxic blooms of phytoplankton and dinoflaggelates and more aesthetic ones like odor and color of water and ecological conditions favoring nuisance blooms of phytoplankton and gelatinous zooplankton.

We also hope to develop a reduced resolution ESM that can be used to interpret the Paleoclimate record through explicit modeling of the Earth System (see Section 3.4). Our understanding of climate change over glacial-interglacial cycles has been achieved in part through interpretation of tracer proxies (^{18}O, ^{13}C, Sr, etc) of climate parameters such as temperature. Many of the interpretations of these tracer records, however, are ambiguous and in some cases seemingly inconsistent. In order to test the validity of these proxies, a long (~100,000 year) run of a "fast" ESM with an explicit sediment module containing the entire suite of geochemical tracers is required. This project would require extensive ESM development at GFDL and close collaboration with paleoclimate scientists at Princeton and elsewhere.

Coastal Processes

The coastal ocean is of fundamental importance to many activities, including fisheries, defense, recreation and human health. It is also the region of the ocean in which human activity has the strongest impact through the modification of freshwater runoff, the introduction of large inputs of nitrogen and other nutrients, the episodic release of pollutants, the physical modification of the seafloor by dredging, and the manipulation of ecosystems by fishing. In the coastal ocean, the physical circulation is extremely complicated, the seafloor morphology itself evolves as a result of sediment transport, and the structure of biological communities varies rapidly on relatively short space and time scales.

The coastal ocean is also a region of intense observational activity, with coastal observatories, a spreading network of coastal radars that map surface currents, video recorders that monitor the near-shore wave field, and other instruments that provide routine fisheries observations. As noted in the "Ocean Sciences at the New Millennium" report published in 2001 by NSF: "Recent advances in computational capabilities, combined with increasingly sophisticated observational technologies (e.g., remote sensing, telemetry, networking, autonomous underwater vehicles, long-term monitoring systems) present unprecedented opportunity to advance understanding of shelf and estuarine systems and their management." The challenges presented by the analysis of coastal data, the assimilation of coastal biogeochemical and physical data, and the development of whole-system models that integrate physics and biology and combine small scales (e.g., river estuaries and continental shelves) with large scales (e.g., oceanic basins and the global ocean) are profound. In particular, the integration of a coastal ocean component within the framework of the next-generation GFDL climate model will allow us to explore decision-support tools that will enable coastal managers to cope with climate change.

Paleoclimate

Measurements are of paramount importance, in any science, for the testing of theories and models. Weather forecasting has made enormous strides because models can be tested daily. By contrast, progress in our understanding of climate, with time-scales of decades or more, is severely observation-limited. The study of past climates is therefore of central importance to any project that attempts to develop climate models for the purpose of anticipating future climate changes. A good example of this is an observation from the pre-instrumental record that receives much attention in policy discussions regarding CO_2 emissions, namely the strong correlation between temperature and atmospheric carbon dioxide over the glacial/interglacial cycles of the past 400,000 years. While the existence of this correlation is indubitable, the significance is not. Is CO_2 primarily a passive tracer of climate, responding to the changes in winds and temperatures associated with glacial-interglacial cycles, or does it have a significant role as an amplifier of these cycles? Answering such a question involves linking observations with mechanisms through models that simulate *both* climate and biogeochemical cycles over long periods of time.

Over the past 40 years, GFDL and Princeton scientists have conducted research into many key topics in paleoclimate that has directly impacted the discussion over global warming. Examples include:

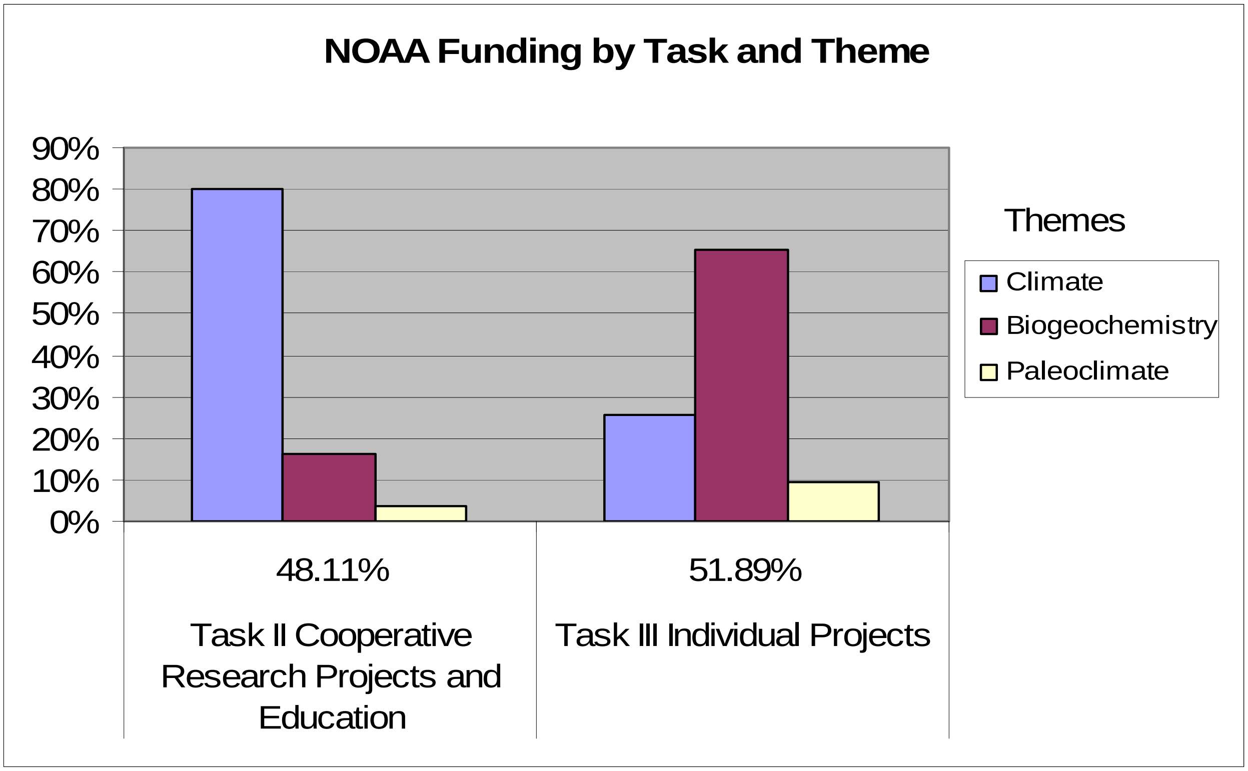
1. What was the climate like during the ice ages and how important was carbon dioxide in producing this climate? What accounts for the 100,000 year cycle? What accounts for rapid changes during deglaciation? How much of the impact of radiation is through ice-albedo feedback and how much is through changes in tropical circulation? Work on the first question has helped to build confidence that carbon dioxide does in fact have a major role in setting Earth's climate. Work on understanding rapid shifts in climate during deglaciation has also helped frame the debate over rapid climate change and climate stability.
2. How do changes in climate produce changes in biogeochemical cycling? What accounts for the correlation of carbon dioxide with climate? Work on these questions has helped to show that changes in ocean circulation associated with global warming could make it much more difficult to stabilize atmospheric carbon dioxide.
3. To what extent is the climate of the present day controlled by the distribution of land masses? Some have claimed that increasing atmospheric carbon dioxide will result in returning climate to an equable past state. Insofar as the distribution of land was significantly different at such times, this claim will not necessarily be true.

In large part, climate change is of interest because it affects living things. As already noted, the addition of Morel, Bender, Ward, and Sigman to the Princeton faculty has created a critical mass of expertise about how oceanic organisms and ecosystems work. The expertise of Morel and Ward's labs in algal physiology helps to develop theories of how changes in environmental conditions are reflected in properties (such as isotopic composition) within individual organisms. Both Bender and Sigman have strong research programs that make high-precision measurements of these properties with the goal of generating integrative measures of the state of the biosphere over time. An example of such an integrative measure is the relative concentrations of the three stable isotopes of oxygen, which Bender's lab is using to generate a measure of global primary productivity- with the goal of linking this measure to long-term climate change.

Despite intense interest in past climates, it has not always been easy to connect the geologic record to physical models of oceans, atmospheres, and climate. The reasons for this are twofold. First, in order to produce a stable climate, it is necessary to integrate a model for many centuries until the ocean comes to equilibrium. Until recently, such integrations have only been possible for low-resolution models, which required either massive simplifications of atmospheric processes or flux adjustments (linearizing about the present climate) to ensure a stable climate. Either strategy calls into question the simulations produced by such models of past climates. Second, many proxy estimates of past climate are associated with living organisms, and it is not always clear how to interpret the signals that living organisms produce (a particularly salient example is tree rings, which are affected by temperature, moisture, and solar radiation during a particular part of the year). Finally, both the high computational cost of fully coupled models and the relatively immaturity of the field of biogeochemical modeling has meant that relatively few biogeochemically-relevant tracers have been included in fully coupled model runs.

Recent developments at GFDL and Princeton have provided a basis for beginning to address all three problems. GFDL has recently completed an intensive model development effort which has resulted in the production of a new set of coupled atmosphere-ocean-sea ice models which run without flux adjustments. The Pacala group at Princeton has developed a terrestrial ecosystem model that is currently being coupled to the climate model. At GFDL, Dunne has built on over a decade of work within the Sarmiento group to incorporate a prognostic ocean ecosystem model into the GFDL level-coordinate ocean model, and work is beginning in Sarmiento's group to incorporate this model within an isopycnal ocean model developed by Hallberg. These new models, coupled with increments in computational resources, mean that the possibility now exists of running coupled models with biogeochemistry that can be integrated for thousands of years.

NOAA Funding Table



Project Reports:

Earth Systems Studies

Project Report: **Numerical methods for ocean climate models**

Principal Investigator: Alistair Adcroft (Massachusetts Institute of Technology)

Other Participating Researchers: Stephen Griffies(GFDL), Robert Hallberg(GFDL), John Dunne(GFDL)

NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:
Develop numerical methods for use in ocean climates models and establish collaboration between MIT and GFDL.

Methods and Results/Accomplishments:
Adcroft was a senior visitor from MIT for the summer of 2003. He collaborated with the GFDL ocean Group on several projects involving ocean model development.

Lagrangian-Eulerian Vertical Coordinates.
Adcroft worked closely with Robert Hallberg (GFDL) on the formulation of vertical coordinates in ocean circulation models. The work culminated in a joint paper with Hallberg. In the paper, they discuss the method of solution in models in which the vertical direction is considered Eulerian and a different method of solution in which uses a Lagrangian treatment of the vertical. These methods of solution turn out to be mutually exclusive. Generalized coordinate models purport to be able to model hybrid coordinates which can be both Eulerian and Lagrangian in nature at the same time but in different parts of the water column. They point out that use of the Eulerian algorithm for a Lagrangian coordinate does not recover the properties of a Lagrangian treatment of the vertical that one would strive for. Further, the generalized algorithm, known as ALE (Arbitrary Lagrangian Eulerian), does not recover the symmetric treatment of the spatial directions that the Eulerian procedure exhibits. The conclusion is that models must either choose a Lagrangian or an Eulerian vertical coordinate; there are no easy hybrid options.

Implementation of a positive advection scheme in MOM4.
Collaborating with John Dunne (GFDL), a third order flux limited scheme previously in use in the MIT code was implemented in MOM4; this was initially motivated for use with the bio-geochemistry package which required positive (positive definite) properties as well as accuracy. Adcroft also implemented a multi-dimensional algorithm designed to preserve shape for divergent flows. The scheme was evaluated over the summer by Dunne in the context of passive tracers but subsequently the scheme has been adopted for the dynamically active scalars (potential temperature and salinity) due to its demonstrably superior properties.

Positive definite advection of potential vorticity
Adcroft explored a new treatment of the primitive equations (in shallow water) which can be discretized so that the implied potential vorticity (PV) equation be treated as "positive". This is motivated by the nature of the PV equation which looks like a simple scalar advection equation; it should be conservative in all moments and conserve extrema. The basic idea is to apply the sophisticated advection schemes that are usually reserved for scalar equations but to

dynamically relevant scalars such as PV; the components of momentum are not conserved and so applying "positive" approaches directly to the momentum equations is unjustified. A test model was developed and evaluated; the approach appears to work in a similar fashion to the anticipated-potential vorticity method of Sadourny and Basdevant. Numerical solutions can be obtained in a near-inviscid limit such that dissipation occurs only where the solution would otherwise be unphysical. For conventional wind-stress forcing in a square ocean basin, the Fofonoff modes emerged in low resolution solutions and at moderate resolutions for which conventional dissipative models would appear laminar, this method produced separated meandering jet (Gulf Stream).

Collaborative frameworks.
During the course of the summer and since, Adcroft and GFDL scientists have been developing the concepts of ocean modeling "frameworks". These represent a community desire to share software between modeling groups and centers and foster stronger collaboration. We have outlined some protocols which would allow collaboration in development between the MIT and GFDL ocean modeling groups. In particular, we envision some shared low level software and are currently defining the form that such shared low-level software can take.

Publications:

Alistair Adcroft and Robert Hallberg, 2004: On methods for solving the oceanic equations of motion in generalized vertical coordinates. Submitted to Ocean Modelling.

Project Report: **Development of GFDL Flexible Modeling System (FMS)**

Principal Investigator: V. Balaji(Princeton)

Other Participating Researchers: GFDL Model Infrastructure (MI) Team.

NOAA's Goal #3: Serve Society's Needs for Weather and Water Information

Objectives: Building model components consistent with the common model infrastructure FMS in support of PU/GFDL modeling activities.

Accomplishments:
Development and maintenance of FMS.
Development of CM2.0 and CM2.1 coupled models.
Climate and climate change simulations in support of NOAA/GFDL's participation in IPCC.
Delivery, maintenance and support of community ocean model MOM4.
Development of Earth System Model ESM0 in conjunction with Stephen Pacala's group-Princeton.
Development of FRE: the FMS Runtime Environment for end-to-end management of modeling: source code maintenance, compilation, run and maintenance of job streams, post-processing and analysis.

References:
http://www.gfdl.noaa.gov

Publications:
Global Atmospheric Model Development Team, 2004: The new GFDL global atmosphere and land model AM2/LM2: Evaluation with prescribed SST simulations, accepted for publication in J. Climate.

Project Report: **Development of Earth System Modeling Framework**

Principal Investigator: Tim Killeen(NCAR), John Marshall(MIT), Arlindo daSilva(NASA).

Other Participating Researchers: (technical leads): V. Balaji(Princeton), Chris Hill(MIT), Cecelia deLuca(NCAR).

NOAA's Goal #3: Serve Society's Needs for Weather and Water Information

Objectives:
Building a common modeling infrastructure for weather and climate models and data assimilation systems.

Accomplishments:
Delivery of ESMF v2.0, June 2004.

References:
http://www.esmf.ucar.edu

Publications:
Architecture of the Earth System Modeling Framework,Computers in Science and Engineering, vol 6, 2004.

Education And Outreach Activities:
Invited Lecture at NASA HPCESS (High Performance Computing in Earth System Sciences) July 2004: Climate model design and the Earth System Modeling Framework.

Practical Parallel Programming Mini-Course at the PICASSO Program, Princeton University: March 2004.

Project Report: **Sensitivity of Jet Latitude to the Surface Friction**

Principal Investigator: Gang Chen (Princeton graduate student)

Other Participating Researchers*:* Advisor: Isaac Held (GFDL)

NOAA's Goal #2 - Understanding Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:
This project aims to understand the climate sensitivity in the GCM with respect to physical parameters, more specifically, the surface friction.

Methods and Results/Accomplishments:
The variation of zonally symmetric component of the atmospheric circulation with the surface friction is studied in an idealized dry GCM (Held and Suarez 1994). As surface friction is reduced, 1) the zonal mean jet becomes stronger but baroclinic eddies becomes weaker (barotropic governor (James 1987)), and 2) the jet shifts poleward (Robinson 1997).

The surface friction can be split into friction on the zonal mean winds and eddies. The friction on the zonal mean is of primary importance for the shift of the jet. Even though in both cases the jet shifts poleward with decreasing friction, eddies behave in opposite ways. When the eddy friction is varied, the jet position agrees with basic idealized models of the Hadley cell and geostrophic turbulence, but no barotropic governor is observed. However, when the mean friction is varied, the barotropic governor is prominent, and the zonally averaged winds match rather well with the case when total friction is varied. Eliassen-Palm diagrams suggest that surface heat flux change plays an important role in producing the jet latitude shift.

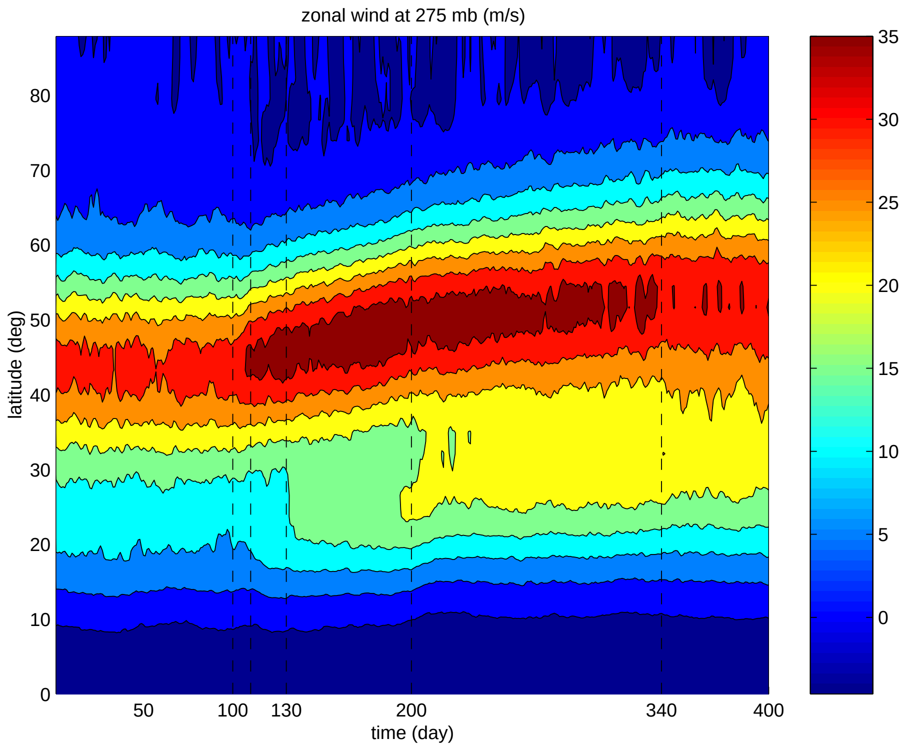
Ensemble experiments are carried out to study the transition from 1 day to 2 day friction. The zonal mean jet amplitude reaches its maximum in 10 days, but jet latitude and eddy strength continue adjusting for more than 100 days. Linear life cycle calculation with the zonal mean jet amplitude change can explain the weakening of barolinic eddies, yet the best explanation for the poleward shift remains obscure.

References

Held, Isaac M., Suarez, Max J. 1994: A Proposal for the Intercomparison of the Dynamical Cores of Atmospheric General Circulation Models. Bulletin of the American Meteorological Society: Vol. 75, No. 10, pp. 1825-1830

James, I. N. 1987: Suppression of Baroclinic Instability in Horizontally Sheared Flows. Journal of the Atmospheric Sciences: Vol. 44, No. 24, pp. 3710-3720.

Robinson, Walter A. 1997: Dissipation Dependence of the Jet Latitude. Journal of Climate: Vol. 10, No. 2, pp. 176-182.



The zonal mean wind shift to the instantaneous surface friction change. (Ensemble average of 10 experiments. The surface friction is reduced by half at day 100.)

Project Report: **Reevaluation and expansion of the idea put forward by Toggweiler and Samuels (1995, hereafter TS95) that the meridional overturning in the Atlantic is linearly proportional to the Southern Ocean (SO) winds.**

Principal Investigator: Agatha M. de Boer(Princeton)

Other Participating Researchers: J. Robert Toggweiler (GFDL)

NOAA's Goal # 2 – Understanding Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:
This project is a reevaluation and expansion of the idea put forward but Toggweiler and Samuels (1995, hereafter TS95) that the meridional overturning in the Atlantic is linearly proportional to the Southern Ocean (SO) winds. Their original result was based on a one basin ocean-only GCM in which the wind stresses south of 30 deg. S were systematically weakened and strengthened about their observed values. Although the idea that SO winds might have a strong influence on the Atlantic overturning is now widely accepted, it is not fully understood. TS95 attributed this response to the Ekman divergence south of the ACC and the conversion of this upwelled deep water into lighter thermocline water north of the ACC; more NADW is formed in the North Atlantic to replace the deep water converted into thermocline water around Antarctica. The answer is not that straightforward. Upwelled water can sink in other high latitude basins too or even in the relatively low latitude Deacon cell. Indeed, preliminary results with MOM3 suggested that the response of the ocean to SO winds is quite different when the model domain is expanded to two basins and forced by less restrictive boundary conditions. The objective is to address these questions.

Methods and Results/Accomplishments:
A suite of varying-wind experiments , using MOM4 coupled to an Energy Moisture Balance Model (EMBM), are being performed. The purpose is to investigate the influence of the SO winds on sinking in the three high latitude ocean basins of the North Atlantic, the Southern Ocean and the North Pacific. Specifically, we are testing the idea that there is a threshold for deep-water formation in each area of the ocean that is governed by basin geometry, the local freshwater forcing, and SO winds.

The ocean model consists of two basins (no Arctic) in an idealized geometry. The grid is 4 x 4 degrees in the horizontal and has 24 vertical levels. To initialize the run we used a horizontally homogeneous version of the Levitus data. The surface wind stress used is zonally averaged ECMWF Trenberth and Olson winds. The winds south of 40S were enhanced by a factor of 0.5, 1, 2 and 3. Several runs were performed to test the optimal processor configuration. Presentation of the Ekman layer (i.e., its thickness) was improved by manipulating the diffusivity and viscosity modules of the code.

An initial set of runs, in which the precipitation and evaporation to the ocean was fixed, has been completed. This override was done to ensure consistency with previous experiments. However, this type of run makes it impossible for the ocean to cool down or heat up by varying its latent heat of evaporation. A revised set of experiments, which uses the full EMBM (as is), is under way.

References:

Toggweiler and Samuels, 1995. Effect of Drake Passage in the global thermohaline circulation. *Deep-Sea Res. 42*, 477-500

Project Report: **Eddies in the Separated Western Boundary Current**

Principal Investigator: Baylor Fox-Kemper(Princeton, now at MIT)

Other Participating Researchers*:* Geoff Vallis (Princeton), Robert Hallberg (GFDL)

NOAA's Goal #2 - Understanding Climate Variability and Change to Enhance Society's Ability to Plan and Respond (50%) and,
NOAA's Goal #3 – Serve Society's Needs for Weather and Water Information (50%)

Objectives:

Fox-Kemper is working with Geoff Vallis (Princeton) and Bob Hallberg (GFDL) on roles of eddies in ocean gyres, with particular emphasis on the eddies located in the region of the separated boundary current dividing the subtropical and subpolar gyres**.** These eddies are intricately linked to the formation of MODE water, which is closely related to the decadal variability of the Subtropical and Subpolar gyres. The problem is approached both analytically and numerically.

Fox-Kemper's work furthers NOAA's goals 1) to Understand Climate Variability and Change to Enhance Society's Ability to 2) Plan and Respond and to Serve Society's Needs for Weather and Water Information equally by working toward improvements in ocean modeling technology and parameterization, as well as understanding some of the physical processes involved in ocean decadal variability.

Methods and Results/Accomplishments*:*

In the past year, useful models for studying the effects of eddies with low diapycnal diffusivity have been created.

The numerical model is a version of Hallberg's Isopycnal Model (HIM) used in an idealized domain with idealized buoyancy and wind forcing. This model, unlike a z-coordinate model, allows for accurate modeling with low interior diffusivity. The model initial conditions and forcing are carefully chosen in such a way that the resulting stratification is realistic, so that the results will be directly interpretable in models with realistic topography and forcing. The model is initialized at low resolution, then spun-up to steady-state. Then the resolution is increased, and then the model is spun-up again. This procedure is iterated a number of times until strong eddies are present. This process provides a range of near-equilibrium results with increasingly sharp features and increasingly energetic time-dependent eddies.

Determining the appropriate thermal boundary condition was a major challenge. Restoring boundary conditions were initially used, and test cases with different rates of restoring were calculated. While it was expected that the restoring rate would affect the steady circulation, it was found that it also strongly affects the strength of the eddies. Eddies were much stronger with weaker restoring. At the suggestion of the Modeling Eddies in the Southern Ocean (MESO group, R. Hallberg and A. Gnanadesikan, GFDL), a mixed flux and restoring boundary condition is now being used. This mixed boundary condition allows for the flow to be restored to the idealized climatological SST without undue damping of eddies. This forcing scheme is particularly effective when used with the bulk mixed-layer formulation of the Hallberg model.

A second major challenge in the model development was insuring that the model accurately and stably estimated the Coriolis terms in regions of strong outcropping. A solution was found that now seems to be working.

A pronounced effect of this low interior diffusivity is a double thermocline in the steady calculations. This confirms in a primitive equation model the Samelson-Vallis theory for a simpler planetary geostrophic model. At higher resolution, eddy fluxes begin to affect this thermocline structure. Their effects are not simple, however, sharpening fronts in some locations and weakening them in others. The implementation of appropriate diagnostics to understand these effects is ongoing.

The numerical model demonstrates a connection between formation of MODE water and the presence of resolved eddies. Modeling the creation of this geochemically-significant water mass was one of the initial goals of the project. There is little or no subtropical MODE water formation in the model in the coarse model with eddy parameterizations being used, but MODE water easily and robustly forms in the correct location and with the correct density when the model resolution produces strong eddies. The formation of the mode water is intimately related to both the eddy dynamics and the dynamics of the mixed layer. The analysis of these effects continues in collaboration with R. Ferrari (MIT).

An analytical model based on the Parsons-Veronis ocean model, but extended to include important effects of eddies has been developed, and shows promise in understanding the effects of eddies in the numerical model results. Currently, a mixed layer is being added to this analytical model as in Nurser and Williams.

Results from the numerical and analytical models were presented at the AGU Ocean Sciences Meeting, and at the Climate and Global Change Summer Institute.

Fox-Kemper has also extended his earlier work with Pedlosky (WHOI) on barotropic basin dynamics. Collaborations on the nature of eddies in the barotropic model continue with B. Nadiga (LANL), R. Ferrari and G. Flierl (MIT), and J. Franklin (MIT Center for Space Research). A number of publications on barotropic work from this year were submitted or appeared.

References:

Parsons, A. T.: 1969, A two-layer model of gulf stream separation. Journal of Fluid Mechanics, 39, 511-528.

Veronis, G.: 1973, Model of world ocean circulation. Part I: Wind-driven, two-layer. Journal of Marine Research, 31, 228-288.

Nurser, A.J.G. And R.G. Williams: 1990, Cooling Parsons Model of the Separated Gulf Stream, Journal of Physical Oceanography, 20(12), 1974-1979.

Publications:

Hallberg. R.W., and B. Fox-Kemper: On the Treatment of Coriolis Terms in Isopycnal-Coordinate Ocean Models, in preparation.

Fox-Kemper & G.K. Vallis: Jan.2004, The Roles of the Separated Western Boundary Current and its Eddies in the General Circulation. AGU 2004 Ocean Sciences Mtg, Portland, OR.

Fox-Kemper, B.: July 2004, Baby steps toward formulating an oceanic general circulation including strong, yet physical, eddies. 6th Summer Institute, NOAA Postdoctoral Program in Climate and Global Change, Steamboat Springs, CO.

Fox-Kemper, B.: 2004, Reevaluating the roles of eddies in multiple barotropic wind-driven gyres. Journal of Physical Oceanography, submitted.

Fox-Kemper, B. & J. Pedlosky: 2004, Wind-driven barotropic gyre I: Circulation control by eddy vorticity fluxes to an enhanced removal region. Journal of Marine Research, 62(2), 169-193.

Fox-Kemper, B.: 2004, Wind-driven barotropic gyre II: Effects of eddies and low interior viscosity. Journal of Marine Research, 62(2), 195-232.

Project Report: **Development of and Studies with an Intermediate Complexity Moist General Circulation Model**

Principal Investigator: Dargan M. Frierson (Princeton graduate student)

Other Participating Researchers: Advisor: Isaac Held(GFDL), Olivier Pauluis(Princeton, now NYU), Pablo Zurita-Gotor(UCAR)

NOAA's Goal #2 - Understand climate variability and change to enhance society's ability to plan and respond.

Objectives:
Frierson has recently completed the development of a simplified moist general circulation model (GCM) which is currently being used in a number of idealized modeling studies. We expect the model to play a central role in the hierarchy of atmospheric models under development at GFDL, used to connect simple theories to full GCM's. The climate phenomena we are studying with this model include the response of static stability and energy transports to increases in moisture content of the atmosphere, and the effect of different convection schemes on the Hadley circulation and the Madden-Julian Oscillation.

Methods and Results/Accomplishments:
The model development has consisted of setting boundary conditions (aquaplanet over a shallow mixed layer), developing a simplified grey radiation scheme, and simplifying the moist convection, surface flux, boundary layer scheme so that they retain only essential features and are describable by a small number of parameters. The model is designed to produce realistic circulations under a wide range of parameter regimes, while retaining maximal simplicity.

Frierson is currently using the model to investigate a variety of atmospheric problems. For example, to investigate the problem of changes in storm and eddy activity under global warming, he has been studying the response of the model to changes in meridional gradients in moisture and temperature, and to the mean moisture content of the atmosphere, focusing on changes in poleward energy transports. He is comparing models with and without convective parameterization schemes to examine how tropical moist convection maintains the stability of the atmosphere, and how they control the strength of the Hadley cell. An additional project involves studying the effect of convection scheme parameters, and the heat capacity of the ocean surface, on the Madden-Julian Oscillation behavior in the model. The model also promises to provide an ideal context for studying the existence and causes of "double ITCZ" behavior, a tendency that is one of the most significant sources of systematic error in the tropical simulations of many GCMs.

Project Report: **Dynamics of the North Atlantic Oscillation and Annular Modes**

Principal Investigator: Edwin Gerber(Princeton graduate student)

Other Participating Researchers: Princeton Advisor: Geoffrey Vallis, Benjamin Cash(COLA), Paul Kushner (GFDL, now U. Toronto)

NOAA's Goal #2 - Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:
To understanding the dynamics of the North Atlantic Oscillation and Annular Modes

Methods and Results/Accomplishments:
Gerber has developed a simple stochastic barotropic model of the North Atlantic Oscillation and annular mode. This work then inspired the construction of a stochastic process to capture the essential nature of the phenomenon. The process illustrates how continuity and the conservation of angular momentum naturally lead to meridional dipole patterns. Gerber used the stochastic process to develop an analytic two-dimensional model. This work provides a simple context for understanding the existence of annular modes, or zonally uniform patterns of variability, in systems where there are no zonally uniform motions.

Having contributed significantly to the understanding of the spatial structure of the annular modes, Gerber is now examining the factors that control the mode's persistence. In this study he is using a dry GCM with idealized forcing, and is currently studying how the persistence is altered when one changes model parameters. He is currently investigating the effect of simple gravity wave parameterizations in the stratosphere, and the effect zonal asymmetries in the forcing.

We work with a hiearchy of models to understand the statistical and dynamical features of extratropical low frequency variability (LFV). LFV refers to variability on length scales of 1,000 to 10,000 kilometers and timescales of 10 to 100 days. In particular, we are interested in the North Atlantic Ocsilliation (NAO) and annular modes, which are also refered to as the Arctic and Antarctic Oscillations (AO,AAO). Models of varying complexity allow us to isolate the processes that are important for the existence and maintanence of NAO and AO anomalies. A better dynamical understanding of such variability will help improve more state-of-the-art GCMs simulate and predict LFV. Ultimate benefits could include better seasonal forecasting, particularly in the Northern Hemisphere winter.

Our simplest models are analytic, stochastic systems that allow us to understand the spatial structure of the NAO and annular modes. At intermediate complexity, we've worked with a stochastically forced barotropic model that captures the first order spatial and temporal structure of both modes, further suggesting that that NAO and AO may the same phenomena. Our current focus is a systematic study with a primitive equation model, the GFDL dry dynamical core. We've found that the persistence of variability in the primitive equation model is very sensitive to horizontal and vertical resolution, particularly in the stratosphere. We are currently investigating the effect of simple gravity wave parameterizations in the stratosphere, and the effect zonal asymmetries in the forcing.

Publications:

G. K. Vallis, E. P. Gerber, P. J. Kushner, and B. A. Cash, 2004: A Mechanism and Simple Dynamical Model of the North Atlantic Oscillation and Annular Modes, Journal of Atmospheric Science, 61, 264-280

E. P. Gerber and G. K. Vallis, A Stochastic Model for the Spatial Structure of Annular Patterns of Variability and the North Atlantic Oscillation. *J. Climate* (in press)

Project Report: **Theories of the inverse energy cascade, and the stratification of the atmosphere**

Principal Investigator: Nedejda Grianik (Princeton graduate student)

Other Participating Researchers*:* Advisor: Geoffrey K. Vallis (Princeton)

NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:

Grianik is a graduate student in the AOS program working with Geoff Vallis, working on theories of the energy spectrum of large-scale eddies in planetary atmospheres and, more specifically, on theories of the inverse energy cascade.

Theories of two-dimensional turbulence suggest that eddy energy should cascade to larger scales than the radius of deformation, the dominant scale of the baroclinic instability, to the Rhines scale, at which the cascade will be halted by the effects of the planetary vorticity gradient. Previous studies have found that no extended cascade exists in the observed large-scale atmospheric turbulence. This was suggested to be due to the observed lack of scale separation between the Rossby deformation radius and the Rhines scale. Are there reasons that these two scales have to remain close to each other, or is an accident of sorts that our atmosphere is such that there 'is little separation between these two scales. Grianik's goal is to clarify this issue, and determine the conditions under which it is the possible to generate an inverse cascade.

Methods and Results/Accomplishments*:*

Grianik has developed a scaling theory which estimates the extent of the scale separation between the Rossby and Rhines scales. One of the predictions of this theory is that the Rossby and Rhines scales can be separated in the case when atmospheric flow breaks into multiple jets (as opposed to one-jet regime in each hemisphere which is current state of our atmosphere). Numerical experiments with the Held-Suarez idealized dry atmospheric model have confirmed that in some regions of multiple jet flows the Rossby and Rhines scales are separated. The effects of this separation on the inverse energy cascade in these regions is currently being studied.

Publications.

Grianik, N, Held, I, Smith, K.S. Vallis, G.K. 2004. The effects of nonlinear drag on the inverse cascade in two-dimensional turbulence. *Phys. Fluids* (in press).

Project Report: **Properties Of Natural Modes Of Oscillation Attributable To Tropical Ocean-Atmosphere Interactions**

Principal Investigator: Arno Hammann(Princeton graduate student)

Other Participating Researchers: Princeton Advisor, S. George H. Philander

NOAA's Goal #2 - Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:
To investigate the factors that determine the properties of natural modes of oscillation attributable to tropical ocean-atmosphere interactions. (Of special interest is an apparent change in the properties of El Nino in the late 1970's.)

Methods and Results/Accomplishments:
Earlier studies identified the intensity of the background zonal winds, and the depth of the equatorial thermocline as parameters with a strong influence on the period and propagation characteristics of the Southern Oscillation. Calculations with an intermediate coupled model, similar to that of Cane and Zebiak, indicate that the meridional and zonal structure of the background winds can also affect the natural modes and can change the class of eigenmodes that is preferentially excited. It is possible that differences in the convection parameterization schemes of much more complex general circulation models lead to differences in the location of wind anomalies with respect to SST anomalies, and hence to differences in the natural modes of the models. Attention is now turning to the seasonal cycle in low latitudes because it too involves natural modes and can be very different in different coupled ocean-atmosphere models.

Project Report: **Development of an experimental 4d assimilation and ENSO prediction system based on the latest MOM4 GFDL model**

Principal Investigator: Eli Tziperman (Harvard)

Other Participating Researchers: Part of a collaborative effort of GFDL, JPL and Harvard
Jake Gebbie **In collaboration with GFDL scientists:** Tony Rosati, Matt Harrison, Andrew Wittenberg, Shaoqing Zhang

NOAA's Goal #2 - Understanding Climate Variability and Change to Enhance Society's Ability to Plan and Respond (50%)
NOAA's Goal #3 - Serve Society's Needs for Weather and Water Information (50%)

Objectives:
The objective of this collaborative effort between GFDL, JPL and Harvard is to develop an adjoint for the latest version of MOM4, build a four dimensional variational data assimilation system based on this adjoint, and apply it to the ENSO prediction problem.

Methods and Results/Accomplishments
Significant progress was achieved during the past year since we started the project. We have recruited Geoffrey (Jake) Gebbie to work at Harvard on this project. Jake has been a student with Carl Wunsch at MIT and has significant experience in adjoint model development. We have been in close contact with the GFDL scientists involved in this project (Tony Rosati, Matt Harrison, Andrew Wittenberg and Shaoqing Zhang), and have together devised a plan for dividing the work into three main parts:

1. Derivation of a tangent linear model using the adjoint compiler
2. Derivation of the adjoint itself
3. Parallelizing the adjoint for optimal performance on parallel computers.

These three different parts of the work will be carried out by GFDL, Harvard, and JPL, correspondingly. Some of the work on these stages can be done in parallel, and stage (1) at GFDL is close to being completed, while some good progress was achieved on (2) at Harvard. We expect stage (3) to start in JPL this year, once sufficient progress is made on (2).

A preliminary adjoint was so far derived for a MOM4 configuration without the physics options (i.e. without mixing parameterizations). The adjoint is derived using the TAF adjoint compiler, and the main work of dealing with "recomputation" and "storage" directives is still ahead of us. This involves adding comments to the MOM4 code that will be interpreted by the adjoint compiler and direct it when to store a forward model variable in order to use it in the adjoint run, and when to recompute it during the adjoint run. These directives will eventually find their way into the MOM4 CVS code for easy use by the wider community. The plan is to proceed to develop the adjoint of a global tri-polar grid model with all state-of-the-art mixing parameterizations. The adjoint will be of this MOM4 configuration coupled to a statistical atmospheric model which will be appropriate for ENSO studies Harrison et al. (2002).

We have just met with Tony, Matt, Andrew and Shaoqing in Cambridge a few weeks ago, and had a chance to refine our future plans. We are all optimistic that these efforts will lead to a working adjoint model for GFDL's MOM4, and later to a working data 4dvar assimilation system based on the adjoint method. We are looking forward to the eventual application, on a time scale of 3-4 years, of the developed assimilation system to the ENSO prediction problem using a full-fledged MOM4 version at a 1 degree resolution (and a higher resolution near the tropics).

We have been involved with the work on the MOM adjoint for some 7 years now, beginning with the development by Eli Galanti of an adjoint of an early MOM4 version, and his sensitivity studies and ENSO prediction experiments which lead to several papers and to the current work we are doing on the latest MOM4 Galanti and Tziperman (2003); Galanti et al. (2002a,b). With the current level of commitment from the involved GFDL scientists, with the support of the MOM4 developers, and given our strong collaboration, we are confident that we should be able to achieve our fairly ambitious goals in this project.

References:

Galanti, E. and Tziperman, E. (2003). A mid-latitude enso teleconnection mechanism via baroclinically unstable long rossby waves. *J. Phys. Oceanogr.*, in press, http://www.weizmann.ac.il/home/eli/reprints/.

Galanti, E., Tziperman, E., Harrison, M., Rosati, A., Giering, R., and Sirkes, Z. (2002a). The equatorial thermocline outcropping -a seasonal control on the tropical Pacific ocean-atmosphere instability strength. *J. Climate*, 15(19):2721–2739.

Galanti, E., Tziperman, E., Harrison, M., Rosati, A., and Sirkes, Z. (2002b). A study of enso prediction using a hybrid-coupled model and the adjoint method for data assimilation. *Mon. Weath. Rev.*, submitted, http://www.weizmann.ac.il/home/eli/reprints/.

Harrison, M. J., Rosati, A., Soden, B. J., Galanti, E., and Tziperman, E. (2002). An evaluation of air-sea flux products for enso simulation and prediction. *Monthly Weather Review*, 130(3):723–732.

Project Report: **Investigation on climatic sensitivity**

Principal Investigator: Yi Huang (Princeton graduate student)

Other Participating Researchers: Advisor: V. Ramaswamy(GFDL), Brian Soden (GFDL, now at the University of Miami), Dan Schwarzkopf (GFDL)

NOAA's Goal # 2 – Understanding Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:

This is an investigation on the climatic sensitivity. Specifically we have looked at the effect of greenhouse gases on the Outgoing Longwave Radiation(OLR), its change due to the variation of different gas constituents. It is also an examination of the GCM radiative transfer(RT) code in the context of radiative adjoints by comparing it to the benchmark line-by-line(LBL) code.

Methods and Results:

The method employed in our study is numerical simulation. The clear-sky OLR transfer process under the Plane-Parallel Atmosphere assumption was simulated with two different codes used at GFDL, slantv(a LBL code) and fms standalone code(a simplified model). Some of the results have been compared with published works as a means of verification. And the LBL computation was later on used as benchmark to test the results of the GCM RT code.

Here we present 3 principle results:

1. The contribution to OLR or Greenhouse Effect(G) by each gas constituents and by multi-gases as a whole.

It is very meaningful to answer how much each gas constituent contributes to the OLR, as studied by [Kiehl&Trenberth 1997] with a narrowband model. We used a more accurate LBL model and the Mid-Latitude Summer(MLS) profile to study the relative importance of different gas constituents. Here we show an example of the study of two most important gases: water vapor and carbon dioxide.

Table 1. OLR at surface and TOA, as well as G

Gas(es) Unit: W m-2	flux_sfc	flux_TOA	G
H2O	422.8	314.4	108.4
CO2	422.8	379.5	43.4
H2O+CO2	422.8	285.3	137.6

So the G contribution by H2O, CO2 and the overlap of the two gases are attributed to 94.2, 29.2 and 14.2 respectively.

More importantly, by looking into the spectral difference of OLR caused by adding or removing a gas to/from the ensemble. The contribution can be quantified to each specific spectral region.

2. A test of the accuracy of transmission multiplication assumption employed in band model.

In band models, band transmission functions are constructed by simply multiplying the transmission of each absorbing gas. This could introduce errors if the absorption lines of different gases are not strictly as assumed non-correlated. Here we constructed a pair of narrowband transmission functions in two ways: by considering all the lines at the same time and by multiplying the transmissions of each gas. Both transmission functions are used to compute the OLR at the top of the atmosphere(TOA). The comparison shows a less than 1% discrepancy of OLR. But if we look at the difference spectrally, in certain spectral region, the discrepancy could be larger than 5%.

3. OLR sensitivity to temperature and water vapor perturbation, and the comparison between LBL model and band model.

By numerical modeling, the change of OLR due to the concentration variation of different gas constituents has been investigated from a spectral angle. For example, we find the sensitivity of spectral OLR at TOA to the variation of layerly water vapor perturbation, which is similar to the result of [Shine&Sinha 1991]). The longwave radiative effect of water vapor perturbation on climate comes from two primary sources: the lower troposphere through continuum absorption in window region and the middle and upper troposphere through absorption in rotation bands. For tropical atmosphere, the continuum absorption in the lower troposphere is dominant while for MLS and MLW atmospheres, where the water vapor is much lesser in the lower troposphere, the continuum effect fades out and absorption in rotation band dominates. It shows lesser sensitivity in viberation-rotation band in spite of the strong absorption there.

References:

1) Kiehl, J.T. and K.E. Trenberth, 1997, Earth's annual global mean energy budget, Bull. Ameri. Meteorol. Soc., 78, 197-208

2) Shine, K.P. and Sinha. A., 1991, Sensitivity of the Earth's climate to height-dependent changes in the water vapor mixing ratio, Nature, 354, 382-384

Project Report: **Development of Haine's Irminger Sea/Denmark Strait Regional Ocean Circulation Model And Data Assimilation System**

Principal Investigators: Thomas Haine(John Hopkins University)

Other participating researchers*:* Steve Griffies, Robert Hallberg, Tony Rosati, Matt Harrison (all GFDL)

NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Overview.
This collaboration formally began in June 2004 and was still at an early stage by the end of the reporting period. The PI, Prof. Haine, visited GFDL on 2 occasions for a total of 6 days to (i) discuss his high resolution numerical ocean circulation model of the Irminger Sea and Denmark Strait, with associated variational data assimilation capability, and (ii) participate in the CLIVAR workshop on IPCC-class ocean GCMs. No specific new results had been attained by the end of June 2004.

Objectives and Accomplishments.
Following discussion with Steve Griffies, Bob Hallberg, Tony Rosati, and Matt Harrison, the PI made detailed plans for a series of numerical experiments to investigate oceanic overflow, entrainment, and mixing using O(1)km resolution regional circulation models of the Denmark Strait and environs. Study of this area using realistic models links well with the idealized experiments of Legg et al (2004) performed recently at GFDL. There are strong links to the NSF-funded project
"Gravity Current Entrainment CPT" led by Sonya Legg of GFDL. The specific advantages of the present project are:
(i) The model should have sufficiently-high resolution to accurately simulate Denmark Strait throughflow and entrainment, plus southward flow on the east Greenland Shelf (based on Legg et al, 2004), (ii) The PI is a participant in oceanographic expeditions to this area and so has first hand knowledge of the extant observational data base, and, (iii) The PI's model has a variational data assimilation capability that can be used to synthesize the high-accuracy regional model with the available real measurements. During the reporting period the PI began to configure the numerical experiments involved. There are no substantial new results by the end of the reporting period.

References.
S. Legg, R. W. Hallberg and J. B. Girton, Comparison of entrainment in overflows simulated by z-coordinate, isopycnal and nonhydrostatic models, Ocean Modelling, submitted, 2004.

Publications.
None (as yet).

Project Report: **Observing Network Design For Improved Prediction Of Geophysical Fluid Flows - Analysis Of Ensemble Methods**

Principal Investigator: Shree P. Khare(Princeton graduate student)

Other Participating Researchers: Advisor: Jeffrey L. Anderson (NCAR)

NOAA's Goal # 3 - Serve Society's needs for weather and water information.

Objectives:
To perform research regarding the design of observational networks for improved prediction of geophysical fluid flows.

Methods and Results/Accomplishments:
The topic of research is the design of observing networks, both adaptive and routine. For routine observing network design, the spatial configuration of the observations is fixed in time. Khare has worked on the development of algorithms to determine the optimal spatial configuration of routine observational networks for improved numerical weather prediction. Observing System Simulation Experiments (OSSEs) provide one framework where the value of many different spatial configurations of a network can be determined. For realistic prediction models, the computational expense associated with OSSEs limits the use of sophisticated optimization tools which require many evaluations of the objective function. A retrospective analysis of forecasts generated from an ensemble prediction system, can be used to define an objective function appropriate for optimizing a routine network. This methodology, called the Retrospective Design Algorithm (RDA), does not require repeated integrations of the prediction model equations and therefore offers significant cost advantages over OSSEs. The underlying theory and computational scaling of the algorithm has been thoroughly investigated. The statistical and dynamical significance of the algorithm has been shown using examples in the the Lorenz 1996 model. Results which demonstrate the utility of the RDA have also been generated in a Held-Suarez configuration of a dry low-resolution atmospheric GCM for a variety of network design problems. The numerical results suggest that the RDA is appropriate for designing networks in real prediction systems.

Adaptive observations methodologies attempt to identify locations of observations at future times which will most improve subsequent weather forecasts. Working in an ensemble filter data assimilation environment, Khare has developed a new Bayesian framework for solutions to the adaptive observations problem. Using a series of OSSEs in the nonlinear Lorenz 1996 model, a fundamental understanding of the approximation which underlies the Bayesian technique has been developed. The results demonstrate that a "covariance localization scheme", appropriate for updating state variables at a given time with observations valid for different times, is the key to realizing the full benefits of ensemble based adaptive observation schemes. The ratio of the ensemble size to state space size in operational systems is orders of magnitude smaller than the ratio used in this study. The results in this work then suggest that when implementing ensemble based targeting schemes in operational systems, the detrimental impact of not accounting for spurious correlations that arise between forecast ensembles valid at different times is potentially large.

A number of novel adaptive observing schemes which do not require explicit or implicit evolution of conditional covariance from the targeting time to verification time have also been derived. A thorough investigation concerning the impact of non-linear evolution of covariance on adaptive observations schemes has been undertaken in the Lorenz 1996 model.

Publications:

Khare, S. P. and J. L. Anderson, 2004: "A Bayesian Framework for Adaptive Observing Network Design:an Analysis of Deterministic Ensemble Square Root Filter Implementations". In review with Monthly Weather Review.

Project Report: **Continental Liquid-Water Cloud Variability and its Parameterization using ARM Data**

Principal Investigator: Byung-Gon Kim(Princeton)

Other Participating Researchers: Stephen Klein(GFDL, now at Atmospheric Science Division, Lawrence Livermore National Laboratory), Joel Norris (Scripps Institution of Oceanography)

NOAA's Goal #2- Understanding climate variability and change to enhance society's ability to plan and respond.

Objectives:
Cloud parameterizations in global atmospheric models have been recognized for decades as a large source of uncertainty in predicting climate change (Arakawa, 1975; Charney, 1979; Houghton et al., 2001). Despite some significant progress, problems still remain. For instance, variability in cloud properties at scales smaller than those resolved by large-scale models may cause significant biases because processes such as cloud microphysics and radiation are non-linear and model calculations do not generally take this into account. Therefore we performed an analysis of subgrid-scale variability of continental liquid-water cloud using Atmospheric Radiation Measurement (ARM) data for the case of an overcast low-level stratus cloud from 1999 to 2001. The goal of this work is to provide the characterization of inhomogeneity in cloud properties, such as cloud base, top, thickness, and liquid water path, and compare parameterized cloud variability with the statistical cloud scheme being developed for the GFDL GCM.

Methods and Accomplishments/Results:
Data from many retrievals is being used including liquid water path (LWP) from the microwave radiometer (MWR), cloud boundaries from actively remote sensed cloud location (ARSCL), best estimates of the millimeter wavelength cloud radar (MMCR), the Belfort ceilometer and the micro pulse lidar. Atmospheric vertical sounding is obtained by the Balloon-Borne Sounding System. Accordingly, cloud geometric depth is the difference between the ARSCL-derived cloud top height and the laser ceilometer-derived cloud base height. The chosen episodes correspond generally but not exclusively with well-mixed boundary layers.

The most favorable cloud type for our purposes is an overcast, liquid water cloud without interference from higher-level ice clouds. Higher-level ice clouds were excluded due to their greater complexity. Since the selected cases have cloud temperatures above 273K most of the time, the clouds can be regarded as liquid-phase only. For simplification, this study considers only single layered clouds and not overlapped or multi-layered clouds. Suitable conditions are carefully selected by subjective examination of time series of retrieved cloud layers at SGP during 1999-2001.

Because the raw data includes large-scale mean temporal variability in addition to advected spatial variability, the subject of this study, time series for each parameter such as cloud boundaries, thickness, and LWP were detrended by subtracting 30-minute running averages. An examination of satellite data for 3 of the selected days indicates that thirty minutes is the longest timescale for which temporal variability at a single point corresponds primarily to spatial variability advected over the site in all cases. For an average horizontal wind speed of 10 m s^{-1}, the spatial scales examined in this study are limited to less than around 20 km. Because of the temporal resolution of the data (~ 20 s), the smallest scales examined are about 200m. Thus the variability studied herein corresponds to spatial scales varying from the larger turbulent scales to the smaller mesoscale.

Through the detailed analyses, several interesting conclusions have arisen. First, variability in cloud top is almost comparable to that of cloud base, which is somewhat different from previous model assumption that cloud top should be flat (Considine et al., 1997). For LWP, most skewness values are positive with a slight tendency for larger LWP dispersion accompanying larger skewness. This is expected for a quantity that is bounded by zero on the low side. Nonetheless it would not be a great error to assume that most LWP probability distribution functions (PDFs) are nearly symmetric. Symmetric PDFs appear to be characteristic of overcast cloud fields (Considine et al., 1997).

We examined the degree of adiabacity through the relationship between LWP and cloud thickness. In order to quantify adiabacity, the adiabatic LWP can be defined on the basis of LWC linearly increasing with height above the cloud base. Figure 1 displays scatter plots of LWP versus cloud thickness for days with ceilometer data. Note that the data have been fitted to the equation LWP=αh^{γ}, and the x- and y-axes have decimal logarithm scales. Cloud LWP exhibits a roughly linear dependence on cloud thickness but with slopes that vary from day to day (~0.5 - 3.5). It is interesting to note that the episode-average of each slope appears to be around 1.2 although the slope for an adiabatic cloud is 2. The relatively high correlation coefficients demonstrate that LWP variability is closely related to cloud thickness variability. Notably most continental cloud could appear to be sub-adiabatic, possibly attributed to drizzle and entrainment. Additionally cloud LWP seemed to be almost linearly proportional to cloud depth.

In addition to simple scaling relationships for variability of LWP and cloud thickness, it is worthwhile examining the role of larger-scale meteorological processes. We investigated the relationship of cloud variability to the thermodynamic structure and wind fields measured by the available soundings. The relationship of cloud variability to the Brünt-Väisälä frequency N^2 (= $(g/\theta)\partial\theta/\partial z$) and the vertical wind shear W (= $\partial|\vec{u}|/\partial z$) in the cloud layer are of particular interest and scatter plots are shown in Figure 2. N^2 and W are calculated using the difference in θ and $|\vec{u}|$ between cloud base and cloud top.

Variability in cloud LWP exhibits significant negative correlation (r = -0.79) with N^2 for the layer from cloud base to cloud top; stronger static stability is associated with decreased cloud variability. The association of stronger stability with lower LWP variability suggests that the suppression of turbulence in the inversion by the vertical static stability reduces cloud variability. However, this hypothesis is contradicted by the negative correlation between LWP and W; the higher vertical wind shear, the lower spatial variability in LWP. This compensation causes the Richardson number Ri, a variable widely used to indicate the potential for mixing (defined as N^2 divided by W^2), to exhibit a relatively weak positive correlation with the σ_{lwp}. Variability in cloud thickness is also negatively correlated with the static stability (r = -0.54), suggesting that the stability of the inversion limits the extent to which turbulent eddies penetrate the inversion. It is interesting to note that the association of static stability with that of the inversion layer is implied by the even larger correlation (r = -0.85) between the variability in LWP and N^2 as measured from inversion base to cloud top. Eventually variability in cloud LWP exhibited significant anti-correlation with the thermal stability; stronger stability appears to decrease the variability of cloud.

Using a linear relationship of cloud depth to LWP, empirical probability distribution function (PDF) for LWP is proposed and also compared with a modified Considine's PDF using the sub-adiabatic rate of liquid water content increase with height. The proposed PDFs agree well with the observed one (Figure 3). This means that scaling the standard deviation of LWP by that of the cloud thickness is effective for explaining the spread in LWP. Additionally the model predicts a quasi-normal distribution to liquid water, consistent with Considine et al. (1997) and Wood and Taylor (2001) for overcast conditions.

References:

Arakawa, A., Modeling clouds and cloud processes for use in climate models. *The physical basis of climate and climate modeling,* GARP Publication series, Vol 16, ICU/WMO, 181-197, 1975.

Charney, J.G., *Carbon dioxide and climates; A scientific assessment*, National Academy Press, 33pp, 1979.

Considine, G., J.A., Curry, and B. Wielicki, Modeling cloud fraction and horizontal variability in marine boundary layer clouds, *J. Geophys. Res.*, 102, 13517-13525, 1997.

Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson, *Climate Change 2001: The Scientific Basis*, Cambridge University Press, 881pp, 2001.

Wood, R., and J. Taylor, Liquid water path variability in unbroken marine stratocumulus cloud, *Quart. J. Roy. Meteor. Soc.*, 127, 2635-2662, 2001.

Publications:

The following work has been also submitted to Journal of Geophysical Research and now in revision.

Kim, B.G., S.A., Klein, and J.R. Norris, 2004: Variability of continental liquid-water cloud and its parameterization using ARM data.

Project Report: **Evaluation of GFDL Single Column Model (SCM) results with the ARM microbase Value Added Products (VAPs)**

Principal Investigator: Byung-Gon Kim(Princeton)

Other Participating Researchers: Stephen Klein -(GFDL, now at Atmospheric Science Division, Lawrence Livermore National Laboratory), Mark Miller (Brookhaven National Laboratory), Gerald Mace (University of Utah)

NOAA's Goal #2- Understanding climate variability and change to enhance society's ability to plan and respond.

Objectives

The sophistication of cloud models in global circulation model (GCM) has increased dramatically over the last several decades. For latest improvements to be completely realized, however, model development must be followed by appropriate advancement of validation procedures to include more quantitative and strict assessments of model performances. Meanwhile a relatively inexpensive and computationally efficient model-evaluation method is the use of so-called single-column model (SCM). The SCM contains all of the physical parameterizations of the GCM but can be forced with observations to simulate observed events. Such procedures require the much wider set of detailed observations of the evolving cloud state, which could be provided by the ARM program, in comparison with the past in-situ measurement campaigns which have provided simultaneous observations usually over a rather short period of time. The activity of the ARM program (Stokes and Schwartz, 1994) collecting quasi-continuous data related to clouds at a single point is suitable for SCM studies.

In this project, one-month (March of 2000) of measurements over the ARM Southern Great Plain (SGP) site are used to evaluate treatment of clouds in the single cloud model which uses the same parameterization as are in the GFDL climate model. This study is supposed to expand the analysis period to one full year continuously in cooperation with Dr. Mace's group of University of Utah.

Methods

In the SCM, clouds are parameterized with separate prognostic variables for the liquid and ice specific humidities. The cloud fraction is also treated as a prognostic variable of the model following the parameterization of Tiedtke (1993). Cloud microphysics is parameterized according to Rotstayn (1997) with an updated treatment of mixed phase clouds (Rotstayn et al. 2000). Additionally, fluxes of large-scale rain and snow are diagnosed and amount of precipitation flux inside and outside of clouds is tracked separately (Jakob and Klein 2000). The SCM is forced with the variational forcing from Zhang et al. (2000). To avoid drift of SCM, a series of 36 h forecasts are made starting at 00Z each day. The data analyzed consist of the 12 to 36 forecast from each forecast.

To reduce comparison issues of single point of the ARM site to GCM grid box, the observations and the model are averaged in time to 3 h. Liquid and ice water equivalent reflectivities (Z) from the radar are first translated into liquid and ice water content (LWC and IWC), using given

LWC-Z and IWC-Z relationships. Because the radar data have much finer vertical grids than the model, the radar data are averaged into the vertical grid (24 levels) of the SCM to facilitate the comparisons. The radar reflectivity is assumed to be temperature-dependent weighted fractions of the liquid and ice water reflectivities.

The preliminary results demonstrate that the model cloud fractions correspond well with radar observations, however model clouds persist slightly longer than observations (Figure 4). Comparison of SCM total cloud to that of the observation indicates binary representation of total cloud fraction relative to partial cloud fraction of the observation.

In general, there seems to be some discrepancy in the lower cloud boundary; most of the observed cloud base touches the ground, which differs from that of SCM. The issue is that the cloud base from ceilometer is not currently available in the VAPs. Especially on 2 March when the distinctive frontal cloud system passed over the SGP site, SCM apparently overpredicts the upper-layer cloud occurrence. Additionally SCM predicts the persistent cloud relative to the observation on 8 March when a clear period was observed.

Figure 5 indicates the vertical profiles of temporally averaged cloud fraction and ice water content. The clear sky coverage by precipitation predicted by the SCM (Jakob and Klein, 2000) is introduced to compare with cloud fraction of the VAPs. By including the clear sky coverage by precipitation, the correlation ($r = 0.7 \sim 0.8$) of cloud fraction significantly improves below 2 km relative to considering cloud only. Notably the IWCs of the model and observations demonstrate remarkably good agreement with the better correlation around 5 km above the ground layer (AGL).

As a whole, comparisons of model products with relevant observations demonstrate the model to be successful in producing the gross features of the cloud. The cloud fraction and IWC simulated by SCM are overally well correspondent with the observations, but the evaluation of LWC is not significant because of substantial biases of LWC during the strong precipitation.

This study is a preliminary report of fruitful interactions among the modeling group and observation group, but still having a couple of problems in both sides. This work will thus expand the analysis period to one full year of 2000 continuously using the revised model outputs and improved VAPs data sets in cooperation with the existing ISCCP simulator.

References:

Jakob, C., and S.A. Klein, A parameterization of the effects of cloud and precipitation overlap for use in general circulation models. *Quart. J. Roy. Meteor. Soc.,*126, 2525-2544, 2000.

Rotstayn, L.D., A physically based scheme for the treatmentof stratiform precipitation in large-scale models. I: Description and evaluation of the microphysical processes. *Quart. J. Roy. Meteor. Soc.,* 123, 1227-1282, 1997.

Rotstayn, L.D., B.F. Ryan, and J. Katzfey, A scheme for calculation of the liquid fraction in mixed-phase clouds in large-scale models, *Mon. Wea. Rev.,*128, 1070-1088, 2000.

Stokes, G.M., and S.E. Schwartz, The Atmospheric Radiation Measurement (ARM) Program: Programmatic background and design of the cloud and radiation testbed, *Bull. Am. Meteorol. Soc., 75,* 1201-1221, 1994.

Tiedtke, M., Representation of clouds in large-scale models, *Mon. Wea. Rev.,* 121, 3040-3061, 1993.
Zhang, M.H., J.L. Lin, R.T. Cederwall, J.J. Yio, and S.C. Xie, Objective analysis of ARM IOP data: Method and sensitivity, *Mon. Wea. Rev.,*129,295-311, 2000.

Presentations

Two poster presentations of these works by Byung-Gon Kim were given to the Atmospheric Radiation Measurement Science Team Meeting, Albuquerque, NM in March 2004. These reports are entitled:

Kim, B.G., S.A., Klein, and J.R. Norris, 2004: Variability of continental liquid-water cloud and its parameterization using ARM data, In *Proceedings of the 14th Atmospheric Radiation Measurement Science Team Meeting*, Department of Energy, Albuquerque, NM.
Kim, B.G., S.A. Klein, M.A. Miller, and K.E., Johnson, 2004: Comparison of single cloud model results for March of 2000 to the prototype ARM microbase value added products, In *Proceedings of the 14th Atmospheric Radiation Measurement Science Team Meeting*, Department of Energy, Albuquerque, NM.

Publications

Kim, B.G., S.E. Schwartz, M.A. Miller, and Q. Min, 2003: Effective radius of cloud droplets by ground-based remote sensing: Relationship to aerosol, *J. Geophys. Res.,* 108(D23), 4740, doi:10.1029/2003JD003721.

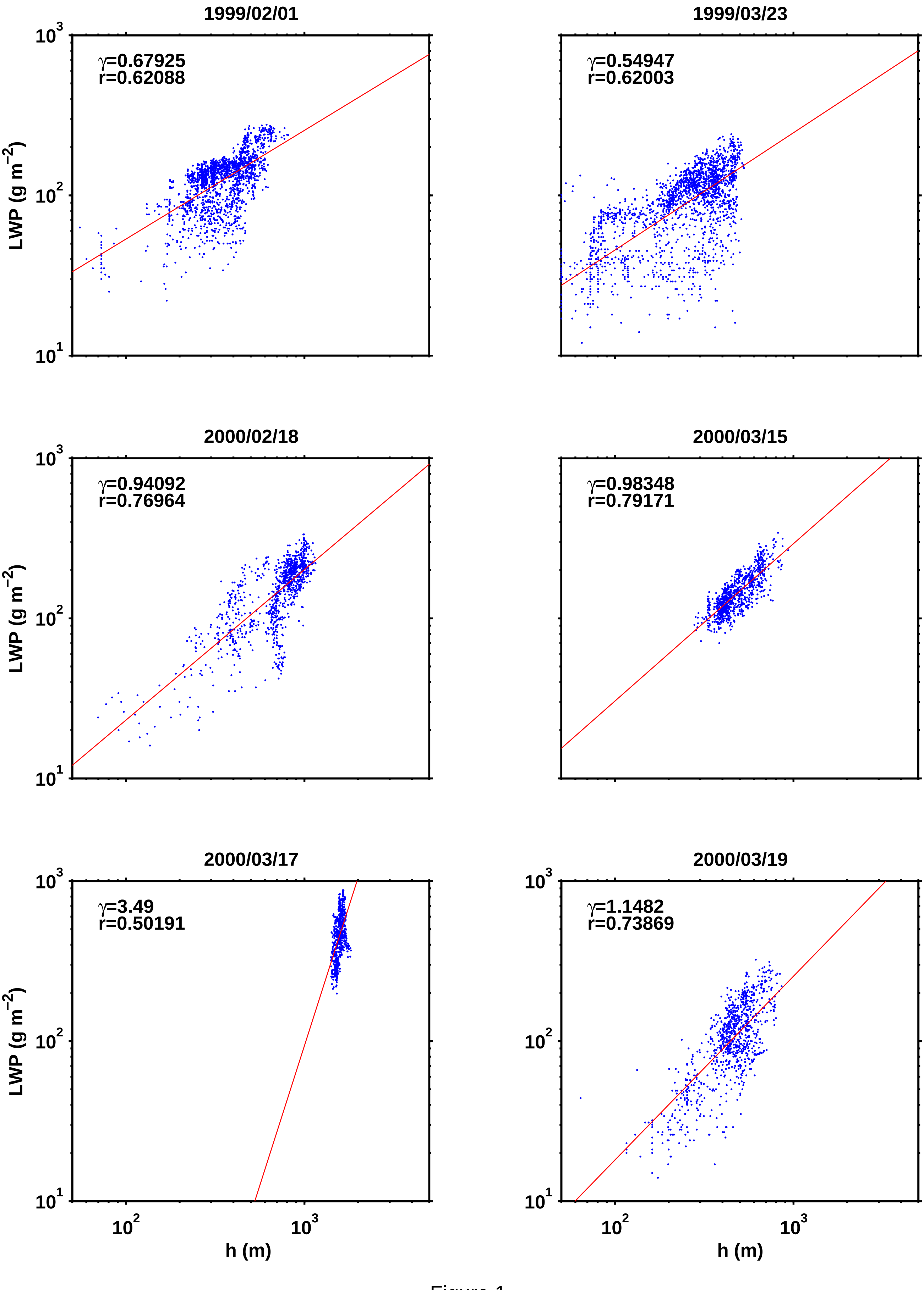

1999/02/01
γ=0.67925
r=0.62088
1999/03/23
γ=0.54947
r=0.62003
2000/02/18
γ=0.94092
r=0.76964
2000/03/15
γ=0.98348
r=0.79171
2000/03/17
γ=3.49
r=0.50191
2000/03/19
γ=1.1482
r=0.73869
LWP (g m⁻²)
h (m)

Figure 1.

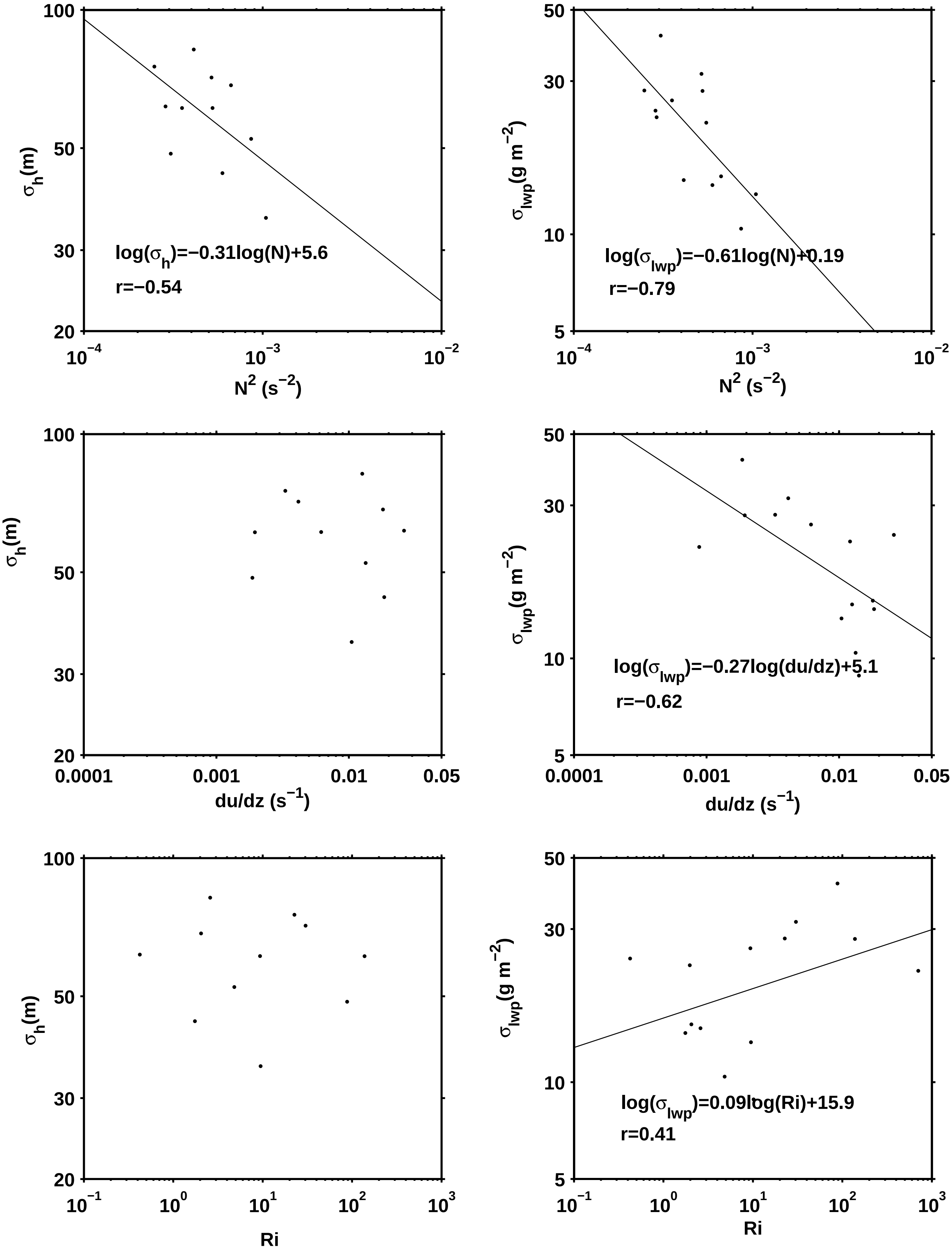

log(σh)=−0.31log(N)+5.6
r=−0.54
σh(m)
N2 (s−2)
log(σlwp)=−0.61log(N)+0.19
r=−0.79
σlwp(g m−2)
N2 (s−2)
σh(m)
du/dz (s−1)
log(σlwp)=−0.27log(du/dz)+5.1
r=−0.62
σlwp(g m−2)
du/dz (s−1)
σh(m)
Ri
log(σlwp)=0.09log(Ri)+15.9
r=0.41
σlwp(g m−2)
Ri

Figure 2

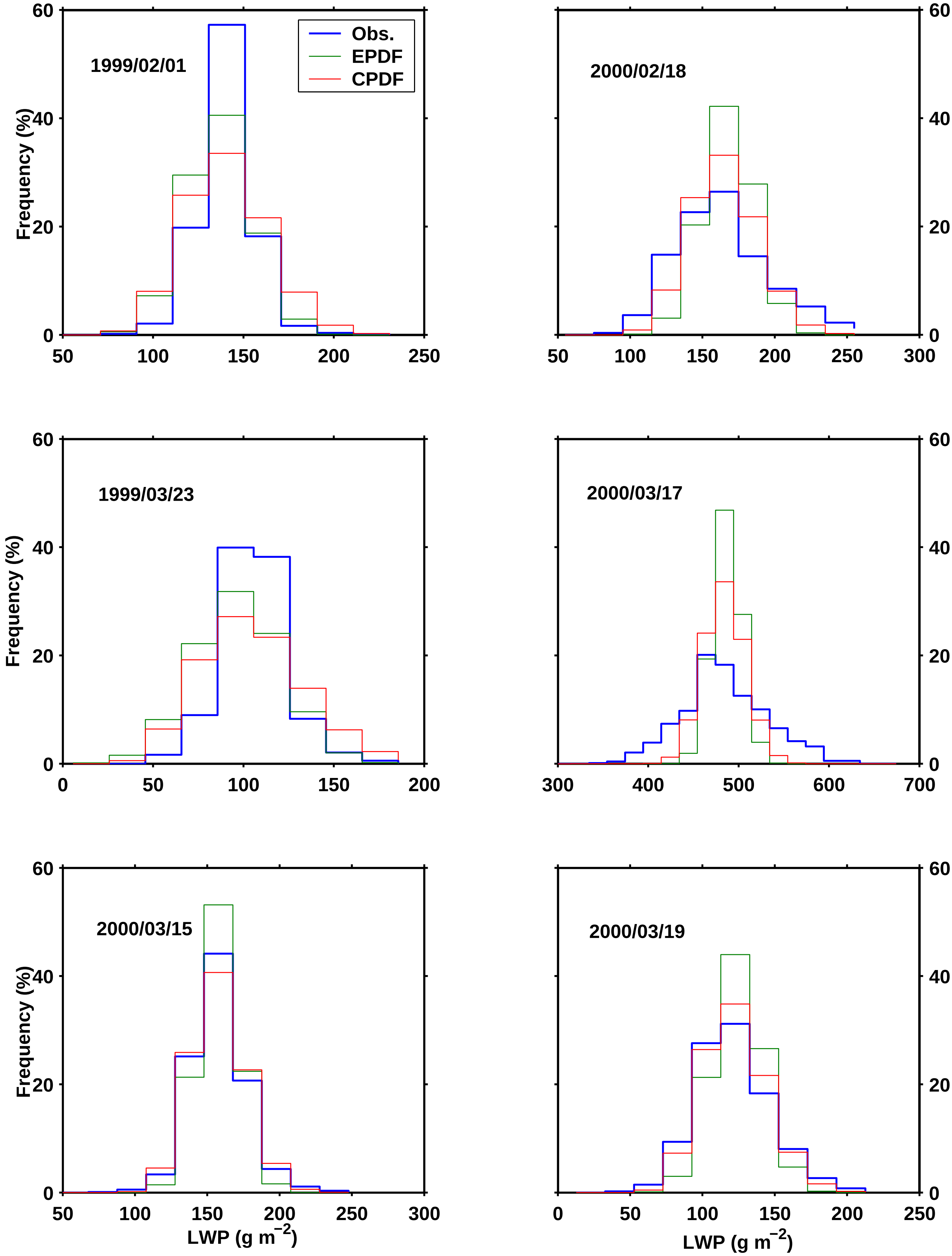

Obs.
EPDF
CPDF
1999/02/01
2000/02/18
1999/03/23
2000/03/17
2000/03/15
2000/03/19
Frequency (%)
LWP (g m^{-2})

Figure 3.

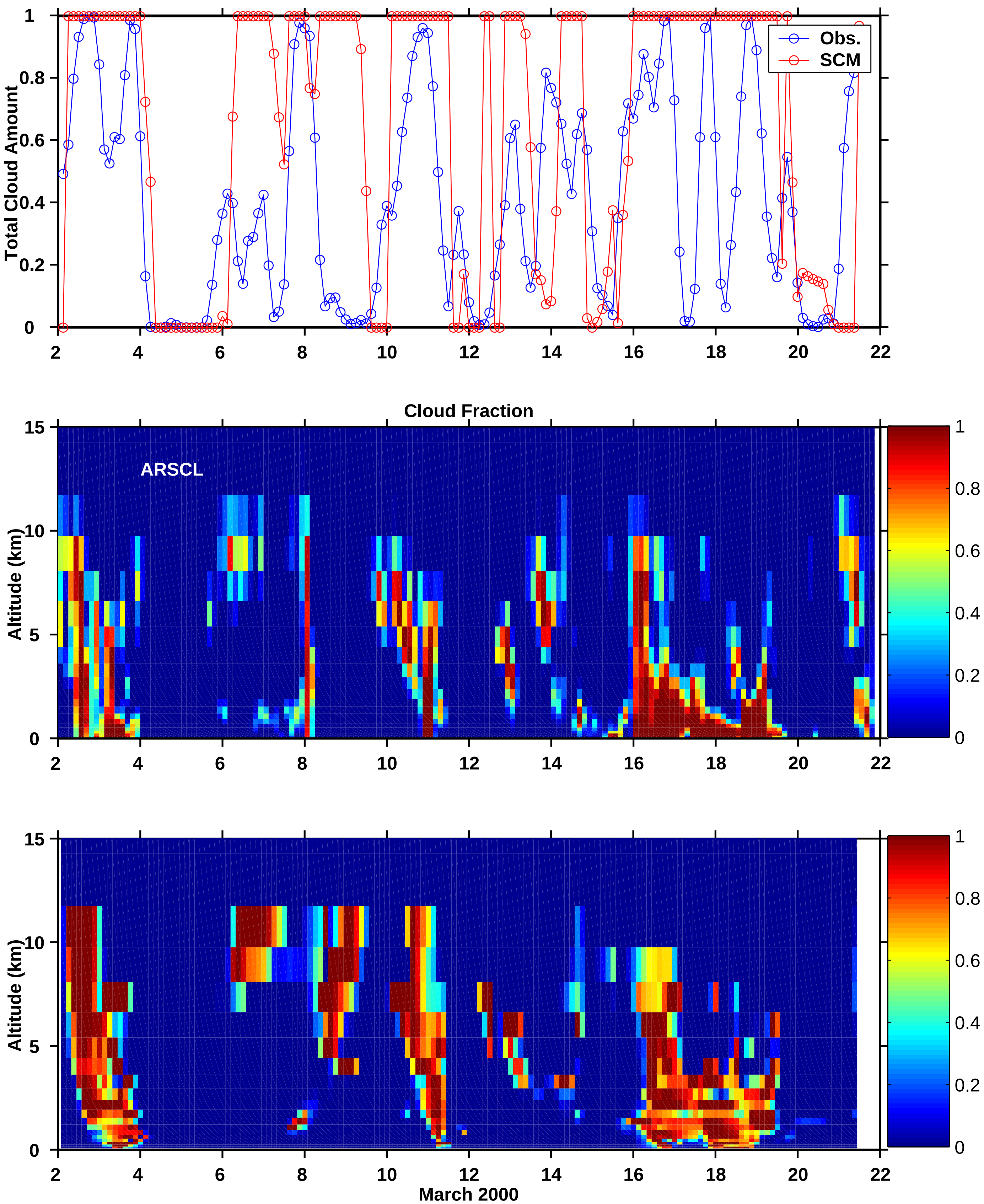
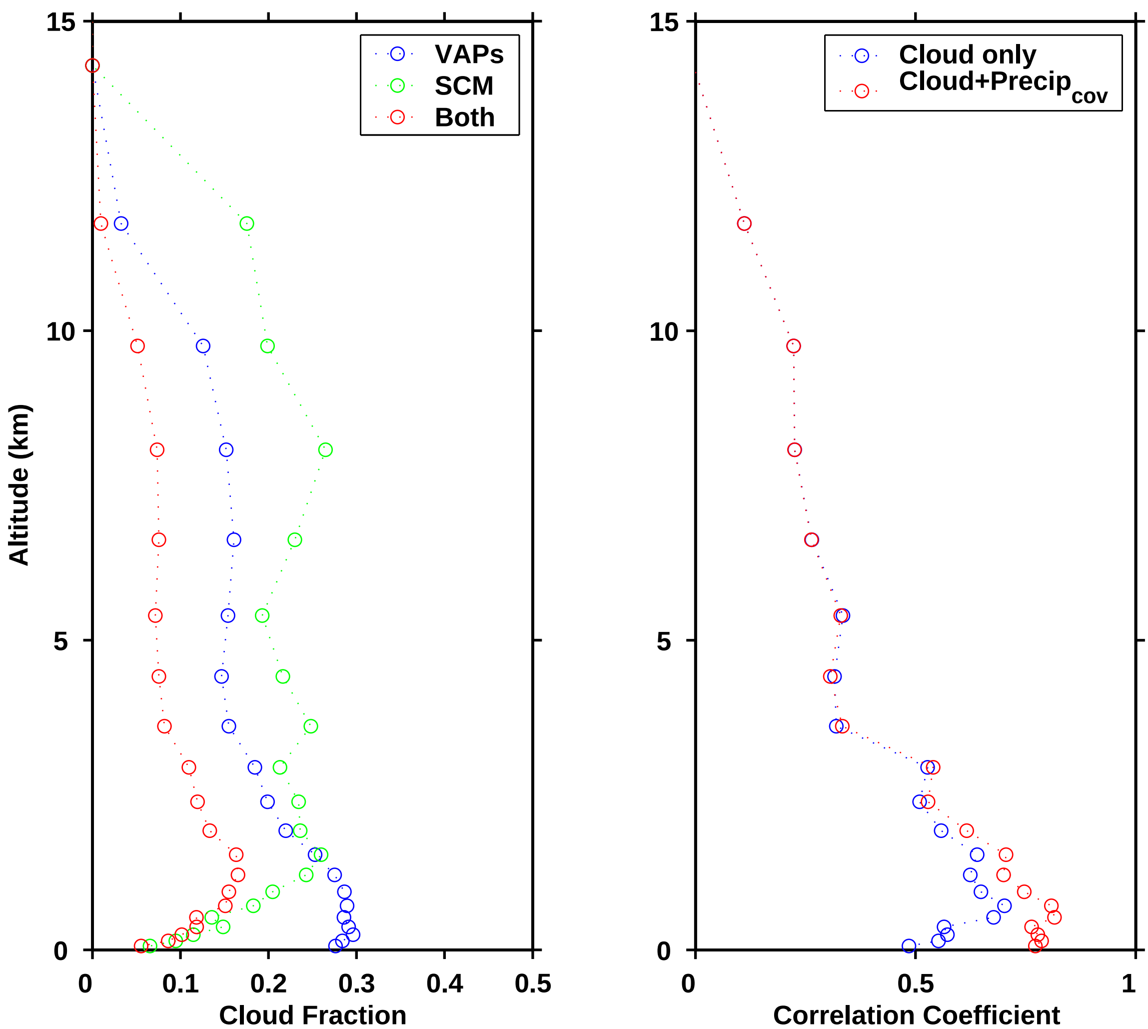

Total Cloud Amount
Obs.
SCM
Cloud Fraction
ARSCL
Altitude (km)
March 2000

Figure 4.



15
10
5
0
Altitude (km)
0
0.1
0.2
0.3
0.4
0.5
Cloud Fraction
VAPs
SCM
Both
15
10
5
0
0
0.5
1
Correlation Coefficient
Cloud only
Cloud+Precip$_{cov}$

Figure 5.

Figure Captions

Figure 1. Scatter plots of LWP vs. cloud thickness for the analysis period on different days. The data have been fitted to the equation LWP=αh^{γ} and the x- and y-axes have decimal logarithm scales. The plot is limited to six cases with ceilometer data.

Figure 2. Relationships of standard deviations of cloud thickness (σ_h) and LWP (σ_{lwp}) to the Brünt-Väisälä frequency N^2 (= $(g/\theta)\partial\theta/\partial z$) and vertical wind shear W (= $\partial\left|\vec{u}\right|/\partial z$) in the cloud layer. N^2 and W are obtained from the available soundings. The number of available comparisons is 14 for the relationship of LWP variability to N^2 and W and, due to the reliability of C_b from the radar, only 11 for the relationship of cloud thickness variability to N^2, and W.

Figure 3. Comparison of the estimated PDFs of LWP to the observed one (thick blue line) for 6 episodes with ceilometer data. The model PDFs are calculated from Eqs. 8 and 10 using the mean LWP from the observations along with σ_h determined after first linearly detrending the data. The observed PDF of detrended LWP is based on the MWR measurement, and displayed with the offset of the mean LWP.

Figure 4. (top) Time series of total cloud fraction from SCM and the satellite observation for 2-21 March 2000, (middle) time-height cloud fraction from surface to 15 km, produced by the observation, and (bottom) simulated by GFDL SCM.

Figure 5. Temporally average of (left) cloud fraction from the observation and SCM as a function of height together with the correlation for a period of 2-21 arch 2000.

Project Report: **The role of aerosol on the cloud development with respect to precipitation and radiation budget**

Principal Investigator: Seoung Soo Lee (Princeton graduate student)

Other Participating Researchers: Advisor: Leo Donner(GFDL), Charles Seman(GFDL), Vaughan Phillips(Princeton)

NOAA's Goal # 2 – Understanding Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:
To understand the role of aerosol on the cloud development with respect to precipitation and radiation budget

Methods and Results/Accomplishments:
I did numerical experiments to do analysis on the impact of CCN number concentration on the cloud development. According to previous research done by Albrecht, the increase in CCN number concentration caused the precipitation suppression. But my result showed contradictory situation to the result of Albrecht because increase in CCN number concentration produced more rain. To resolve this contradictory result, I analyzed microphysical terms of rain and graupel first and found that cold microphysical processes are the main reason for those contradictory results. In the case of warm microphysical processes, as Albrecht result, the increase in CCN number concentration caused the precipitation suppression due to suppressed autoconversion process. But due to stronger collection of cloud water by gruapel , snow and rain, the increase in CCN number concentration finally gave rise to more precipitation.

The first reason for the stronger collection was the elongated residence time of cloud water due to slower autoconversion process in the case of higher CCN number concentration. And the second reason was the higher supersaturation produced by stronger updraft in the experiment with higher CCN number concentration. The stronger updraft was produced because of higher efficiency of cloud water evaporation. When CCN number concentration increased, the ratio of cloud water mass density to rain water mass density increased and finally more evaporation occurred to produce more active downdraft. This more active downdraft formed stronger convergence near the surface to cause stronger updraft to produce higher supersaturation.

Conclusively, in the case of clouds whose cold microphysical processes are very strong, Albrecht¢¯s theory is not applicable. So His theory cannot be applied to all kinds of clouds and the impact of aerosol on climate should be re-considered.

References:
Khain A., D. Rosenfeld, A.Pokrovsky, 2004:Aerosol impact on the dynamics and microphysics of convective clouds. Submitted to Quart.J.Roy.Meteor.Soc

Publications:
Lee.S.S, L.J.Donner, 2004: The impact of the CCN number concentration on deep convections. Plan to submit to JGR

Project Report: **Workshop on Policy and Carbon**

Principal Investigator: Michael Oppenheimer(Princeton)

NOAA's Goal #2 - Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:
The objective of this grant is to advance understanding of views of long term risk held by the general public and to apply that understanding to the global warming problem, with an emphasis on findings relevant to risk communication.

Methods:
A workshop, "Global Warming: The Psychology of Long Term Risk", scheduled for 12 November 2004 at the Woodrow Wilson School of Princeton University, will be sponsored with support from this grant. Papers delivered are expected to be published as a special issue of a climate change journal. A copy of the agenda is appended. The workshop is being planned jointly by Michael Oppenheimer and Alexander Todorov, Assistant Professor of Psychology. Experts have been invited (and accepted) from the fields of psychology, risk assessment, and public opinion. These experts will be joined by natural scientists working on global warming in order to create a fertile cross-disciplinary discussion.

Results:
Reporting of results awaits the outcome of the conference.

Princeton University Woodrow Wilson School of International and Public Affairs

Workshop on Global Warming: The Psychology of Long Term Risk
300 Wallace Hall
Morning Session

8:30 a.m. - 8:55a.m.	**Continental Breakfast** 300 Wallace Hall
9:00a.m. - 9:15 a.m.	**Background Presentation on Climate Science, Article 2 of Framework Convention** Dr. Stephen S. Schneider Stanford University - tenative Discussant: Dr. Michael Oppenheimer - Princeton University
9:20 a.m. - 10:50 a.m.	**Panel I: Public Opinion/Public Values** Dr. Jon Alexander Kronsnick - Ohio State University Dr. Anthony A. Leiserowitz - University of Oregon Dr. Nick Pidgeon - University of East Anglia - tentative Discussant: Dr. Dale W. Jamieson - New York University
10:55 a.m. -12:15 p.m.	**Panel 2: Individual Perception of risk-how people view long term risk** Dr. Elke Weber - Columbia University Dr. Timothy L. McDaniels - University of British Columbia Dr. W. Kip Viscusi - Harvard Law School Discussant: Dr. Klaus Keller - The Pennyslvania State University
12:20 p.m. - 1:20p.m.	**Lunch** **Luncheon Speaker -** Dr. Daniel Kahneman - Princeton University - tentative

Afternoon Session

1:25 p.m. 2:55 p.m.	**Panel 3: Judgment and decision-making with respect to long term risk** Dr. Jonathan M. Baron - University of Pennyslvania Dr. Richard Zeckhauser - Harvard University Dr. Shane Frederick - Sloan School of Managemnet Discussant: Dr. Stephen Pacala - Princeton University
3:00 p.m. - 4:30 p.m.	**Panel 4: Communicating Risk (by Scientists, political leaders)** Dr. Max H. Bazerman - Harvard Buisness School Dr. Cass R. Sunstein - University of Chicago Dr. Baruch Fischhoff -Carnegie Melon University Discussant: Dr. Daniel P. Schrag - Harvard University
4:35 p.m. - 4:55 p.m.	**Cocktail reception for panelist and invited guest -** Room 333 Wallace Hall
5:00 p.m. - 7:00 p.m.	**Informal dinner for panelist and invited guest** Room 300 Wallace Hall

Project Report: **Moist Convection in The Earth's Climate**

Principal Investigator: Olivier Pauluis (Princeton, now at NYU)

Other Participating Researchers: Isaac Held, Steve Garner and Leo Donner (GFDL), Pablo Zurita (UCAR), Dargan Frierson (Princeton), Andy Majda (NYU), Kerry Emanuel (MIT)

NOAA's Goal #2 - Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond
NOAA's Goal #3: Serve Society's Needs for Weather and Water Information,and in particular in predicting severe precipitation.

Objectives:
Olivier Pauluis' research aims at understanding the role of moist convection in the earth's climate. A first aspect of this work lies in the development of a new generation of high-resolution climate model that would directly simulate convection rather than parameterize it. This would provide researchers with a new set of tools to understand how convective systems interact with the large-scale atmospheric circulation, and would also greatly improve on the accuracy of climate forecasts. A second aspect involves research on new conceptual models to provide new insights on the nature of convection.

Methods and Results/Accomplishments:
Pauluis has focused on the development of a version of the ZETAC non-hydrostatic as a cloud resolving model for GFDL, and the use of that model in high resolution simulations of tropical convection. In close collaboration with Steve Garner and Chris Kerr, the ZETAC model has been developed to the point that it is now ready to be utilized for studies of moist convection. In the past year, developments include the construction of an FMS compatible interface that allows the model to use physical parameterizations from the global GCM, including radiative transfer, implementation of a Piece-wise Parabolic Advection scheme which leads to dramatic improvement in the model behavior, particularly for the advection of water vapor, potential temperature and condensed water, a new three-dimensional turbulent closure scheme., and an external interface to facilitate the use of inputs from field data. The model is being evaluated in the cloud-resolving mode by comparing with specific observational datasets (TOGA-COARE, ARM, GATE) in collaboration with Leo Donner, Vaughan Phillips and Charles Seman at GFDL. A study of the sensitivity of the model to horizontal resolution shows that it produces very realistic cloud statistics at horizontal resolution of up to 10km. That the model is viable at such large scales could provide an alternative for convective parameterizations in high resolution GCMs. Innovative large-scale simulations of Hadley and Walker simulation to compare atmospheric flows with explicit and parameterized convection are also underway. Improvements to the model, particularly with regard to its conservation properties, are continuing.

Pauluis has also been collaborating with Andy Majda (NYU) and Dargan Frierson (Princeton) on a new theory for the dynamics of the interface between dry regions and moist regions in the tropics. Mathematically, this discontinuity behaves as a dissipative shock in idealize models of the tropics, leading to some very surprising behavior. Notably, the propagation speed of this interface is different from the propagation speed of moist or dry disturbances, and waves encountering the interface can be partially reflected. Theoretical analysis is ongoing and will hopefully lead to insights into the statistics of the precipitation Field in the tropics.

Pauluis has also been collaborating with Isaac Held, Dargan Frierson, and Pablo Zurita-Gotor on idealized moist GCMs. With Frierson, he has developed several simple convection parameterization schemes that capture some of the variety of the methods in use in global models. These will be r to investigate the sensitivity of the atmospheric circulation to the representation of moist convection.

Publications:

Pauluis, Olivier, 2004: Boundary layer dynamics and cross-equatorial Hadley Circulation. *J. Atmos. sci.*, **61**, 1161-1173.

Pauluis, Olivier, and Kerry A. Emanuel, 2004: Numerical instability resulting from infrequent calculation of radiative heating. *Monthly Weather Review*, **132**, 673-686.

Book Chapter:

Pauluis, Olivier, 2004: Chapter 9. Water vapor and entropy production in the Earth atmosphere. In Non-Equilibrium Thermodynamics and the Production of Entropy: Life, Earth, and Beyond, Kleidon and Lorenz Ed. Springer Verlag, for publication in Fall 2004

Project Report: **Comparison of 2D and 3D CRM simulations**

Principal Investigator: Vaughan Phillips(Princeton)

Other Participating Researchers: Leo Donner(GFDL)

NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond (50%);
NOAA's Goal # 3: Serve Society's Needs for Weather and Water Information (50%).

Objectives:
The aim is to compare 2D and 3D CRM simulations, with a view to determining whether the application of 2D CRMs as super-parametrisations in GCMs introduces a bias in the predicted radiative properties and cloud statistics.

Methods and Results/Accomplishments:
Currently, I am engaged in finishing a paper about 2D-3D comparisons of CRM simulations with the WRF model with Leo Donner. Apparent problems in the forcing dataset took several months to resolve, concerning temperature biases at the top of the troposphere. Eventually it was determined that such biases were impossible to eliminate, given the probable inaccuracy of the observed forcing at upper levels. Recently, efforts have been made to improve the accuracy of the predicted radiative fluxes in these 2D-3D simulations. A paper is nearing completion, and will be submitted for publication soon. This paper follows a paper about observational evidence for the boundary layer control of CAPE, also with Leo Donner.

Publications:
Donner, L.J., and V.T.J. Phillips, 2003: Boundary-layer control on convective available potential energy: Implications for cumulus parameterization. *J. Geophys. Res*. In press.

Project Report: **Cloud Microphysics and Aerosols**

Principal Investigator: Vaughan Phillips(Princeton)

Other Participating Researchers: Alexander Khain and Andrei Pokrovsky(Hebrew University), Steve Sherwood(Yale), Constantin Andronache(Boston College), V. Ramaswamy, Leo Donner, Charles Seman and Paul Ginoux(GFDL),Yefim Kogan(University of Oklahoma), Yi Ming(UCAR)

NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond (50%);
NOAA's Goal # 3: Serve Society's Needs for Weather and Water Information (50%).

Objectives:
The aim is to study particular microphysical phenomena in clouds with highly explicit microphysical models that discretise the size distribution of hydrometeors with "size-bins" (such models are referred to as "bin microphysics models"). These phenomena include ice nucleation in thunderstorms and aspects of the melting process. In addition we aim to include the dependence of precipitation development and radiative properties of clouds, in their representation in the GCM.

Methods and Results/Accomplishments:
This year I have started introducing double moment microphysics (ie. both mass of particles and number of particles being predicted quantities) into the Weather, Research and Forecasting (WRF) model. I wrote a report for Leo Donner on various strategies for improving the bulk microphysics schemes applied in cloud-resolving models at GFDL this summer. The overall goal is to apply the same approach to adding double moment microphysics in the GFDL GCM. I have been assisting Yi Ming in this respect, with group meetings organized by V. Ramaswamy. In particular, Ramaswamy, Donner and I have been helping Yi Ming to refine a paper concerning his new droplet parametrisation scheme for cloud-bases in a GCM. We are now working as a team on implementing droplet nucleation throughout clouds at all levels in the GFDL GCM.

This summer I prepared a paper for a refereed journal with Alexander Khain and Andrei Pokrovsky, concerning the effect of melting on the cloud dynamics and precipitation of a maritime storm. This followed substantial refinement of the detailed melting scheme that I wrote for the Hebrew University Cloud Model (HUCM) this year. The paper is now being modified with Khain and colleagues at Hebrew University to incorporate their simulations of an extra case of deep convection into the paper, prior to its submission. My detailed melting scheme has been implemented in the latest version of the HUCM this year.

In May 2004, a paper was submitted to a refereed journal about ice nucleation processes affecting anvil glaciation in a thunderstorm observed by aircraft near the Florida peninsula. In this paper, our key discovery was that in the updraft of a cumulonimbus cell, anvil crystals aloft are invariably formed by the homogeneous freezing of droplets.

This storm was observed in the NASA Cirrus Regional Study of Tropical Anvils and Cirrus Layers Florida Area Cirrus Experiment (CRYSTAL-FACE), which I participated in with Dr Steve Sherwood from Yale University during July 2002. A second paper is currently being circulated among possible co-authors, concerning the sensitivity of the glaciation of the storm with respect to electric fields in the storm.   Another paper will be prepared later this year, inter-comparing microphysical simulations of dusty and clean days in CRYSTAL-FACE. The difference between these two days is primarily in the ice nucleus concentration of the environmental air.

An ongoing collaboration with Constantin Andronache and Paul Ginoux is focusing on elucidating the effects of aerosols on the microphysics of thunderstorms, combining satellite and aircraft observations with double-moment CRM and microphysical models.   We submitted a grant application, which I wrote the scientific component for, to NASA's Tropical Cloud Systems Processes project this summer.   Finally, Yefim Kogan at the University of Oklahoma has transferred to me the codes for his 3D bin-microphysics model, which I have agreed to improve. A paper will be written when the work is done, and it appears possible that other scientists at GFDL will be given permission to use the Oklahoma 3D bin model once its development is completed.

Publications:

Phillips, V.T.J., Sherwood, S.C., Andronache, A., Bansemer, A. Conant, W.C., DeMott, P.J., Flagan, R.C., Heymsfield, A., Jonsson, H., Poellot, M., Rissman, T.A., Seinfeld, J.H., Vanreken, T., Varutbangkul, V. and J.C. Wilson, 2004: Anvil glaciation in a deep cumulus updraft over Florida simulated with an Explicit Microphysics Model. Part I: The impact of various nucleation processes. Submitted to *Q. J. R. Met. Soc*

Grandpeix, J.Y., Phillips, V.T.J., and R. Tailleux, 2004: Improved mixing representation in Emanuel's scheme.   Accepted for publication at *Q. J. R. Met. Soc*

Salzmann, M., Lawrence, M.G., Phillips, V.T.J. and L. J. Donner, 2004:   Modelling tracer transport by a cumulus ensemble: lateral boundary conditions and large-scale ascent.   *Atmos. Chem. Phys. Discuss.*, **4,** 3381-3418

Khain, A., Pokrovsky, A., Pinsky, M., Seifert, A. and V.T.J. Phillips, 2004: Simulation of effects of atmospheric aerosols on deep turbulent convective clouds by using a spectral microphysics mixed-phase cumulus cloud model. Part 1: Model description and possible applications. Accepted for publication at *J. Atmos. Sci.*

Project Report: **Dynamics of stratospheric-troposphere coupling**

Principal Investigator: Thomas Reichler(Princeton, now at University of Utah)

Other Participating Researchers: Paul Kushner(GFDL, now at University of Toronto) and Lorenzo Polvani (Columbia)

NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond (50%);
NOAA's Goal # 3: Serve Society's Needs for Weather and Water Information (50%).

Objectives:
On intraseasonal timescales, observations show that anomalies of the Northern Hemisphere wintertime stratospheric polar vortex frequently precede persistent changes to the tropospheric circulation that resemble the Arctic Oscillation. This may be useful in improving the predictability of the extratropical troposphere on time scales of the order of several weeks. The tropospheric circulation may also be linked to the stratosphere on longer timescales. For example, it has been found that stratospheric perturbations associated with ozone depletion, volcanic aerosols, or the quasi-biennial oscillation exhibit a signature in surface climate. Such a coupling may be important for simulations of anthropogenic climate change in response to changes of greenhouse gases.

Methods and Results/Accomplishments:
Reichler has used an idealized atmospheric model: the spectral dynamical core of the GFDL climate model in T42 resolution with simple dry physics and 40 vertical levels located between the surface and the mesosphere. He has induced stratospheric circulation anomalies by a technique that involves time varying topography. After the initial forcing period, the model was allowed to evolve freely to study the stratospheric anomalies for 100 days. The same experiment was repeated many times using different initial conditions to create an ensemble of over 400 members.

Robust tropospheric perturbations in response to the stratospheric circulation anomalies were observed, but only when the data was stratified to isolate certain types of initial conditions. In particular, an initially weak upper stratospheric (1-10 hPa) polar vortex was found to be important for generating a signal propagating downward from the stratosphere to the troposphere. The idealized model provides a very useful tool or analyzing the dynamics of this downward influence of the stratosphere on the troposphere.

Reichler intends to re-examine this problem in a more realistic model, a stratospheric version of AM2 developed by John Wilson (GFDL), to determine if the downward propagation of signals is similar in realistic and idealized GCMs, and if there are similar relationships between initial conditions and the downward propagation in both models.

Reichler is also undertaking a new study to determine if the extent of the Hadley cell, or the area covered by a deep tropical tropopause, has been expanding in the past few decades. A previously developed and tested algorithm for the determination of the thermally defined tropopause is being applied to reanalysis data to derive a time series of the width of the tropics over the past 50 years. If such a trend can be found in the reanalysis data, the same kind of analysis will be applied to the output of the AM2 model to see whether such a trend is simulated by the model. Initial indications are that there is a substantial trend, especially in the Southern hemisphere. The causes and implications for such a trend will be investigated further.

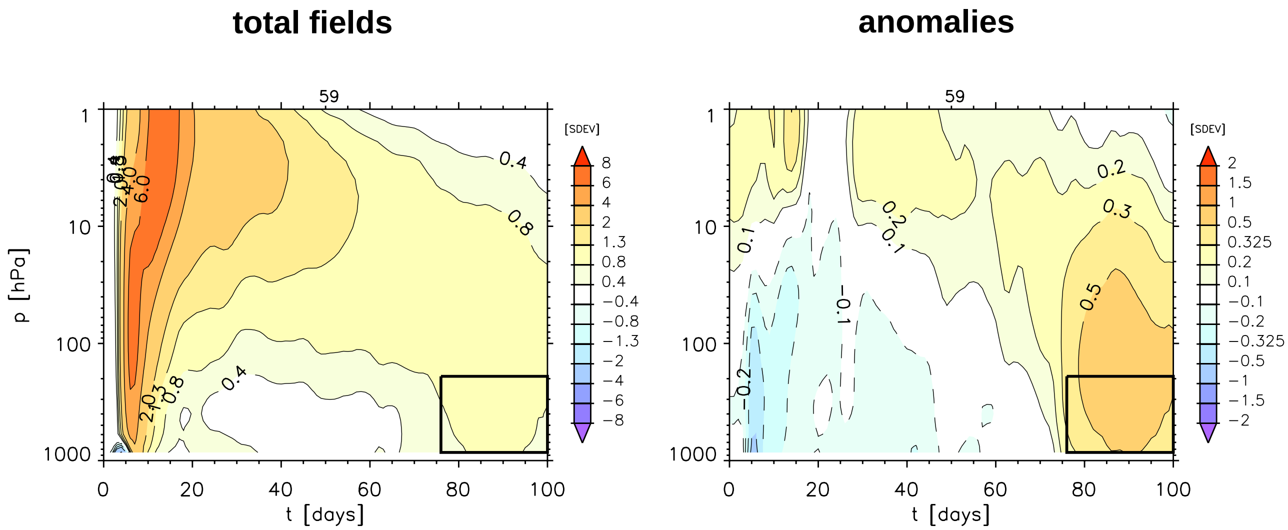


Fig. 2. The composite mean response of the model atmosphere to tropospheric wave forcing for cases with a late (day 75-100) tropospheric return signal. Shown are normalized geopotential height anomalies over the polar cap as a function of time and pressure.

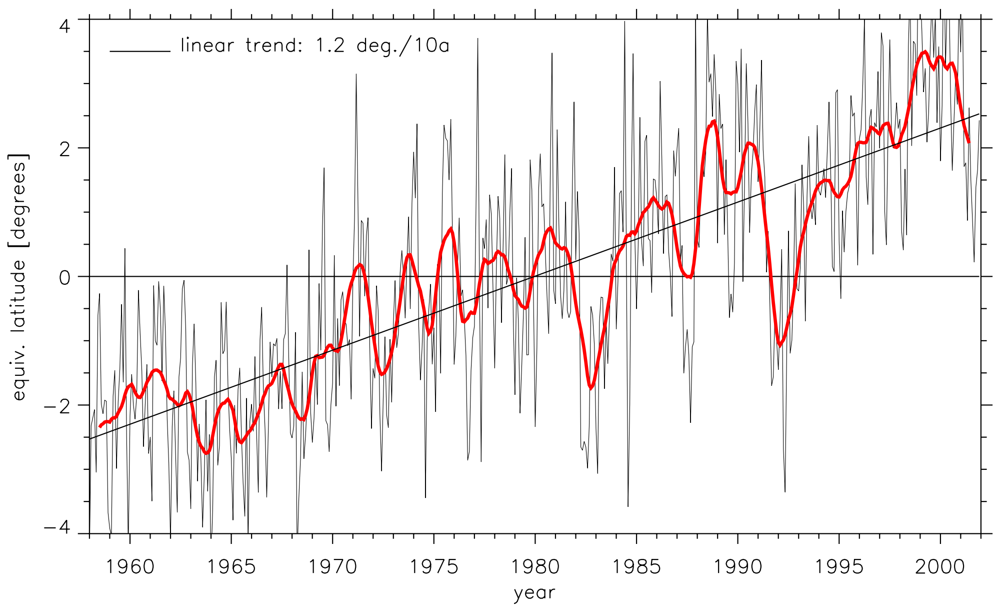


Fig. 2. Monthly-mean time series of anomalies in the zonal-mean equivalent latitudinal extent of the tropics calculated from NCEP/NCAR reanalysis. The extent of the tropics is given by the difference between the northern and southern boundary. The boundaries are defined as the latitudes where the tropopause pressure reaches 140 hPa. The climatological seasonal cycle is modeled individually at each longitude with annual and semiannual harmonics and removed.

The thick curves are the smoothed time series using a 13-months running mean filter, and the straight lines are least-square fits to the monthly-mean data.

Also in collaboration with Wilson, Reichler will implement the Alexander & Dunkerton gravity wave drag scheme, in use in the stratospheric version of the AM2 model, into the simple GCM and analyze the response. It is to hope that the model would be able to produce a QBO at high enough amplitude, which in turn may have important consequences for the simulation of extratropical stratosphere-troposphere interactions. Also, the model will provide valuable information on the horizontal and vertical resolution needed to simulate the QBO in this context.

Publications:

Reichler, T., P. Kushner, L. Polvani (2004): The coupled stratosphere-troposphere response to impulsive forcing from the troposphere, J. Atmos. Sci. (submitted).

Project Report: **Atlantic Storm Track Variability And Its Relation With The North Atlantic Oscillation.**

Principal Investigator: Gwendal Rivière(Princeton)

Other Participating Researchers*:* Isidoro Orlanski (GFDL)

NOAA's Goal #2 - Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:
The aim of Riviere's research is to provide a better understanding of the Atlantic storm track variability and trends. One focus of the study will be feedbacks of high frequency eddy activity onto the quasi-stationary circulation, particular with regard to the North Atlantic Oscillation (NAO). The planned work consists in the analysis of observations using reanalysis data, and numerical simulations from two GFDL models: the new global model AM2, and the high resolution, non hydrostatic regional model (ZETAC).
One of the objectives of the data analysis has been to examine the relation between storm track variability over the Atlantic and high frequency wave activity upstream over Eastern Pacific and North America. Wave activity upstream of the storm track entrance could be an important source of the Atlantic storm track variability through downstream development, as has already been shown for the Pacific in recent work by Orlanski and collaborators. The role that play synoptic eddies coming from the Pacific on Atlantic storm track variability and on NAO has been in question in different recent papers (Chang and Fu, 2002; Benedict et al., 2004; Franzke et al., 2004) but is still not well understood. Storm track activity also depends strongly on local baroclinicity which itself can be modified by SST anomalies and land surface temperature anomalies. The hypothesis is that *upstream seeding* and *local baroclinicity* are the proper variables in term so which one should analyze changes in the Atlantic storm track.

Methods and results:
Results already obtained from reanalysis data since the beginning of the postdoctoral research has allowed us to define more clearly the problematics involved, and to identify the phenomenon that we will try to simulate with AM2 and ZETAC models.

Results on reanalysis data:

Two contrasting behaviors have been identified concerning the impact of the Pacific high frequency wave activity on NAO which are summarized in Fig.1. Color and black contours in figures 1.a-d correspond respectively to the square of the high-frequency meridional velocity (v'^2) and to the zonal wind (u) which are classical diagnostic parameters respectively to quantify synoptic activity and to observe jet structures. Regression patterns in Figs.1.a-d obtained with monthly values data show that positive NAO is largely correlated with a strong synoptic activity over Eastern Pacific during the period 1955-1970 whereas it is not at all the case during the period 1983-1998, it is even slightly anticorrelated during the latter period. Indeed, regression patterns on NAO index show a strong signal of synoptic activity at longitude 140W for the 1st period (see the red contours at this longitude in Fig.1.a) whereas such a signal is completely missing during the 2nd period (see Fig.1.c). Moreover, regressions based on a Pacific synoptic activity index confirms that Pacific synoptic activity during the 1st period induces positive NAO (Fig.1.b) whereas during the 2nd one it leads to a slightly negative NAO signal over the Eastern Atlantic (Fig.1.d). All these results have been already checked to be statistically significant and have been confirmed by using daily values data. The two periods 1955-1970 and 1983-1998 are well known to be different in terms of NAO anomalies (Hurrell, 1995) as during the first period, the NAO index has more often low negative values whereas during the second one, it has more often high positive values, but the results of Fig.1 exhibit another contrasting behavior between these two periods which has not been yet described in the litterature.

Numerical simulations / planned work:

The aim of the numerical simulations made with the present AM2 global circulation model and the regional high resolution ZETAC simulations is the following; first to reproduce a similar behavior to that previously shown in reanalysis data and secondly to explain it by performing a number of sensitivity runs by modifying the amplitude of the upstream eddy activity and by testing different SST or land surface temperatures forcing and other physics packages. It will allow us to identify the different sources of variability and especially the parameters responsible for the two contrasting behaviors described in the previous paragraph. Furthermore, these sensitivity runs can allow us to reveal model biases that may then improve model simulations and may lead to a better prediction of NAO.

Finally, once the dynamical processes between upstream eddy activity, Atlantic storm track and NAO will be more clearly understood, global warming simulations will also be studied to closely examine the behavior of the Atlantic storm track in these models, with a focus on the possibility of changes in the frequency and the geographical location of future extreme weather events caused by climate change. In this sense, our research activities are related to two NOAA goals, *goal 2* on climate variability and *goal 3* on weather events information.

Recent publications:

-Riviere, G., Hua B. L. and Klein, P. 2004. Perturbation growth in terms of baroclinic alignment properties. *Quart. J. Roy. Meteor. Soc.* **130,** 1655-1673.

-Riviere, G. and Hua B. L. 2004. Predicting areas of sustainable error growth in quasigeostrophic flows using perturbation alignment properties. *Tellus A*, in press.

-Riviere, G., and Joly, A. 2004a. Role of the low-frequency deformation field on the explosive growth of extratropical cyclones at the jet exit. Part I: barotropic critical region. *To be submitted to J. Atmos. Sci.*

-Riviere, G., and Joly, A. 2004b. Role of the low-frequency deformation field on the explosive growth of extratropical cyclones at the jet exit. Part II: baroclinic critical region. *To be submitted to J. Atmos. Sci.*

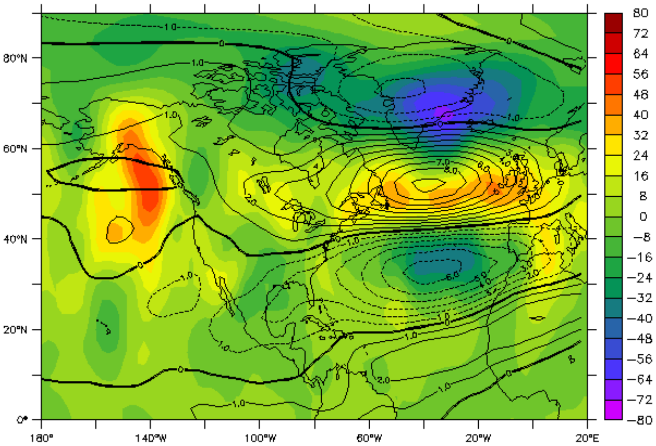
References:

-Benedict, J. J., Lee, S. and Feldstein, S. B. 2004. Synoptic view of the north atlantic oscillation. *J. Atmos. Sci.,* **61**, 121-144.

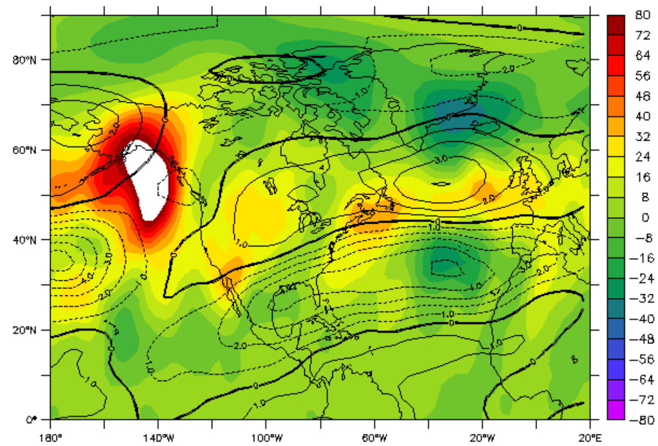
-Chang, E. K. M. and Fu, Y. 2002. Interdecadal variations in northern hemisphere winter storm track intensity. *J. of Climate*, **15**, 642-658.

-Franzke, C., Lee, S. and Feldstein, S. B. 2004. Is the north atlantic oscillation a breaking wave ? *J. Atmos. Sci.,* **61**, 145-160.

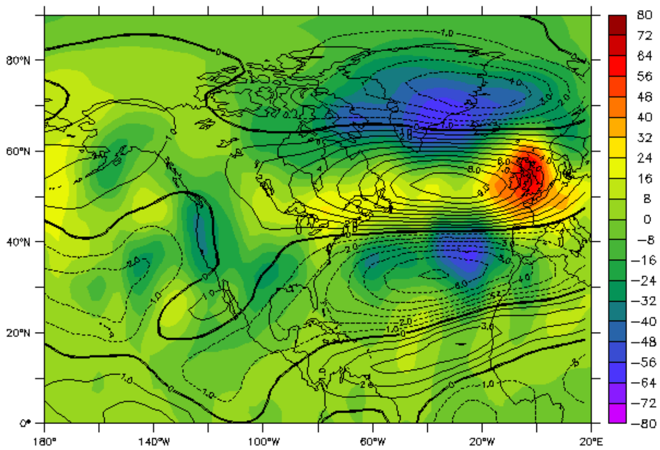
-Hurrell, J. W. 1995. Decadal trends in the North Atlantic oscillation: regional temperatures and precipitation. *Science*, **269**, 676-679.



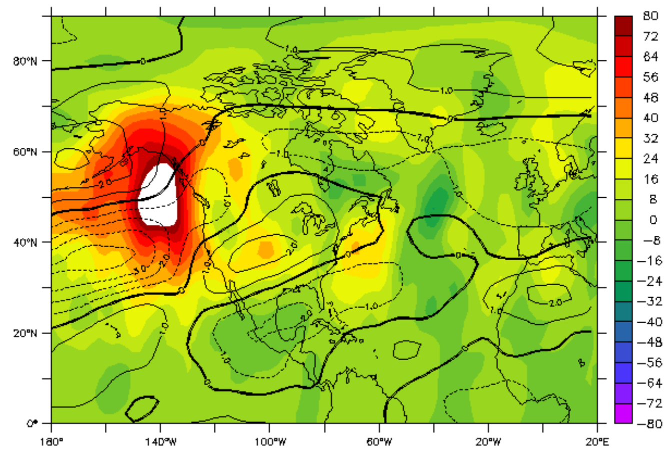
(a) Regression on NAO index for the period 1955-1970



(b) Regression on <v′²>$_{pac}$ index for the period 1955-1970



(c) Regression on NAO index for the period 1983-1998



(d) Regression on <v′²>$_{pac}$ index for the period 1983-1998

Figure 1: Regressions of the 300 hPa zonal wind u (black contours), and of the 300 hPa v'^2 (color contours) on the NAO index are represented for the period (a) 1955-1970 and (c) 1983-1998. Regressions of the same variables on a Pacific synoptic activity index (defined as the average of v'^2 between 150W-130W and 20N-70N and denoted as $\langle v'^2 \rangle_{pac}$) are plotted for the period (b) 1955-1970 and (d) 1983-1998.

Project Report: **Scaling Space, Time, Heterogeneous Hydrologic Dynamics**

Principal Investigator: Ignacio Rodriguez-Iturbe (Princeton University)

Other Participating Researchers: Michael A. Celia (Princeton University), Michael J. Puma (graduate student, Princeton University)

NOAA's Goal #2 - Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond(50%)
NOAA's Goal #3 - Serve Society's Needs for Weather and Water Information (50%)

Objectives:
Specifically, the research focuses on two major issues. The first issue is the temporal scale of rainfall data and its effect on model estimation of soil moisture and transpiration. The second issue is the effect of horizontal spatial scale on the relationship between soil moisture and evapotranspiration, when vegetation and rainfall heterogeneities exist in horizontal space.

Methods And Results/Accomplishments:
The time-space scaling properties of soil moisture and evapotranspiration are examined using detailed simulation studies of the soil, plant, and climate system, highly resolved in time and space. First, we examine the temporal resolution required of rainfall data to estimate accurately soil moisture and transpiration for a specified system. That is, rainfall is a continuous intermittent process, yet rainfall data are available often only as cumulative totals over a fixed temporal interval [19,20]. Historical rainfall data, collected at different discrete temporal intervals, are used directly as rainfall input into a model of the soil, plant, and climate system. The model simulates vertical infiltration and redistribution, including evapotranspiration, using the one-dimensional Richards' equation with a suitable sink term to account for evapotranspiration [7,16,17,22]. Using this model with historical rainfall input, we assess how the scale of discrete rainfall data affects model estimation of soil moisture and evapotranspiration relative to the data with the finest resolution (15 minutes intervals). This analysis is performed for two water-limited ecosystems: one in a Colorado grassland and the other in a Texas brushland. Figure 1 presents root-zone saturation (relative soil moisture) traces produced by rainfall at different aggregation levels for the grass *Bouteloua gracilis* in Colorado. Figure 1a shows that the saturation traces for the 15-minute and daily rainfall aggregation levels do not produce any significant differences in model estimation, while Figure 1b reveals considerable difference in the trace of saturation when the resolution of the rainfall data decreases to 2 weeks and a month.

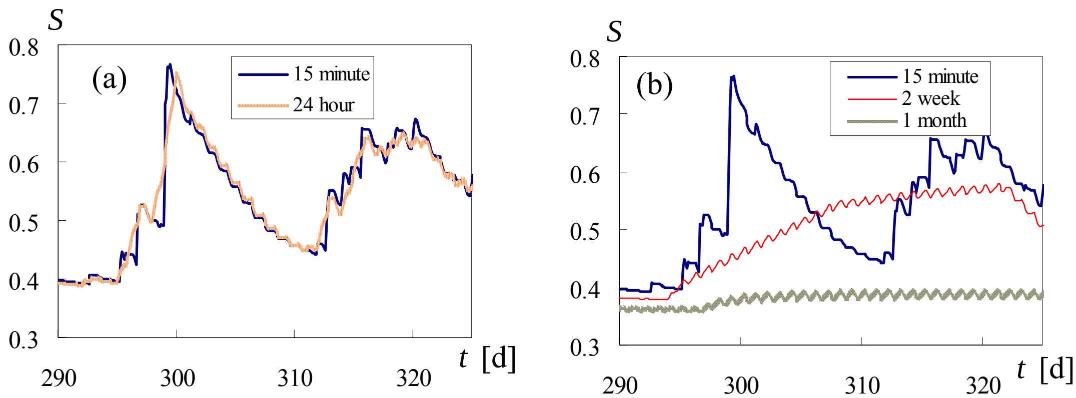


Figure 1: Examples of root-zone saturation traces for different rainfall aggregation levels for the grass *Bouteloua gracilis* in Colorado soil: (a) Averaging depth 30 cm for 15-minute and daily rainfall aggregation levels (b) Averaging depth 30 cm for 15-minute and greater-than-daily rainfall aggregation levels.

Figure 2 presents the probability density functions (pdfs) of the ratio of instantaneous actual transpiration to potential transpiration (T_{act}/T_{pot}) that result when rainfall at different aggregation levels are used as model input. The pdfs produced by the 15-minute data and daily data are almost identical in Figure 2a. The pdfs for the 2-week and monthly rainfall aggregation levels are different from the 15-minute data for the Colorado data in Figure 2b. The probability that T_{act}/T_{pot} is between 0.2 and 0.8 is greater for 2-weeks that the 15-minute data and increases for the interval equal to a month. More striking, however, is that the probability that T_{act}/T_{pot} is a value close to zero is extremely low for the monthly data, whereas it is relatively high probability for the 15-minute and 2-week data. Simulation of a tree in a Texas ecosystem reveals very similar results as those presented in Figures 1 and 2. That is, historical rainfall data, resolved at the daily level, allow accurate estimation of soil moisture and transpiration when used directly as model input.

The success of daily rainfall input in the model is a consequence of the characteristics of the precipitation, soil, and plants in these ecosystems. An essential part of this analysis is to allow for generalization of the results obtain through study of Colorado and Texas, so that insight as to the temporal resolution of rainfall data required for a specific soil, plant, and climate system can be obtained *a priori*. Guswa et al. [7] proposed dimensionless groups of parameters to characterize ecosystems, such that decisions regarding the temporal and spatial resolution of a model can be made based on the groups. The parameters are measurable quantities that characterize the soil, plants, and climate of a particular ecosystem. We focused on three dimensionless groups of parameters that were discussed by Guswa et al. [7] and found them to be useful in the determination of the temporal scale of rainfall data that is required for accurate estimation of soil moisture and transpiration.

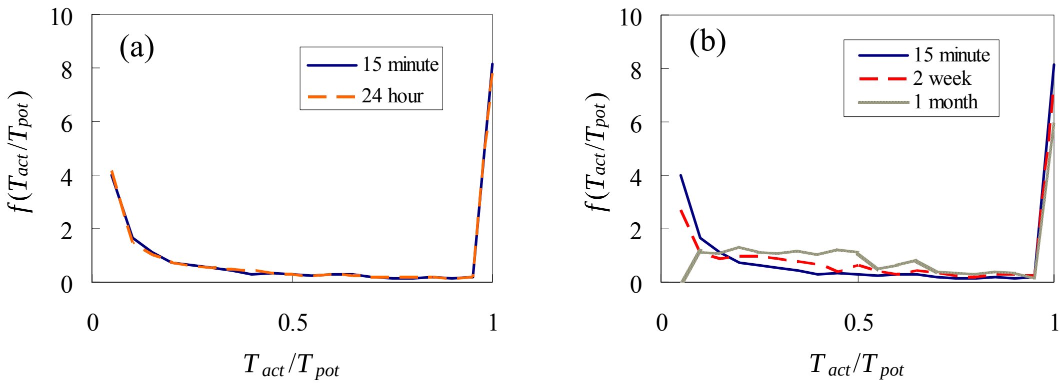


Figure 2: Examples of probability density functions of instantaneous T_{act}/T_{pot} for different rainfall aggregation levels for the grass *Bouteloua gracilis* in Colorado soil: (a) 15-minute and daily rainfall aggregation levels (b) 15-minute and greater-than-daily rainfall aggregation levels.

While it is useful to understand the effect of the scale of historical rainfall data when used as direct input in a model, rainfall data is often collected to derive parameters for a rainfall model. The objective of a probabilistic model of the rainfall process at a point is the description of the behavior of precipitation in time [18]. Much work has been done that judged the goodness of a model based on its ability to match the statistics of the rainfall record [e.g. 18,19,20]. Yet if the primary objective is to estimate soil moisture or transpiration, then it is necessary to reevaluate a model to the extent that it allows accurate estimation of these variables. That is, the accuracy of a rainfall model is assessed by considering the effect of rainfall input, after it is filtered by land surface processes, on soil moisture and transpiration. As before, we assume that the historical rainfall data at the finest resolution represents reality (15-minute data) and judge the rainfall model and its derived parameters relative to this reality. For an initial investigation, we use a simple rectangular pulses Poisson model [e.g. 19,20]. Figure 3a compares the pdfs of saturation when the rainfall model parameters are derived from 15-minute and daily rainfall data to the pdf resulting from using the historical discrete 15-rainfall as model input. The pdf with the rainfall derived from the daily data provides a much closer match than the pdf derived from the more highly resolved 15-minute data. Figure 3b compares the pdfs of instantaneous T_{act}/T_{pot}, and we again find that the pdf with the rainfall derived from the daily data provides a much closer match than the pdf derived from the more highly resolved 15-minute data.

Consequently, a simple rectangular pulses Poisson model with parameters derived from daily rainfall data allows accurate estimation of soil moisture and transpiration. We are currently investigating the effect of rainfall data resolution when using the Neyman-Scott model. This model is more complex in its representation of the rainfall process and is used extensively as a rainfall generator. Through this analysis, we can highlight the importance of temporal scale when used to derive rainfall model parameters. In addition, the success of the simple rectangular pulses Poisson model with the daily rainfall data suggests that a more complex model (e.g. Neyman-Scott) might not be necessary to estimate accurately soil moisture and transpiration for ecosystems with characteristics similar to the two simulated in this research. As before, we are working with dimensionless parameters to make these results general.

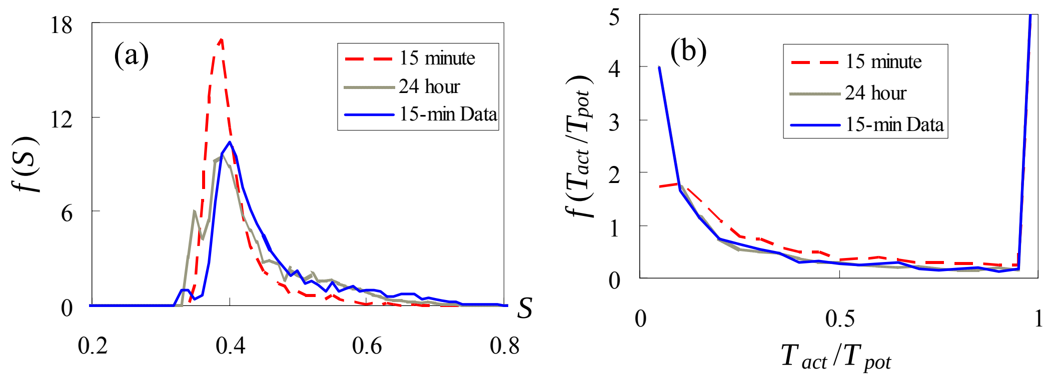


Figure 3: Examples of (a) probability density functions (pdfs) of saturation and (b) pdfs of instantaneous T_{act}/T_{pot} for rainfall generated using the rectangular pulses model with parameters derived from 15-minute and daily rainfall aggregation levels for the grass *Bouteloua gracilis* in Colorado soil.

The second issue investigated in this research project is the effect of horizontal spatial scale on the relationship between soil moisture and evapotranspiration, when vegetation and rainfall heterogeneities exist in horizontal space. At the scale of a single plant, the relationship between these two variables has been modeled successfully. For example, Rodriguez-Iturbe et al. [25] adopted a piecewise linear soil moisture limitation function on evapotranspiration, which has been recently validated in savanna field experiments by Williams and Albertson [23]. In large-scale land surface models, the relationship between soil moisture and evapotranspiration observed at the plant scale is used at the scale of these models, which range from 10^1 to 10^5 meters. Yet there is no reason to believe that the plant-scale relationship should hold at larger scales, especially when heterogeneity in rainfall, soil, and vegetation exist at the larger scale. Therefore, we are investigating the relationship between soil moisture and evapotranspiration to understand the effect of scaling and to obtain an 'up-scaled' functional relationship between soil moisture and evaporation that can be used in large-scale models (e.g. regional-scale models, GCMs).

Our approach follows that of Koster and Suarez [12], where a large area corresponding to a grid cell in a large-scale model is divided into smaller grid cells with homogeneous properties (the so-called 'mosaic' approach). The scale of our grid cell is 5 m, which is approximately the plant scale. We apply a piecewise linear soil moisture limitation function on evapotranspiration [14,25,7], since we know it is valid at the plant scale [23]. We model each 5×5 m grid cell as a 'bucket' by computing the soil moisture balance at a point and using the analytical expressions for inter-storm soil drying from Laio et al. [14]. As an initial investigation, we want to look at two types of heterogeneities: due to vegetation and rainfall. The initial assumptions of the proposed methodology are that the soil is uniform, atmospheric conditions (excluding rainfall) are uniform, and vegetation is static in time (that is, there is no growth). Initially, we use the spatial rainfall model presented in Rodriguez-Iturbe et al. [26]. We model the savanna of Nylsvley (South Africa), which has both grass and tree vegetation. We create a distribution in space of trees and grasses which corresponds to the distributions typical of savannas. We are interested in the following parameters in space and time: rainfall, evapotranspiration, and soil moisture. Specifically, we are investigating the effect of scaling on the relationship between soil moisture and evapotranspiration by assessing changes to the relationship as we increase averaging area. Currently, simulations are running to investigate this issue, and we plan to continue work to investigate other heterogeneities (e.g. soil).

During the period July 1, 2003 to June 30, 2004, we were successful in accomplishing our objectives. In summary, we found that historical rainfall data resolved at the daily level allow accurate estimation of soil moisture and transpiration when inputted into a model and when used to derive rainfall model parameters for the two ecosystems studied. In order to determine the appropriate scale of rainfall data for any given ecosystem, we have found that dimensionless groups of parameters that characterize a system can be identified to determine the scale *a priori*. These results relate to Goal 3 (*to serve society's needs for weather and water information*), because they clarify how frequently rain gage stations should take rainfall measurements (if the goal is to obtain data to model soil-moisture dynamics). Since rain gage stations require a significant monetary investment, this information is extremely valuable. These results also are important for Goal 2 (*to understand climate variability and change to enhance society's ability to plan and respond*), because they enable more accurate modeling of soil-moisture dynamics. For example, modeling of soil moisture is essential to determine the effect of climate variability and change on vegetation in term the vegetation's health. With accurate models of soil-moisture dynamics, effective management strategies can be developed to combat problems such as desertification. The second issue investigated in this research is also important for both Goals 2 and 3 through its potential to improve large-scale land surface models. That is, it is important to obtain information on soil moisture and evapotranspiration and to predict climate variability and change.

References:

[1] Ács F, Szász G. Characteristics of microscale evapotranspiration: a comparative analysis. Theor. Appl Climatol. 2002;73:185-205.

[2] Calenda G, Napolitano F. Parameter estimation of Neyman-Scott processes for temporal point rainfall simulation. Journal of Hydrology 1999;225:45-66.

[3] Crow WT, Wood EF. The value of coarse-scale soil moisture observations for regional surface energy balance modeling. Journal of Hydrometeorology 2002; 3: 467-482.

[4] Famiglietti JS, Wood EF. Effects of spatial variability and scale on areally averaged evapotranspiration. Water Resour Res 1995;31(3):699-712

[5] Feddes RA, Hoff H, Bruen M, Dawson T, de Rosnay P, Dirmeyer P, Jackson RB, Kabat P, Kleidon A, Lilly A, Pittman AJ. Modeling root water uptake in hydrological and climate models. Bull Amer Meteor Soc 2001;82(12):2797-2809.

[6] Giorgi F, Avissar R. Representation of heterogeneity effects in earth system modeling: experience from land surface modeling. Review of Geophysics 1997;35(4):413-438.

[7] Guswa AJ, Celia MA, Rodriguez-Iturbe I. Models of soil moisture dynamics in ecohydrology: A comparative study. Water Resour Res 2002;38(9):1166, doi:10.1029/2001Wrooo826.

[8] Guswa AJ, Celia MA, Rodriguez-Iturbe I. Effect of vertical resolution on predictions of transpiration in water-limited ecosystems. Adv Water Res 2004;27:467-80.

[9] Hopmans JW, Bristow KL. Current capabilities and future needs of root water and nutrient uptake modeling. In: Sparks DL, editor. Advances in Agronomy, vol. 77. San Diego: Academic Press; 2002. p. 103 – 81.
[10] Hu Z, Islam S, Jiang L. Approaches for aggregating heterogeneous surface parameters and fluxes for mesoscale and climate models. Boundary-Layer Meteorology 1999;93:313-336.
[11] Jones HG. Plants and microclimate: a quantitative approach to environmental plant physiology. 2nd ed. Cambridge, UK: Cambridge University Press; 1992.
[12] Koster RD, Suarez MJ. Modeling the land surface boundary in climate models as a composite of independent vegetation stands. J of Geophysical Research 1992;97(D3):2697-2715.
[13] Laio F, Porporato A, Fernandez-Illescas C, Rodriguez-Iturbe I. Plants in water-controlled ecosystems: active role in hydrologic processes and response to water stress IV. Discussion of real cases. Adv Water Res 2001;24(7):745-62.
[14] Laio F, Porporato A, Ridolfi L, Rodriguez-Iturbe I. Plants in water-controlled ecosystems: active role in hydrological processes and response to water stress II. Probablistic soil moisture dynamics. Adv Water Res 2001;24(7):707-23.
[15] Lauenroth WK, Sala OE, Coffin DP, Kirchner TB. Root dynamics of *Bouteloua gracilis* during short-term recovery from drought. Funct Ecol 1987;1:117-24.
[16] Lhomme J-P. Formulation of root water uptake in a multilayer soil-plant model: does van den Honert's equation hold? Hydrology and Earth System Science 1998;2(1):31-40.
[17] Puma MJ, Celia MA, Rodriguez-Iturbe I, Guswa AJ. Functional relationship to describe temporal statistics of soil moisture over different averaging depths. Adv Water Res (*accepted for publication, August 2004*).
[18] Rodriguez-Iturbe I, Cox DR, Isham V. Some models for rainfall based on stochastic point processes. Proc R Soc London Ser A 1987; 410:269-288.
[19] Rodriguez-Iturbe I, Febres de Power B, Valdés JB. Rectangular Pulses Point Process Models for Rainfall: Analysis of Empirical Data. J Geophys Res 1987; 92(D8): 9645-9656
[20] Rodriguez-Iturbe I, Gupta VK, Waymire E. Scale considerations in the modeling of temporal rainfall. Water Resour Res 1984;20(11):1611-1619.
[21] Sala OE, Lauenroth WK, Parton WJ, Trlica MJ. Water status of soil and vegetation in a shortgrass steppe. Oecologia 1981;48:327-31.
[22] Verburg K, Ross PJ, Bristow KL. SWIMv2.1 User Manual, Divisional Report 130. CSIRO Division of Soils, 1996.
[23] Williams CA, Albertson JD. Soil moisture controls on canopy-scale water and carbon fluxes in an African savanna. Water Resour Res 2004, vol 40, doi:10.1029/2004WR003208.
[24] Wood EF. Effects of soil moisture aggregation on surface evaporative fluxes, Journal of Hydrology 1997;190:397-412.
[25] Rodriguez-Iturbe I, Porporato A, Ridolfi L, Isham V, Cox D. Probabilistic modelling of water balance at a point: The role of climate, soil, and vegetation. Proc R Soc London Ser A 1999; 455: 3789 – 3805.
[26] Rodriguez-Iturbe I, Cox DR, Eagleson PS. Spatial modeling of total storm rainfall. Proc R Soc London Ser A 1986; 403: 27 – 50.

Publications:

Puma MJ, Celia MA, Rodriguez-Iturbe I. Temporal Scale of Rainfall Data and its Implications for Model Estimation of Soil Moisture and Transpiration. (*To be submitted, October 2004*).

Project Report: **Impact of ENSO on atmospheric transient activity based on observations and GCM simulations**

Principal Investigator: Chi-Yung Tam (Princeton graduate student)

Other participating researchers*:* Advisor: Ngar-Cheung Lau(GFDL)

NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:
To study the impact of ENSO on atmospheric transient activity based on observations and GCM simulations

Methods and Results:
The impact of ENSO on the MJO, intraseasonal activity over the North Pacific and summertime synoptic-scale disturbances in the tropics are assessed, through analyzing data from observations and a GCM experiment. A model experiment was conducted by imposing observed tropical SST during the period of 1950-1999 for atmospheric model integration, and there are eight realizations with identical boundary forcing (Alexander et al. 2002).

The MJO convective signals during the boreal winter is found to penetrate more to the east, during warm events as compared to cold events. Over the North Pacific, both the amplitude and dispersion characteristics of intraseasonal circulation anomalies are found to be sensitive to the phase of ENSO. Evidence that such sensitivity is related to the different behavior of the MJO-related convection during ENSO is presented. Finally, tropical summertime synoptic-scale waves over the western Pacific exhibit an eastward (westward) shift of their active region, during warm (cold) events. All of the aforementioned effects of ENSO can be seen in both the real and model atmospheres, although in general the GCM simulations are more realistic for transient eddies in the extratropics than for those in the tropics.

Results/Accomplishments:
The results have been summarized in the dissertation of CYT (Tam 2003).
The Impact of ENSO on Tropical and Extratropical Atmospheric Variability on Intraseasonal and Synoptic Time Scales as Inferred from Observations and GCM Simulations, Ph.D. dissertation, Princeton Univ., New Jersey, 197 pp.

References:

Alexander, A.M., I. Blade, M. Newman, J.R. Lanzante, N.-C. Lau, and J.D. Scott, 2002: The atmospheric bridge: The influence of ENSO teleconnections on air-sea interaction over the global oceans. J. Climate, 15, 2205-2231.

Tam, C.-Y., 2003: The Impact of ENSO on Tropical and Extratropical Atmospheric Variability on Intraseasonal and Synoptic Time Scales as Inferred from Observations and GCM Simulations, Ph.D. dissertation, Princeton Univ., New Jersey, 197 pp.

Publications:

Tam, C.-Y., and N.-C. Lau, 2004a: The impact of ENSO on atmospheric intraseasonal variability as inferred from observations and GCM simulations. Part I: Effects on the Madden-Julian Oscillation. J. Climate, submitted.

Tam, C.-Y., and N.-C. Lau, 2004b: The impact of ENSO on atmospheric intraseasonal variability as inferred from observations and GCM simulations. Part II: Influences on the extratropical circulation. J. Climate, submitted.

Project Report: **Diurnal Cycle of Precipitation, Clouds, and Water Vapor in Both Models and Satellite Data**

Principal Investigator: Baijun Tian (Princeton, now at Caltech)

Other Participating Researchers: B. J. Soden and S. Klein(GFDL), X. Wu(NESDIS)

NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:

These studies are motivated by the fact that the diurnal cycle of precipitation and clouds provides a stringent test of a model's convection and cloud modules. Yet many aspects of the observed diurnal cycle, including that of upper tropospheric humidity (UTH), are poorly documented. This study documents the diurnal cycle of UTH and its relationship to deep convection and high clouds in the whole Tropics, and evaluates the ability of the new GFDL AM2/LM2 to simulate these diurnal variations, relying on a new data set constructed from global, high-resolution (3-hourly, 0.1°x0.1° longitude-latitude) water vapor (6.7 μm) and window (11 μm) radiances from multiple geostationary satellites.

Methods and Results/Accomplishments:

Tian has documented the diurnal cycle of UTH and its relationship to deep convection and high clouds in the entire Tropics, utilizing a new data set of global, high-resolution water vapor and window radiances from multiple geostationary satellites, and he has evaluated the ability of the new GFDL AM2 model to simulate these diurnal variations. The observational study has highlighted distinct diurnal cycles of oceans and over land. For example, the diurnal cycle in UTH tends to peak around midnight over ocean in contrast to 0300 LST over land. Furthermore, UTH is observed to lag high-cloud cover by about 6 hours, and the latter further lags deep convection, implying that deep convection moistens the upper troposphere through the evaporation of the cirrus anvils.

Compared to the satellite observations, AM2 roughly captures the diurnal phases of deep convection, high-cloud cover, and UTH over land; however, the magnitudes are noticeably weaker in the model. Over the oceans, the AM2 has difficulty in simulating both the diurnal phase and amplitude of these quantities. These results reveal some important deficiencies in the model's convection and cloud parameterization schemes. In collaboration with S. Klein and Soden, Tian has experimented with some modifications to the model's convection scheme, but none of these have substantially improved the model's diurnal cycle over the oceans.

Publications:

Tian, B., B. J. Soden, and X. Wu, 2004: Diurnal cycle of convection, clouds, and water vapor in the tropical upper troposphere: Satellites versus a general circulation model. *J. Geophys. Res.*, **109**, D10101, doi:10.1029/2003JD004117.

Project Report: **Diurnal Cycle of Summertime Deep Convection over North America**

Principal Investigator: Baijun Tian (Princeton)

Other Participating Researchers: B. J. Soden, I. M. Held, and N.-C. Lau (GFDL), S. D. Schubert, M.-I. Lee (GSFC), R. W. Higgins and H.-K. Kim (NCEP)

NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:
The purposes of this study are two-fold: First, we assess the reliability of satellite radiances for inferring the diurnal cycle of precipitation by comparing satellite retrievals with surface precipitation observations, which are both available over the US for the year 1999. Second, relying on the high-resolution (0.1°x0.1°, 3-hourly) satellite radiances, we document the spatial structure of the diurnal cycle of summertime deep convection and precipitation over North America.

Methods and Results/Accomplishments:
Tian has used high resolution satellite data to study the diurnal cycle of summertime precipitation over North America. In this study a remarkable agreement is found in the diurnal phase of precipitation between satellite and surface data. The diurnal amplitude of precipitation from satellite data is also comparable to that from surface data over most regions of the United States, except for the Great Plains, where the diurnal amplitude from satellite data is systematically larger than that from surface data. This result indicates that satellite IR radiances are reliable for inferring the diurnal cycle of precipitation, especially the diurnal phase, over land regions. Based on the satellite data, the largest diurnal cycle of precipitation over North America is found over northwestern Mexico, along the western slope of the Sierra Madre Occidental (SMO), which is associated with the NAM. The diurnal amplitude is around 10 mm/day and the precipitation tends to peak in early evening. In addition, the diurnal phase shift from early evening at the east of the Rockies to midnight at the Great Plains due to the decrease of surface elevation is well resolved by the satellite data. It will be difficult for GCMs to simulate these aspects of the diurnal cycle of precipitation without much higher horizontal resolution.

Publications:
Tian, B., I. M. Held, N. C. Lau, and B. J. Soden, 2004: Diurnal cycle of summertime deep convection over North America: A satellite perspective. Submitted to *J. Geophys. Res.*

Project Report: **Large-scale atmospheric and oceanic dynamics**

Principal Investigator: Geoffrey Vallis (Princeton),

Other Participating Researchers Roger Samelson (OSU), Bill Dewar (FSU), Adam Scaife (Hadley Center).

NOAA's Goal #2 - Understanding Climate Variability and Change to Enhance Society's Ability to Plan and Respond (50%) and,
NOAA's Goal #3 – Serve Society's Needs for Weather and Water Information (50%)

Objectives:
(1)To develop an understanding of the dynamics and predictability of the North Atlantic Oscillation; (2)To develop an understanding of the structure of the main oceanic thermocline.

Methods and Results/Accomplishments*:*
Over the past few years we have developed a theory of the North Atlantic Oscillation and so-called annular modes, showing how they are a product of eddy-meanflow interaction and the variability of the eddy-driven jet. We have developed both barotropic and idealized stochastic models of these phenomena that illustrate their essential dynamics in a transparent way (Vallis et al 2004; Gerber and Vallis, 2005)

In collaboration with Adam Scaife of the Hadley Center, we have explored the mechanisms that have led to an increase in the NAO index over the last two decades. While much of this increase is undoubtedly a product of natural variability, we have shown that a proper representation of the stratosphere is essential if such effects are to be captured in General Circulation models.

On the oceanic side, in collaboration with Samelson and Dewar, we have developed a theory for the formation and maintenance of 'Mode Water', which is one of the most prominent isostads in all the world's subtropical basins.

Finally, in collaboration with B. Fox-Kemper, E. Gerber, R. Zhang, and N. Grianik we have variously explored the effects of oceanic mesoscale eddies on the thermocline, developed an analytic model of annular modes, shown how Great Salinity anomaly events can significantly impact the North Atlantic, and are exploring the factors determining atmospheric stratification, respectively. These activities are detailed elsewhere in this report.

Publications:
G. K. Vallis, E. P. Gerber, P. J. Kushner, and B. A. Cash, 2004: A Mechanism and Simple Dynamical Model of the North Atlantic Oscillation and Annular Modes, *J. Atmcs Sci.*, 61, 264-280

E. P. Gerber and G. K. Vallis, 2004 A Stochastic Model for the Spatial Structure of Annular Patterns of Variability and the North Atlantic Oscillation. *J. Climate* (in press),

A. Scaife, J. Knight, C. Folland and G. Vallis, 2004 A winter surface climate response to changes in upper level circulation.. Submitted to *Science*.

Grianik, N, Held, I, Smith, K.S. Vallis, G.K. 2004. The effects of nonlinear drag on the inverse cascade in two-dimensional turbulence. *Phys. Fluids* (in press).Zhang, R. and G. K. Vallis, 2004.

The Role of the Deep Western Boundary Current in the Gulf Stream Path and Northern Recirculation Gyre, *J. Phys. Oceanog.* (submitted).

Project Report: **Tropical Climate Variability And Prediction**

Principal Investigator: Andrew T. Wittenberg(Princeton, now at GFDL)

Other Participating Researchers: Tony Rosati (GFDL), Matthew Harrison (GFDL), Shaoqing Zhang (UCAR), Gabriel Vecchi (UCAR), George Philander(Princeton), Alexey Fedorov (Princeton), Frédéric Marin (Princeton), Marcelo Barreiro (Princeton), Eli Galanti (IRI/LDEO), Chidong Zhang (Univ. Miami/RSMAS), Javier Zavala-Garay (Univ. Miami/RSMAS), Andrew Moore (Univ. Colorado, Boulder), Eli Tziperman (Harvard), Jake Gebbie (Harvard),Tony Lee (JPL/NASA), Ichiro Fukumori (JPL/NASA), Patrick Heimbach (MIT), Ralf Giering (FastOpt), Steve Hankin (PMEL), Ansley Manke (PMEL), Kevin O'Brien (PMEL), NOAA/CDEP ODASI Consortium (COLA, GFDL, IRI, LDEO, NCEP, NSIPP)

NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond (70%)
NOAA's Goal #3: Serve Society's Needs for Weather and Water Information (30%)

Objectives:
1. Improve simulations of the tropical Pacific and ENSO in coupled GCMs.
2. Improve seasonal-to-interannual climate forecasts.
3. Develop accurate ocean state estimates for the scientific community.

Rationale:
Seasonal-to-interannual (SI) climate variations, including the El Nino / Southern Oscillation (ENSO), have potent impacts on global weather, agriculture, and natural ecosystems. Yet these variations remain difficult to predict. Improving SI forecasts requires improved models, better initial conditions, and a better representation of forecast uncertainty, and these in turn call for improved understanding and more accurate observational analyses. Society also needs to know how tropical variability like ENSO may respond to possible future climate change. Wittenberg's work targets each of these, with a focus primarily on the tropical Pacific upper ocean and lower atmosphere.

Methods And Results/Accomplishments:
Wittenberg (2002) provided a detailed analysis of tropical Pacific surface observations over the past four decades, advanced a new hybrid statistical/dynamical model of El Nino, and drew upon theoretical and GCM results to explain how and why ENSO behavior and predictability are sensitive to the tropical climatology. An intercomparison of observational wind stress analyses (Wittenberg 2004) was published. Wittenberg also utilized the statistical atmosphere and hybrid coupled model to explore the role of noise in ENSO variability (Wittenberg & Harrison 2003), the impact of this noise on ENSO predictability (Fedorov et al. 2003), and the effect of the climatological meridional wind stress on ENSO (Wittenberg & Philander 2004).

Recent Activities (prior to GFDL/NOAA hire 15 March 2004):

1. Working to improve the simulation of the tropical Pacific in the atmospheric, oceanic, and coupled GCMs developed at GFDL, and assessing the impact of slow climate changes on ENSO. Wittenberg has been part of a team analyzing ENSO variability in a series of coupled

climate models that were evaluated during the development of GFDL's next coupled climate model (CM2). Interesting findings include the improvement of the ENSO-driven surface wind stress changes and the period of ENSO due to including cumulus momentum transport, and the sensitivity of the ENSO amplitude to oceanic mixing and low cloud parameterizations. To facilitate the GCM analysis, Wittenberg developed a suite of climatological, ENSO regression, and time series diagnostics that are now generated automatically for GFDL scientists whenever a new atmospheric or coupled integration is performed. In the coming year, Wittenberg will collaborate with GFDL scientists in studying how the model's ENSO is modified by increasing greenhouse gases. He is also collaborating with Frédéric Marin, Marcelo Barreiro, and George Philander (Princeton AOS Program) on applying the hybrid GCM and intermediate model to paleoclimatic problems.

2. Exploring how intraseasonal forcing, model physics, and assimilation procedures affect the simulation and prediction of ENSO. Wittenberg coupled a statistical atmosphere to a global version of the GFDL Modular Ocean Model (MOM4). The hybrid coupled model includes both deterministic and stochastic components, and provides a convenient testbed for coupled data assimilation and SI forecasting. This year he worked closely with Shaoqing Zhang of UCAR to implement and evaluate an Ensemble Adjustment Kalman Filter (EAKF) in the hybrid model, and to assess the skill of SI forecasts initialized using this technique (Zhang et al. 2004a,b). He has continued working to improve the statistical atmosphere and the hybrid GCM for use in operational ENSO forecasts, in collaboration with GFDL researchers and Eli Galanti and Dave DeWitt of the IRI. With the ODASI consortium, Wittenberg investigated the impact of TAO buoy data on ENSO forecasts; a report was presented at NOAA's 28th Climate Diagnostics and Prediction Workshop in October 2003.

The hybrid model is a powerful tool for understanding intraseasonal/ENSO interactions and ENSO predictability, and Wittenberg has pursued these avenues by assessing the relative roles of ocean preconditioning and atmospheric stochastic forcing in observed ENSO events over the past two decades. Results were presented at the AGU/CGU Joint Assembly in May 2004. Wittenberg also collaborated with Tony Rosati and Matt Harrison of GFDL, Chidong Zhang and Javier Zavala-Garay of the University of Miami, and Andrew Moore of the University of Colorado at Boulder, to assess the extent to which the Madden-Julian Oscillation (MJO) represents a particularly effective forcing for ENSO.

3. Developing an end-to-end quasi-operational SI assimilation and forecast system. Wittenberg has worked with GFDL and outside scientists to prepare accurate boundary forcings, streamline the data input and analysis, and develop a common self-describing data interface for ocean data assimilation. Special attention is being paid to the quality, physical consistency, representativeness, and error of the measurements. The goal is to provide operational climate forecasters at NOAA's Applied Research Centers (ARCs) with realistic ocean initial conditions, in near-real time, over the Internet. These initial conditions are currently being used to run SI ensemble hindcasts with the GFDL coupled climate model (CM2), and Wittenberg is using the hybrid coupled GCM to evaluate the relative merits (in terms of SI forecast skill) of traditional 3DVAR assimilation versus EAKF assimilation.

4. Creating an adjoint model for MOM4. The adjoint will be a key component of a planned four-dimensional variational (4DVAR) ocean data assimilation system at GFDL. Wittenberg has

configured a global version of MOM4 as a prototype for the adjoint and 4DVAR development, and with Shaoqing Zhang and Matt Harrison of GFDL, Ralf Giering of FastOpt,
Eli Tziperman and Jake Gebbie of Harvard, Tony Lee and Ichiro Fukumori of JPL, and Patrick Heimbach of MIT, he is working to ensure compatibility of the MOM4 Fortran-90 source code with TAF.

Publications:

Fedorov, A. V. , S. L. Harper, S. G. Philander, B. Winter, and A. Wittenberg, 2003: How predictable is El Nino? Bull. Amer. Meteor. Soc., 84, 911-919.

GFDL Global Atmospheric Model Development Team, 2004: The new GFDL global atmosphere and land model AM2/LM2: Evaluation with prescribed SST simulations. J. Climate, in press.

Wittenberg, A. T., 2002: ENSO response to altered climates. Ph.D. thesis, Princeton University. 475pp.

Wittenberg, A. T., 2004: Extended wind stress analyses for ENSO. J. Climate, 17, 2526-2540.

Zhang, S., J. L. Anderson, A. Rosati, M. Harrison, S. P. Khare, and A. T. Wittenberg, 2004: Multiple time level adjustment for data assimilation. Tellus A, 56, 2-15.

Zhang, S., M. J. Harrison, A. T. Wittenberg, A. Rosati, J. L. Anderson, and V. Balaji, 2004: Tropical Pacific ocean data assimilation using a parallelized ensemble filter with a stochastic hybrid coupled GCM. Mon. Wea. Rev., in revision.

Presentations:

Wittenberg, A. T., and A. Rosati, 2004: Tropical Pacific Climate & ENSO in the GFDL CM2/2. control simulations. Geophysical Fluid Dynamics Laboratory, Princeton, NJ.

Wittenberg, A. T., and A. Rosati, 2004: Tropical Pacific climate & variability in the GFDL CM2 global coupled GCM. 1st International CLIVAR Science Conference, Baltimore, MD. Also presented at the Ninth Annual CCSM Workshop, Santa Fe, NM.

Wittenberg, A. T., and A. Rosati, 2004: Sensitivities of ENSO: Lessons from the GFDL CM2 global coupled GCM. 1st International CLIVAR Science Conference, Baltimore, MD. Also presented at the Ninth Annual CCSM Workshop, Santa Fe, NM.

Galanti, E., M. Tippet, S. Zebiak, S DeWitt, A. T. Wittenberg, M. Harrison, T. Rosati, and M. Rienecker, 2004: On data assimilation and ENSO dynamical prediction. International Research Institute for Climate Prediction, Palisades, NY.

Wittenberg, A. T., and E. Galanti, 2004: Assessing the impact of stochastic forcing on ENSO events. 2004 Joint Assembly, Montreal, Canada.

Wittenberg, A. T., and S. G. H. Philander, 2004: The Pacific cold tongue and ENSO: Sensitivity to the meridional wind stress climatology. 12th Ocean Sciences Meeting, Portland, OR.

W. Stern, A. Rosati, R. Gudgel, M. Harrison, and A. T. Wittenberg, 2004: Subseasonal to interannual prediction sensitivities in the GFDL/FMS GCM. 84th AMS Annual Meeting, Seattle, WA.

Wittenberg, A. T., T. Rosati, and I. Held, 2003: ENSO in the GFDL coupled model. Eighth Annual CCSM Workshop, Breckenridge, CO.

Project Report: **Land Surface Predictability and Prediction Studies at GFDL**

Principal Investigator: Eric F. Wood(Princeton)

Other Participating Researchers: Lifeng Luo , Sergey Malyshev and Stephen Dery(Princeton) Tony Gordon(GFDL)

NOAA's Goal # 2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

NOAA's Goal # 3: Serve Society's Needs for Weather and Water Information

Objectives

Background

Understanding the role of the terrestrial hydrosphere-biosphere in Earth's climate system, especially the coupling of land surface hydrologic processes to atmospheric processes over a range of spatial and temporal scales, is an integral component of the World Climate Research Programme's (WCRP) Global Water and Energy Experiment (GEWEX), NOAA's GEWEX Americas Prediction Project (GAPP), which is now part of the NOAA/OGP Climate Prediction Project for the Americas (CPPA).

CPPA blends NOAA's existing PACS and GAPP programs into a single process research program with the goal to extend the scope and improve the skill of intraseasonal-to-interannual climate prediction over the Americas. Research under CPPA will focus in four areas (Patterson, 2004

– determining the predictability of warm-season precipitation anomalies over the Americas on intraseasonal and longer timescales,
– achieving an improved understanding and more realistic model simulation of ocean, atmosphere, and land process which give rise to climate predictability,
– defining, developing, and improving the requisite observing and prediction systems for monitoring and predicting climate variations in the Americas,
– providing decision support through interpretation of climate forecasts for water resource management applications.

Project Research Objectives

The project "Land Surface Predictability and Prediction Studies at GFDL" is directly responsive to the CPPA research program, and has the following research objectives:

1. To carry out seasonal predictability studies using the GFDL climate model within the Flexible Modeling System (FMS), to establish scientific sound methodologies to create initializations based on the land surface states derived from observations and make seasonal predictions. This addresses the GAPP/CPPA objective related to determining the predictability of warm-season precipitation anomalies over the Americas, in determining the effects of soil moisture and snow cover on the initialization in seasonal predictions, and to understand better the seasonal cycle of snow and soil moisture.
2. To develop seasonal hydrological forecast system in collaboration with the University of Washington, which addresses the CPPA research of developing a prediction system for the Americas and providing decision support through interpretation of climate forecasts for water resource management applications.

3. To interact with GFDL climate modeling group to incorporate essential elements of the Princeton VIC land surface model into the new GFDL climate models, and to test the impact of the new land surface scheme in climate predictions, which addresses the CPPA goal of achieving an improved understanding land process which give rise to climate predictability.

Our research falls under the following goals established by NOAA: (1) Understand climate variability and change to enhance society's ability to plan and respond (**70%**) and (2) Serve society's needs for weather and water information (**30%**).

Methods and Research Accomplishments

The work done at Princeton University followed three efforts: (i) predictability of seasonal climate by the GFDL model; and (ii) operational hydrologic seasonal forecasts useful for applications, and (iii) Arctic hydrology predictability from AO anomalies. These efforts are well connected, but each of them addresses the research goals from a different perspective.

Precipitation Predictability Study

This area focuses on answering questions related to predictability of the hydrological cycle, such as: (i) what is the predictability of precipitation at seasonal-to-interannual time scale? (ii) what are the factors that contribute to the predictability?; (iii) can we improve the seasonal precipitation forecast by increasing our knowledge on those contributing factors?.

The approach for this predictability research is to design and perform numerical experiments (GCM integrations) with the GFDL climate model, and to analyze the model output and quantify the predictability of terrestrial hydrological system. We have been using the GFDL flexible modeling system (FMS) to carry out GCM simulations. The set of experiments are shown in Table 1, and are designed to enable us to separate the impact of different components in the climate system on precipitation variability and potential predictability. These components include ocean boundary conditions (SST) and land surface boundary conditions (land surface model). Contribution from SST can be investigated by comparing model integrations forced with observed SST time series with integrations forced with climatological SST. Contribution from land can be investigated by comparing model integrations among climatological land conditions, prescribed interannually varying land conditions and fully interactive land conditions. The combination of these components results in 6 experiments listed below.

Table 1: Experiments performed at GFDL

	Climatological Land	***Prescribed interannual-varying Land***	***Interactive land***
Climatological SST	A	ALX	AL
Observed SST	AO	AOLX	AOL

We have performed six 22-year (1979-2000) ensemble runs for each of the experiments. This gives us 132 years (or 126 years if we omit the first year) of model outputs for each experimental setup. The Hurrell SST is used from 1979- 2000. The climatological land comes from the climatology of six AOL ensembles. The prescribed interannually varying land condition comes from the first ensemble of the AOL experiment.

We have started analyzing the model output, with focus on the land contribution to mid-latitude precipitation variability. All the results and the progress on this can be found at http://hydrology.princeton.edu/~luo/research/SI. As one example of the results, look at Figure 1 and 2 below.

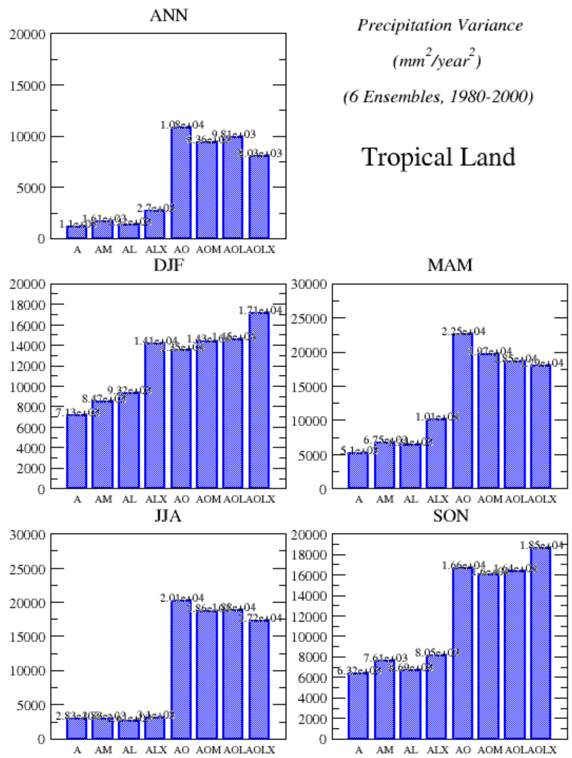


Figure 1: Precipitation variance for Tropical Land for the eight experiments, from left to right being A, AM, AL, ALX, AO, AOM, AOL, AOLX, and M means the climatology uses the Ensemble mean.

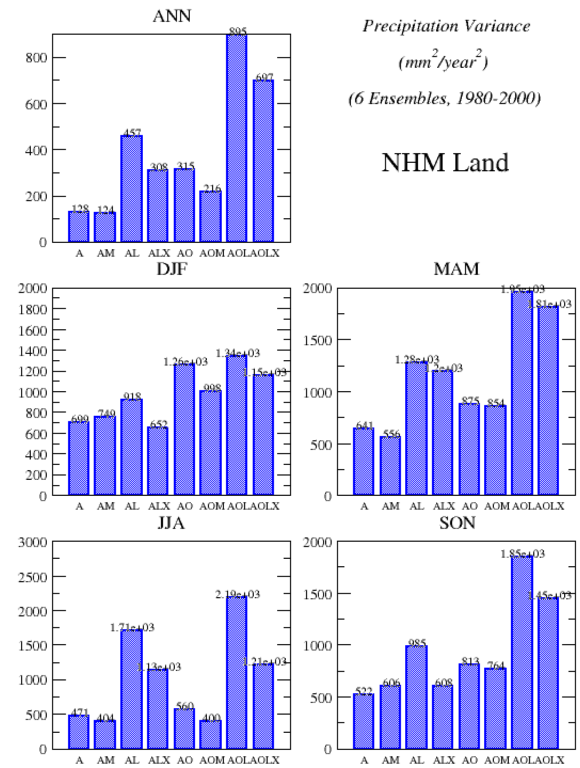


Figure 2: Precipitation variance Northern Hemisphere mid-latitude land for the eight experiments, from left to right being A, AM, AL, ALX, AO, AOM, AOL, AOLX, and M means the climatology uses the Ensemble mean.

Figure 1 shows the change in precipitation variability across the ensembles as ocean or land variability is added. For the tropics, these preliminary results demonstrate that almost all precipitation variability (in the GFDL FMS climate model) can be attributed to ocean variability. For the with the Northern Hemisphere mid-latitude land area, summertime land variability (AL and AOL experiments) contribute to the precipitation variability but for the winter season (DJF), ocean variability dominates the precipitation variability. This suggests that knowledge of ocean SST will contribute to seasonal precipitation predictability in the winter but land states (mostly soil moisture) contribute to seasonal summertime precipitation predictability.

Figure 3 shows the change in precipitation potential predictability - represented by the coherence among ensembles – between AOL and AOLX. The increase in potential predictability is due to the information coming from the land surface condition. This result indicates that having an initialization scheme for the land surface conditions (soil moisture, snow cover, etc) has the hope to improve the seasonal forecast over the North America (and other parts of the world). This needs to be consolidated with real forecast that we will carry out this year.

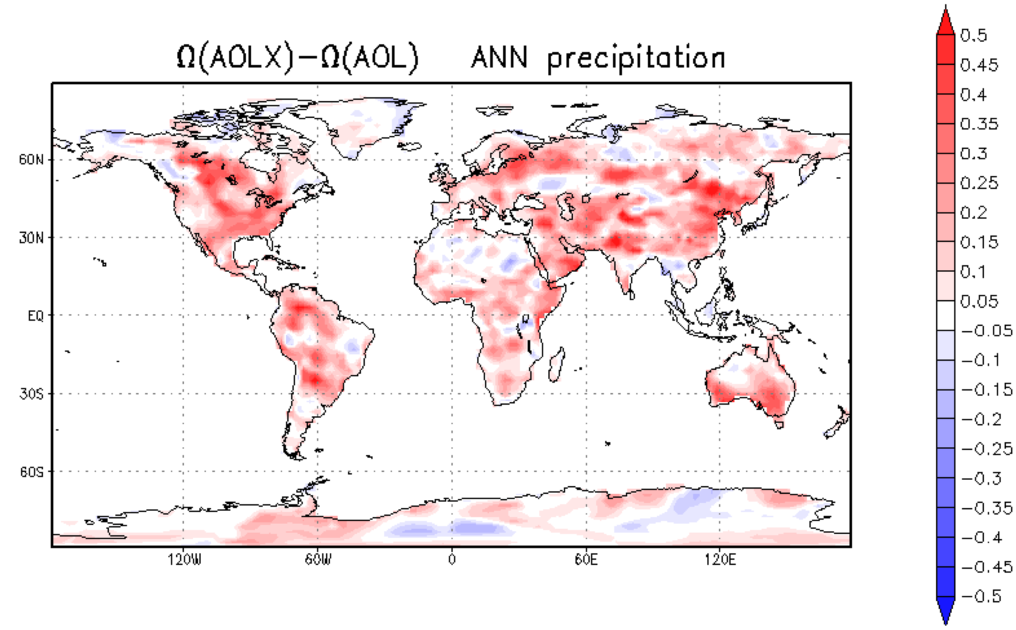


Figure 3: The coherence among ensembles (potential predictability) in annual precipitation increases over the land area in the northern hemisphere mid-latitude, when the land surface conditions are known. This result gives hope that a soil moisture initialization scheme will help improve seasonal precipitation forecast.

Further analysis of the ensembles and a quantitative description of the GFDL FMS seasonal predictability will be the focus for the coming year. Additionally, we need to determine whether we need to compute additional ensembles and/or extend the length of each run if necessary. Then we will start to perform testing seasonal forecast/hindcast using the GFDL FMS, to augment the Global Spectral Model (GSM) work we are doing under the operational/applications track, whose progress is described below. In summary, we are on schedule with this work.

Seasonal Hydrology Forecast System

This area focuses on answering questions related to the usefulness of seasonal climate predictions for hydrologic forecasting at river basin scales, and focuses on the scientific issues of (i) downscaling seasonal climate scales to hydrologic scales and (ii) skill of seasonal predictions for applications. Thus, this effort focuses on building a seasonal hydrologic forecast system using seasonal climate predictions, and testing its suitability for operational use and applications. In doing so, we also are able to investigate the predictability of streamflow and other land surface hydrologic conditions using the VIC land surface model with the current seasonal forecast released from operational centers.

The approach used is to develop a quasi-operational hydrologic forecast system and initially test it over the Ohio basin, using seasonal forecasts based on NOAA's Global Spectral Model (GSM) at NCEP and NASA Seasonal-to-Interannual Prediction Project (NSIPP) 6-month forecasts. This goal has been met. Initially, the prototype hydrologic forecast system for the

Ohio River basin is based on the VIC hydrological model, but it can be extended to include other land surface models. We use the seasonal forecasts from to force VIC, and a simple routing model to produce streamflow forecast for specific gauge locations within the Ohio basin. The forecast system takes the monthly mean precipitation and near surface air temperature from GSM and NSIPP and corrects them for bias. This is done using the historical probability distribution of the observations in comparison to the model's climatological distribution estimated from either the hindcast set of runs or a multi-decades AMIP-type integration. The bias correction method is described by Wood et al. (2002). The bias correction is done at the GCM grid-scale and the correction factors are downscaled to 1/8 degree at which the hydrological forecast system is running. This method efficiently reduces the bias in the GCM precipitation and air temperature both in their first and second statistical moments (Figure 4). The forecast system is running at a daily time step, the atmospheric forcing comes from re-sampling and adjusting of the observations; namely the 50 year NLDAS forcing described by Maurer et al, (2002). The initial condition of the land surface system is the spin-up state using the real-time NLDAS forcing. We have also implemented the NWS's Ensemble Streamflow Prediction (EPS) approach (basically resampling from the historical record and utilizing the NLDAS initial land state for the streamflow forecasts).

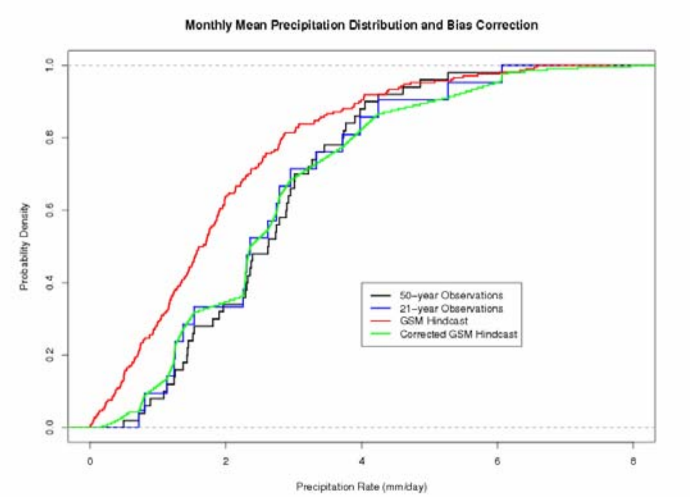


Figure 4: The bias correction scheme efficiently removes the systematic bias that exits in the GCM precipitation and temperature fields.

At present, we are able to produce 6-month streamflow forecast over Ohio basin, and it will be extended to other eastern US river basins. These forecasts are 'issued' every month in an operational fashion closely following the release of GSM and NSIPP seasonal forecast. The preliminary forecast products are available at: http://hydrology.princeton.edu/~luo/research/FORECAST/. We also perform streamflow hindcasts (retrospective forecasts) each month over the Ohio basin using the GSM hindcast. These hindcast will be the basis for the validation and evaluation of the forecast system as well as the GSM forecast accuracy. Figure 5 gives an example for USGS gauge 03373500, East fort White River at Shoals, IN in the Lower Ohio basin and with a basin area of 4927 sq. mi. Such a forecast system enables us to resolve whether seasonal climate forecasts are skillful and whether this skill can be transferred into useful hydrological forecast at seasonal timescale. Our focus now is to improve this forecast system over the Ohio basin before we extend the forecast area to the entire east portion of continental US.

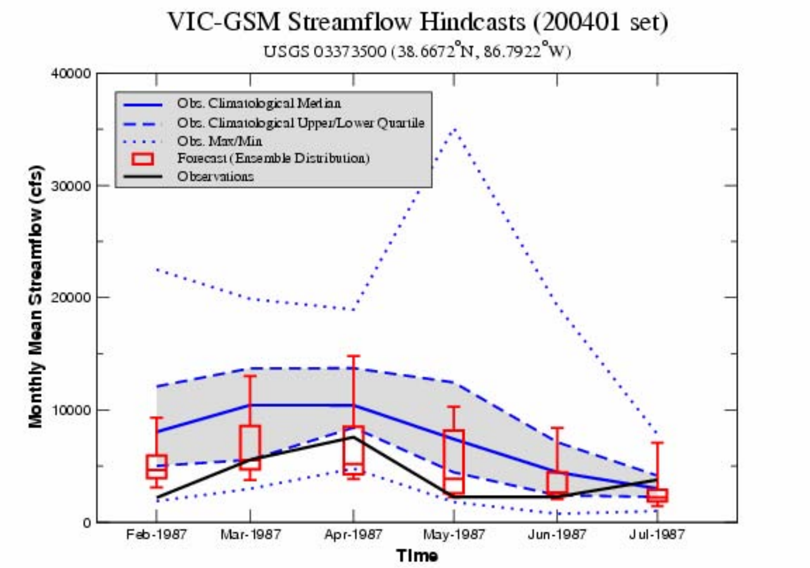


Figure 5: Six months seasonal streamflow forecast for the East fort White River at Shoals, IN for the period of February 1987 to July 1987 based on NCEP GSM seasonal forecasts and its companion hindcasts released in January 2004. The black line is the observations for the hindcast period.

Over the next year we will evaluate the streamflow forecasts in terms of its predictability and forecast accuracy over the Ohio basin and perhaps extending the products to include soil moisture and snow cover. Then we will be able to expend the system to cover other basins. We will perhaps include IRI's suite of seasonal climate model predictions in the forecast system.

Once we can do seasonal forecasting with the GFDL FMS climate model (i.e. the work described in section 3.1), we will merge the FMS predictability work with the seasonal hydrologic forecasts, and provide GFDL FMS-based seasonal hydrological forecasts.

Predictability in Arctic Terrestrial Hydrology

Riverine inflows to the Arctic Ocean play a key role in climate, both regionally and globally. Low net radiation over the pan-Arctic drainage area and the ocean/sea ice surface results in low evaporative demand, and hence a large net export of freshwater from the Arctic Ocean. This export of freshwater has important implications for the thermohaline circulation of the global ocean. Snow plays a major role in the water balance of the region's land surface, and is the dominant source of streamflow. Nonetheless, notwithstanding the importance of land processes to arctic and global climate, relatively little is known about the interaction of land surface hydrological variability in the Arctic and climate, and whether high-latitude hydrology is predictable based on large-scale climate anomalies such as PDO, AO or NAO.

The central science question around which this element is focused is

> "How do the dynamics of large–scale high latitude climate interact with and effect the temporal and spatial variability and change of freshwater discharge, how will the coupled arctic climate system respond to changes in riverine discharge of freshwater?"

Although numerous studies have hypothesized effects on the global climate system of changes in the arctic freshwater balance, the more specific effects of temporal and spatial changes in river discharge have yet to be examined. One argument holds that because the transport time for sea ice out of the Arctic Ocean is several years, changes in seasonality and the spatial distribution of river discharge would be damped out in terms of their broader scale effects on climate. However, changes in freshwater discharge such as those that have been observed over the last few decades in several large Russian rivers almost certainly will affect the distribution of sea ice in the estuaries and continental shelf waters, and in turn energy exchanges over larger areas. Whether such local changes, when integrated over the major rivers and numerous smaller ones discharging to the Arctic could affect climate at regional and global scales is an unknown that we intend to address. Similarly, teleconnections between the global climate system and regionally the arctic climate system, and changes in the space-time distribution of snow cover over land and the subsequent riverine discharge are poorly known. Earlier ablation of snow cover has a large effect on the albedo of the land surface, and hence a direct effect on land-atmosphere energy exchanges, but it also affects the seasonality of river flows with consequent possible effects outlined above.

The research is closely connected to related research being carried out jointly by Princeton University (EF Wood), University of Washington (DP Lettenmaier) and the University of Victoria (Andrew Weaver) under NSF funding. The methods being used include:

(i) Development and compilation of high latitude climate data sets that can be used for diagnostic analyses, off-line model forcings and validation studies;

(ii) Teleconnection studies using observations, off-line hydrologic model runs, ERA40 reanalysis model output and GFDL (and other) GCM model outputs; and

(iii) Sets of model runs based on an experimental design that include a series of uncoupled, partially coupled, and fully coupled simulations with a combination of sea ice, atmosphere, and ocean models that are currently components of the University of Victoria’s Earth System Climate Model, and the University of Washington and Princeton University’s Variable Infiltration Capacity (VIC) land surface model.

Both sets of models have been designed for, and extensively tested with, arctic data. The science questions will be posed through a combination of model runs in which sea ice, ocean, and land surface models are run in off-line mode, and various aspects of the off-line climatologies (for a retrospective period ranging from 20 to 50 years) will be prescribed in partially coupled ensemble runs of the fully coupled model system. These partially coupled model results will be compared with results of fully coupled ensemble climate simulations to isolate the effects of interactions among the land, sea ice/ocean, and atmosphere.

Besides looking at river discharge into the Arctic Ocean, a compilation of river discharge into Hudson, James, and Ungava Bays was carried out. The catchment of the Hudson Bay system cover most of the central portion of Canada and extend westward to the Rocky mountains (across the prairies). Their discharge is an important source of freshwater into the Labrador Sea, but is under-studied. A paper on the discharge characteristics and trends in the discharge is under review. ('Characteristics and Trends of River Discharge into Hudson, James, and Ungava Bays, 1964-1994'). During the last year the research focused on carrying out teleconnection studies that related AO anomalies to riverine discharge across the arctic, with a focus on the into Hudson, James, and Ungava Bays region, an area that is understudied and has climate implications because of its discharge into the Labrador Sea. A paper on the discharge characteristics and trends in the discharge is under review. ('Characteristics and Trends of River Discharge into Hudson, James, and Ungava Bays, 1964-1994'). It is hypothesized that their magnitude and variability affects the freshness of the Labrador Sea with significant seasonal climate implications.

Analysis of the variability of the total river discharge into the Hudson Bay system has revealed a significant teleconnection between it and the Arctic Oscillation (AO) index. A paper describing this finding is in press (*Geophysical Research Letters*) ('Teleconnection between the Arctic Oscillation and Hudson Bay river discharge'). During the next year we plan to compile all remaining river discharges for the Canadian Arctic, excluding the Mackenzie River, since the latter data is widely available, and look carefully at the predictability of Arctic terrestrial hydrology.

References:

Dery, Stephen J., Marc Stieglitz, Edward C. McKenna, and Eric F. Wood, "Characteristics and Trends of River Discharge into Hudson, James, and Ungava Bays, 1964-1994", Climate, p. , vol. , ( ). Submitted

Dery, Stephen J. and Eric F. Wood, "Teleconnection between the Arctic Oscillation and Hudson Bay river discharge", Geophysical Research Letters, in press.

Maurer, E.P., A.W. Wood, J.C. Adam, D.P. Lettenmaier, and B. Nijssen, 2002, A long-term hydrologically-based data set of land surface fluxes and states for the conterminous United States, J. Climate. 15, 3237-3251

Patterson, M (2004) “NOAA Pan American Climate Studies and the New Climate Prediction Project for the Americas”, presentation at the US CLIVAR Pan American Workshop, Boulder, Colorado, September 16-18, 2003. (see http://www.usclivar.org/Meeting_Files/PanAm_0903/PanAm_PACS_Patterson.pdf)

Wood, A.W., Maurer, E.P., Kumar, A. and D.P. Lettenmaier, 2002, Long range experimental hydrologic forecasting for the eastern U.S. J. Geophys. Res., 107(D20), 4429, doi:10.1029/2001JD000659

Publications and Presentations:

Dery, Stephen J., Marc Stieglitz, Edward C. McKenna, and Eric F. Wood, "Characteristics and Trends of River Discharge into Hudson, James, and Ungava Bays, 1964-1994", Climate, p. , vol. , ( ). Submitted

Dery, Stephen J. and Eric F. Wood, "Teleconnection between the Arctic Oscillation and Hudson Bay river discharge", Geophysical Research Letters, in press.

Dery, Stephen J., Marc Stieglitz, E. McKenna and Eric F. Wood 2004 Recent trends and changes in freshwater discharge into Hudson, James, and Ungava Bays, *Eos Trans. AGU,85*(17), Jt. Assem. Suppl., Abstract H34A-03

Luo, Lifeng, Andrew Wood, Eric F. Wood, Dennis P Lettenmaier 2004. An Experimental Seasonal Streamflow Prediction System and The Streamflow Predictability Over the Ohio River Basin, *Eos Trans. AGU,85*(17), Jt. Assem. Suppl., Abstract H33A-04.

Luo, Lifeng Eric F Wood, Tony Gordon and Sergy Malyshev 2004 Precipitation variability and predictability in the GFDL General Circulation Model, *Eos Trans. AGU,85*(17), Jt. Assem. Suppl., Abstract H31E-05.

Project Report: **Scaling of Space, Time, Heterogeneous Hydrologic Dynamics**

Principal Investigator: Eric F. Wood(Princeton)

Other Participating Researchers: Dr. Hatim Sharif (Princeton)

NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Research Objectives:

Long-term basin-scale hydrologic response is related to interannual climatic variations. Topography as well as large-scale atmospheric processes, soil memory, and vegetation change control multi-year land surface and subsurface processes. The use of long records of observational data to determine the variability of land surface moisture fluxes and storages is instrumental for answering key science questions concerning the degree to which the global hydrologic cycle is intensifying in response to potential anthropogenic climate forcing. General Circulation Model simulations and regional and global water budget analyses have highlighted the importance of land-surface hydrology for regional- and global-scale energy and water exchanges. Conversely, long term simulation, when coupled with the study of climatic controls and variables, can improve the prediction of hydrologic responses associated with interannual climatic variability. Thus, the main goals of the research under this element are:

The objectives of this study are to:
Identify physiographic and climatic controls on the spatial variability of terrestrial hydrologic fluxes and states, and the scales at which they are most dominant;
Develop sub-grid parameterization approaches for hydrologic processes that are appropriate for GCMs; Examine the spatial scaling properties of soil moisture; and perform a statistical analysis of the teleconnection between climatic variables and land surface states and processes, such as soil moisture and evapotranspiration.

Methods and Research Accomplishments:

The approach taken is to utilize a very high resolution (1-km2 modeling grids) observational data set, developed by investigators for the 576,000 km2 Arkansas-Red River basin located in the Southern Great Plains (SGP) of the United States (see figure 1), to force a coupled water-energy land surface model, and to use the modeled hydrologic variables in lieu of observations for the heterogeneity and scaling studies. The Red/Arkansas River basin has extensive meteorological and hydrological data collection networks. For this reason, these basins were the first large scale areas studied under the Global Energy and Water Experiments (GEWEX) Continental Scale International Project (GCIP). The basin contains a number of U.S. Department of Agriculture - Agricultural Research Service (USDA-ARS) experimental catchments; the U.S. Department of Energy Atmospheric Radiation Cloud and Radiation Testbed (ARM-CART) site; and the Cooperative Atmosphere-Surface

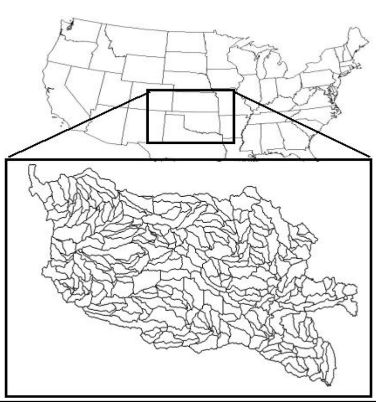


Figure 1: Location of the Arkansas-red River basin in the Southern Great Plains region of the United States. The basin was divided into 314 sub-basins shown on the inset

Exchange Study (CASES) boundary layer facility. Portions of the basin were the site of the 2002 International H2O Project (IHOP-2002), and the Department of Energy IOP 2002 experiments. In addition, the National Weather Service's Arkansas-Red River Forecast Center was the first prototype site for modernized River Forecast Centers technologies and operations.

The rainfall climatology of the basin displays a strong east/west gradient, with drier conditions prevailing in the western part of the basin. The region generally receives its maximum precipitation in the spring and fall and has a relatively dry late summer. Significant orographic summer precipitation at the highest elevations in the west near the continental divide is an exception. As for winter precipitation, snow accumulation provides a significant contribution to the headwaters, but covers a relatively limited area and does not significantly influence the climatology and hydrology of the basin. Runoff ratios (the ratio between runoff and precipitation) in the basin are generally on the order of 10 to 20%. Typical seasonal cycles of soil moisture exhibit maximums during the late spring and minimums during the late summer and early fall as a result of precipitation and temperature seasonality. Late growing season minimums can be pronounced and soil moisture control on evapotranspiration is common during the summer months.

2.1 Dataset Over view

Table 1 presents the various sources that form the basis for the forcing data set. The data includes soil, vegetation and topographic data, as well as precipitation and radiation data. Also needed are the basic parameters within the land surface model.

Table 1: Variables and data sources for the Red-Arkansas simulation study.

Variable	Description	Source
Soil	1-km texture/classification, soil depth, residual moisture	State Soil Geographic database (STATSGO)
Soil hydraulic properties	Conductivity, porosity	Rawls et al (1982), Clapp and Hornberger (1978), Crosby et al (1984)
Topography	1-km digital elevation data	U. S. Department of Agriculture
Land cover	Classification	AVHRR-based
Surface parameters	e.g. Albedo, LAI, emissivity, roughness, evaporative resistance,	Various sources
Surface meteorology	Precipitation, air temperature, pressure dew point	50-year (1949-2000) Maurer et al. 2002
Surface radiation	Insolation, downdwelling longwave	50-year (1949-2000) Maurer et al. 2002

The long climate simulations began Jan 01 1949 at 00:00 UTZ and ended on July 31 2000 at 24:00 UTZ. One of the main challenges in this study is handling of the massive (100's GB) input and output data, and the computing power needed to perform these model runs. Several utility programs and scripts were developed to compress, decompress, and reformat the input data. The land surface model used to generate the surface hydrology was run at NCAR in a semi-parallelized mode making use of the domain decomposition into 314 sub-basins. All water and energy fluxes were computed for the subcatchments and for the entire basin at hourly time steps. These fluxes include: infiltration-excess and saturation-excess runoff, baseflow, depth to ground water table, vertical water fluxes, canopy water balance, evapotranspiration, sensible, latent, and ground heat fluxes, surface and soil temperature. In addition, hourly soil moisture states for the four soil layers were produced at 1-km scale for the entire temporal and spatial domains, as soil moisture is the most important variable for this study.

2.2 Results and accomplishments

A 51-year simulation of water and energy fluxes over the entire Arkansas-Red based using a fully distributed land surface model was generated. The simulations were performed at fine temporal (hourly) and spatial (1 sq km) resolutions in an effort to bridge the gap between traditional hydrologic modeling, typically at finer temporal spatial resolutions on relatively small catchment, and regional land surface modeling. Our approach in model validation is to focus on both the accuracy of streamflow simulations at the sub-basin scale and diagnostics for the heat and water exchange at the land surface-atmosphere interface. This approach allows analyses of the biases and assures that biases at the sub-basin scale won't grow nonlinearly over time and lead to larger basin-scale biases.

Preliminary analysis of the simulations shows that the spatial patterns of temporarily averaged water balance components are similar to published climatological patterns, and clearly illustrates the observed strong east-west gradients of precipitation, runoff, and evapotranspiration (see figure 2). Streamflow accumulations at the sub-basin scale show good agreement betweens simulated and observed streamflow for catchments ranging in size between 880 km2 and 4211 km2.

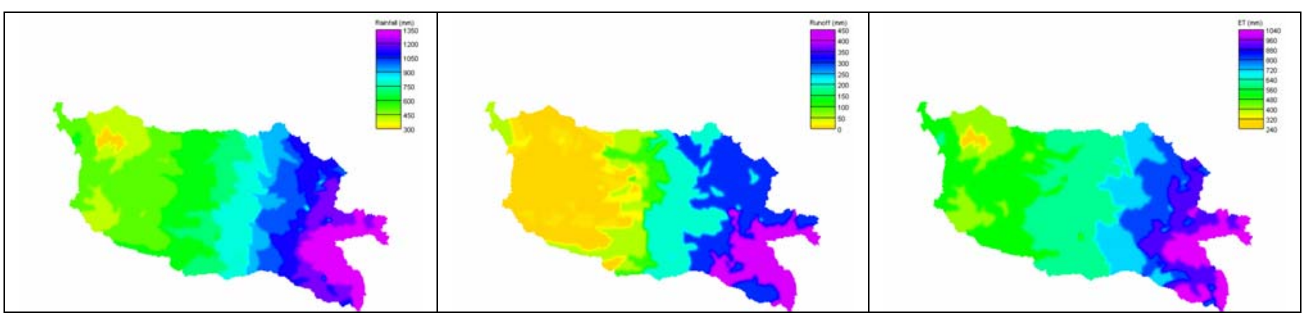


Figure 2: Spatial distribution of (left to right) mean annual precipitation, ranging from 300-1350 mm/yr; mean annual surface runoff, ranging from 0 to 450 mm/yr; and mean annual evapotranspiration, ranging from 240 to 1040 mm/yr, for the 1949-2000 period.

The analysis carried out to date show interesting trends in the water balance components: namely, (i) that surface runoff does not show a distinct shift of the east-west gradient during the summer months, as observed for precipitation; (ii) the variability of inter-annual basin-averaged precipitation varies strongly and decreases with time over the 50-year study period; (iii) precipitation variability is amplified in computed runoff but also decreases with time; (iv) both basin-averaged precipitation and computed surface runoff increased over the study period, on average, at different rates which indicates that evapotranspiration has increased over this period. This latter conclusion is supported by analysis of evapotranspiration at the sub-basin scale and observed discharge. Results agree with the mounting evidence of an accelerating hydrologic cycle over the conterminous United States. Monthly precipitation and runoff have also increased over the study period with the exception of May And July. The relationship between precipitation anomalies and runoff and soil water storage anomalies is being examined. While runoff amplifies positive anomalies in precipitation soil water storage amplifies negative anomalies.

The preliminary results presented here make us comfortable with the accuracy of the derived of soil moisture values that are being used in scaling and parameterization studies. The correlation between mean-monthly, seasonal, and annual variations in surface energy fluxes, soil moisture, and stream flow and large-scale atmospheric patterns is also being examined. We expect that the results of this analysis will clarify the sources of long-term hydrologic variability within the basin. Following the analysis of the variability across the basin, scaling studies will be initiated/

References:

Clapp, BJ, GM Hornberger, RB Clapp and TR Ginn 1984 A statistical exploration of the relationships of soil moisture characteristics to the physical properties of soils. Water Resourc. Resear. 20(6): 682-690.

Clapp, BJ and GM Hornberger 1978 Empirical relationships for some soil hydraulic properties, Water Resourc. Resear.14(4):601-604.

Maurer, E.P., A.W. Wood, J.C. Adam, D.P. Lettenmaier, and B. Nijssen, 2002, A long-term hydrologically-based data set of land surface fluxes and states for the conterminous United States, J. Climate. 15, 3237-3251

Rawls, WJ, Dl Brakensiek, and KE Saxton 1982. Estimation of soil-water properties, Trans. Of the ASAE, 25(5): 1316 &.

Project Report: **Hurricane Prediction and Dynamics**

Principal Investigator: Chun-Chieh Wu(National Taiwan University)

***Other Participating Researchers**:* Isaac Ginis (Rhode Island), Morris Bender (GFDL), Tim Marchok (GFDL)

NOAA's Goal #3 – Serve Society's Needs for Weather and Water Information

Objectives:
Wu is a senior visiting scientist, from National Taiwan University, collaborating with GFDL scientists on hurricane prediction and dynamics.

***Methods and Results/Accomplishments**:*
Using the GFDL Hurricane prediction System, Wu is evaluating the value of new dropsonde data available from the DOTSTAR project (Dropsonde Observations for Typhoon Surveillance in the Taiwan Region) on tropical cyclone (TC) prediction. Data-denial experiments have been run to study the impact of the dropsonde data. He is also studying different adaptive observation strategies.

Wu is also interested in the impacts of the typhoon-induced cold wake on regional climates. The typhoon-induced SST cold wake remains in the ocean for weeks, which potentially can affect the heat exchange between the ocean and the atmosphere, and thus affects the regional climate. Wu is collaborating with Gabriel Lau and starting to evaluate such effect from the GFDL GCM using the newly-analyzed SST satellite data from TRMM/TMI.

Wu's recent work, using the hurricane intensity prediction scheme of Emanuel (MIT) has suggested some perplexing new results on the role of warm oceanic eddy on the intensity evolution of Typhoon Maemi (2003). Work with Isaac Ginis (Rhode Island) and Morris Bender (GFDL) is on going to use the GFDL Hurricane-ocean coupled model to study the role of the upper ocean structure on the typhoon intensity.

A collaboration with Tim Marchok (GFDL) is also ongoing to investigate the mechanisms for tropical storm genesis in the operational global (AVN) model, and to gain better insight into the predictability of tropical storms.

Project Report: **Building A Real Time National Streamflow Information System**

Principal Investigators: Youlong Xia(Princeton), Chris Milly (GFDL)

Other participating researchers: Krista Dunne (GFDL), George Milly(GFDL summer student)

NOAA's Goal #3 - Serve Society's Needs for Weather and Water Information

Objective:
Xia is collaborating with Chris Milly (USGS and GFDL) and other scientists at the GFDL to build a Real Time National Streamflow Information System (NSIS). The overall purpose is to use GFDL land surface models (LM2 and LM3) and newly developed forcing data of North American Land Surface Assimilation System (NLDAS), U.S. Geological Survey streamflow data, and new soil and vegetation data to develop the NSIS. The NSIS is to serve society's needs for weather and water information in the United States (goal 3). A development strategy is shown in Figure 1.

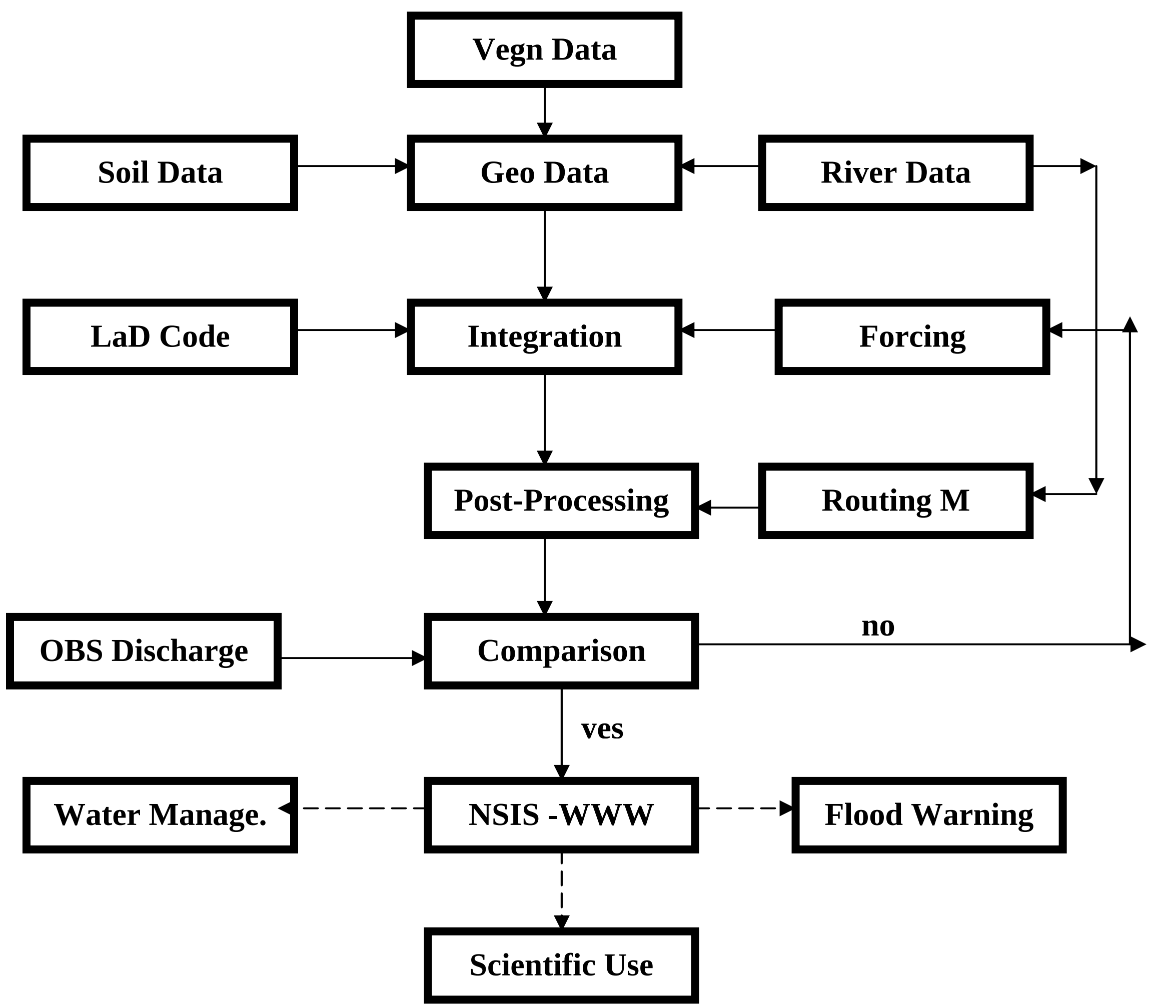


Figure1. A diagram about basic conceptual design for the NSIS

Methods and Results/Accomplishments:
The methods used in this project involve GFDL land surface models, optimization algorithms (e.g., very fast simulated annealing), uncertainty estimation techniques, and data statistical analysis techniques. The land surface models involve two versions being developed as part of GFDL's earth system modeling effort. The first version is LM2, currently available and in use in several GFDL models. The second is LM3, currently under development. LM2 has been used for global modeling of land water and energy balance by Milly and collaborators, and is being used in GFDL's coupled climate model at present. Because of its limitations, Xia used it to focus primarily on streamflow simulations at monthly, seasonal and annual time scales. LM3 is under development at GFDL and will include a more realistic soil hydrological model, a multi-layer snow submodel, and a new river routine model. LM3 is expected to provide better national streamflow simulations at fine time scales (e.g. hourly, daily) when available.

In order to run the land surface models, we need soil data, vegetation data, and atmospheric forcing data. Although GFDL land group had soil data, vegetation data and atmospheric forcing data, they exist some disadvantages, e.g., all data have a 1-degree resolution. These low-resolution databases need to be updated through new high-resolution (e.g., 0.125 degree) databases. In addition, forcing data based Global Soil Wetness Project Phase 1 have only two-year (1987-1988) data although Milly and Shmakin (2002a, 2002b) used long-term precipitation and radiation data. As shown in Milly and Shmakin (2002a; 2002b) and Shmakin et al. (2002), these data may be appropriate to study interannual variability of simulated streamflow. However, for monthly, daily and hourly streamflow, these data may be result in large errors for streamflow simulations.

For soil and vegetation data, George Milly, a student employed by GFDL for summer vacation time, help us to download new USGS soil and vegetation databases. He transferred image products of these two databases into input files with NETCDF format for 0.125^{o}, 0.5^{o},and 1^{o} resolution. These transferred databases are convenient in use not only for the NSIS but also for regional climate simulation at the GFDL.

For atmospheric forcing data, we downloaded 8-year (09/1996-7/2004) retrospective and 3-year (2002-2004) real-time hourly forcing data sets for the United States (and parts of Canada and Mexico) developed from NLDAS based on multi-institute efforts (Cosgrove et al., 2003). Quality of the NLDAS precipitation data was evaluated in part by comparing with lower resolution data sets currently available at GFDL. Because NLDAS precipitation data exist systematic biases from topographic effects, wind-blowing, wet loss, wet evaporation etc., we used very fast simulated annealing (VFSA) algorithm to select optimal adjustment factor to correct systematic bias from gauge measurements. As an example, we firstly used the VFSA algorithm to Valdai site, Russia, widely used in the Project for Intercomparison of Land-surface Parameterization Schemes phase 2d (Schlosser et al., 2000) to study the use of different hydrological variables and optimal parameter estimation of a land surface model. This work has been published as an extended abstract in *Proceedings of the 2nd international CAHMDA workshop on: The Terrestrial Water Cycle: Modeling and Data Assimilation Across Catchment Scales*, edited by A. J. Teuling, H. Leijnse, P. A. Troch, J. Sheffield and E. F. Wood, pp.96-99, Princeton, NJ, Oct. 25-27 and it was also submitted to *Journal of Geophysical Research*. After that, we used the VFSA algorithm to optimize the WMO regression models developed from WMO Solid Precipitation Measurement

Intercomparison using NLDAS retrospective precipitation, wind speed and air temperature and climate averaged correction factor derived by Legates and Willmott (1990). We used the derived optimal regression models to adjust NLDAS precipitation to reduce systematic bias from gauge measurements. In addition, we used Bayesian stochastic inversion algorithm to estimate the uncertainty of the adjusted NLDAS precipitation. This work will be appeared in AGU Fall meeting 2004, San Francisco, CA and will be submitted to *Journal of Geophysical Research*. To reduce systematic bias from topographic effect, we used monthly PRISM (Precipitation-elevation Regressions on Independent Slope Model) climate precipitation data from the Oregon State University (OSU) website (http://www.ocs.oregonstate.edu/prism/) for the same period to scale NLDAS precipitation data at monthly scale. After adjustment of systematic biases for NLDAS precipitation, a new NLDAS precipitation database was established.

At the same time, we designed 4 experiments using GFDL LM2P7 version: (1) 7-year NLDAS retrospective run (1997-2003), (2) 3-year NLDAS realtime run (2002-2004), (3) 7-year topographically corrected NLDAS retrospective run, and (4) 7-year topographically corrected ETA model precipitation run. We compared the simulated annual and mean monthly runoff to the results from the continental water, climate and earth-system dynamics project (PI: Chris Milly) and observed streamflow at 44 USGS gauge sites. In addition, we compared simulated evapotranspiration, soil moisture, sensible heat fluxes and latent heat fluxes for 4 experiments and previous results from Shmakin et al. (2002) as well.

References:

Cosgrove, B. A, and Coauthors, 2003: Real-time and retrospective forcing in the North American Land Assimilation System (NLDAS) project, *J. Goephys. Res*., 108, 8842, doi:10.1029/2002JD003118.

Milly, P.C. D., and A. B. Shmakin, 2002a: Global modeling of land water and energy balances: Part I: The Land Dynamics (LaD) model, *J. Hydrometeor*., 3, 283-299.

Milly, P. C. D., and A. B. Shmakin, 2002b:Global modeling of land water and energy balances: Part II: Land-charateristic contributions to spatial variability, *J. Hydrometeor*., 3, 301-310.

Shmakin, A. B., P. C. D. Milly, and K. A. Dunne, 2002: Global modeling of land water and energy balances: Part III: Interannual variability, *J. Hydrometeor*., 311-325.

Legates, D. R., and C. J. Willmott, Mean seasonal and spatial variability in gauge-corrected, global precipitation, *Int. J. Climatol*., *10*, 111-127, 1990.

Publications and Manuscripts:

Xia, Y., Z. L. Yang, C. Jackson, P. L. Stoffa, M. K. Sen, 2004a: Impacts of data and length on optimal parameter and uncertainty estimation of a land surface model, *J. Geophys. Res*., 109, D07101, doi:10.1029/2003JD004419.

Xia, Y., P. L. Stoffa, C. Jackson, and M. K. Sen, 2004b:Effect of forcing data errors on calibration and uncertainty estimates of CHASM model : A multi-dataset study, In *Observations, Theory, and Modeling of Atmospheric and Oceanic Variability, World Sci. Ser. On Meteorol. of East Asia*, vol.3, 340-358, World Sci., Singapore.

Xia, Y., M. K. Sen, C. S. Jackson, and P. L. Stoffa, 2004c: Multidataset study of optimal parameter and uncertainty estimation of a land surface model with Bayesian stochastic inversion and muticriteria method, *J. Appl. Meteorol*. (in press).

Xia, Y., Z. L. Yang, P. L. Stoffa, and M. K. Sen, 2004d: Optimal parameter and uncertainty estimation of a land surface model: Sensitivity to parameter ranges and model complexities, *Adv. Atmos. Sci.* (conditionally accepted with minor revision).

Xia, Y., Z. L. Yang, P. L. Stoffa, and M. K. Sen, 2004e: Use of different hydrological variables and impacts of atmospheric forcing errors on optimization and uncertainty analysis of the CHASM surface model at a cold catchment, In *Proceedings of the 2nd international CAHMDA workshop on: The Terrestrial Water Cycle: Modeling and Data Assimilation Across Catchment Scales*, edited by A. J. Teuling, H. Leijnse, P. A. Troch, J. Sheffield and E. F. Wood, pp.96-99, Princeton, NJ, Oct. 25-27 (conditionally accepted with minor revision for *J. Geophys. Res*.).

Xia, Y., P. C. D. Milly, and K. A. Dunne, 2004f: Optimization and Uncertainty estimates of WMO regression models for precipitation-gauge bias in the United States, AGU Fall Meeting 2004, San Francisco, CA (to be submitted to *J. Geophys. Res*.).

Project Report: **The Role of the Deep Western Boundary Current in the Gulf Stream Path and Northern Recirculation Gyre, and the role of Great Salnity Anomalies**

***Principal Investigator**:* Rong Zhang(Princeton)

***Other Participating Researchers**:* Geoff Vallis(Princeton)

NOAA's Goal #2 - Understanding Climate Variability and Change to Enhance Society's Ability to Plan and Respond

***Objectives**:*
Studying the mechanism affecting the Gulf Stream path and the formation of northern recirculation gyre, and understanding the mechanism of North Atlantic low frequency variability

***Methods and Results/Accomplishments**:*

The factors controlling the separation of the Gulf Stream from the North American coast remains a central problem in oceanography, and one of great importance for modeling the mean state and variability of the Atlantic Ocean (Dengg et al., 1996). Zhang and Vallis have investigated the mechanism affecting the Gulf Stream path and the formation of northern recirculation gyre with a hierarchy of models, including a robust diagnostic model and a prognostic model using a global 1^o ocean general circulation model coupled to a 2-dimensional atmospheric Energy Balance Model with hydrological cycle, and a simple numerical barotropic model. The results show that the Gulf Stream path and the formation of northern recirculation gyre are sensitive to both the magnitude of lateral viscosity and the strength of deep western boundary current (DWBC). In particular, we show that the bottom vortex stretching induced by a downslope DWBC near the south of the Grand Banks leads to the formation of a cyclonic northern recirculation gyre and keeps the Gulf Stream path downstream of Cape Hatteras separated from the North American coast. Both south of the Grand Banks and at the crossover region of the DWBC and Gulf Stream, the downslope DWBC induces strong bottom downwelling over steep continental slope, and the magnitude of the bottom downwelling is locally stronger than surface Ekman pumping velocity, providing strong positive vorticity through bottom vortex stretching effects. The bottom vortex stretching effect is also present in an extensive area in the North Atlantic, and the contribution to the North Atlantic subpolar and subtropical gyres is on the same order as the surface wind stress curl. Analytical solutions show that the bottom vortex stretching is important near the western boundary only when the continental slope is wider than the Munk frictional layer scale.

In addition, observed North Atlantic low frequency variability is often thought to be driven directly by the atmospheric North Atlantic Oscillation. Zhang and Vallis show that coherent large-scale low frequency variability in the North Atlantic, including variations of thermohaline circulation, deep western boundary current, northern recirculation gyre and Gulf Stream path, can be induced by the observed high-latitude oceanic Great Salinity Anomaly events, using a global 1^o ocean general circulation model coupled to a 2-dimensional atmospheric Energy Balance Model with hydrological cycle. Recent atmospheric studies have suggested that a positive low frequency North Atlantic Oscillation phase can be forced by a dipolar sea surface temperature anomaly (warming off US east coast and cooling south of

Greenland). Zhang and Vallis show that such dipolar anomaly (Figure 2.1) can be triggered by the Great Salinity Anomaly events some years in advance and this can provide long-term predictability to the system. Their diagnoses of the 20th century observations show on multi-decadal timescales that the positive (negative) Great Salinity Anomaly phase, associated with more (less) Iceland sea ice extent, leads Labrador Sea surface cooling (warming) and a positive (negative) North Atlantic Oscillation phase (Figure 2.2).

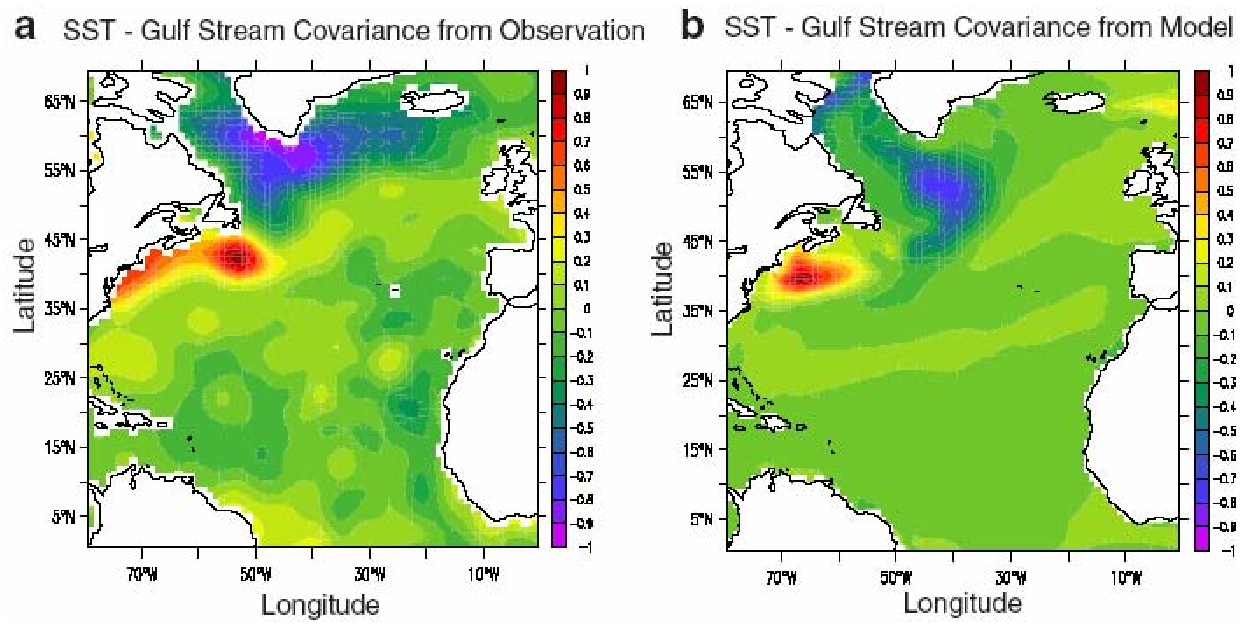


Figure 2.1 **a**, Normalized covariance between observed SST anomaly and 1-year lagged shifts of Gulf Stream path diagnosed from observations (Levitus et al. 2000). **b**, Normalized covariance between modeled SST anomaly and modeled 1-year lagged shifts of Gulf Stream path. The covariance pattern indicates that the dipole SST anomaly (warming off US east coast and cooling south of Greenland) leads the northward shifts of Gulf Stream path by about 1 year.

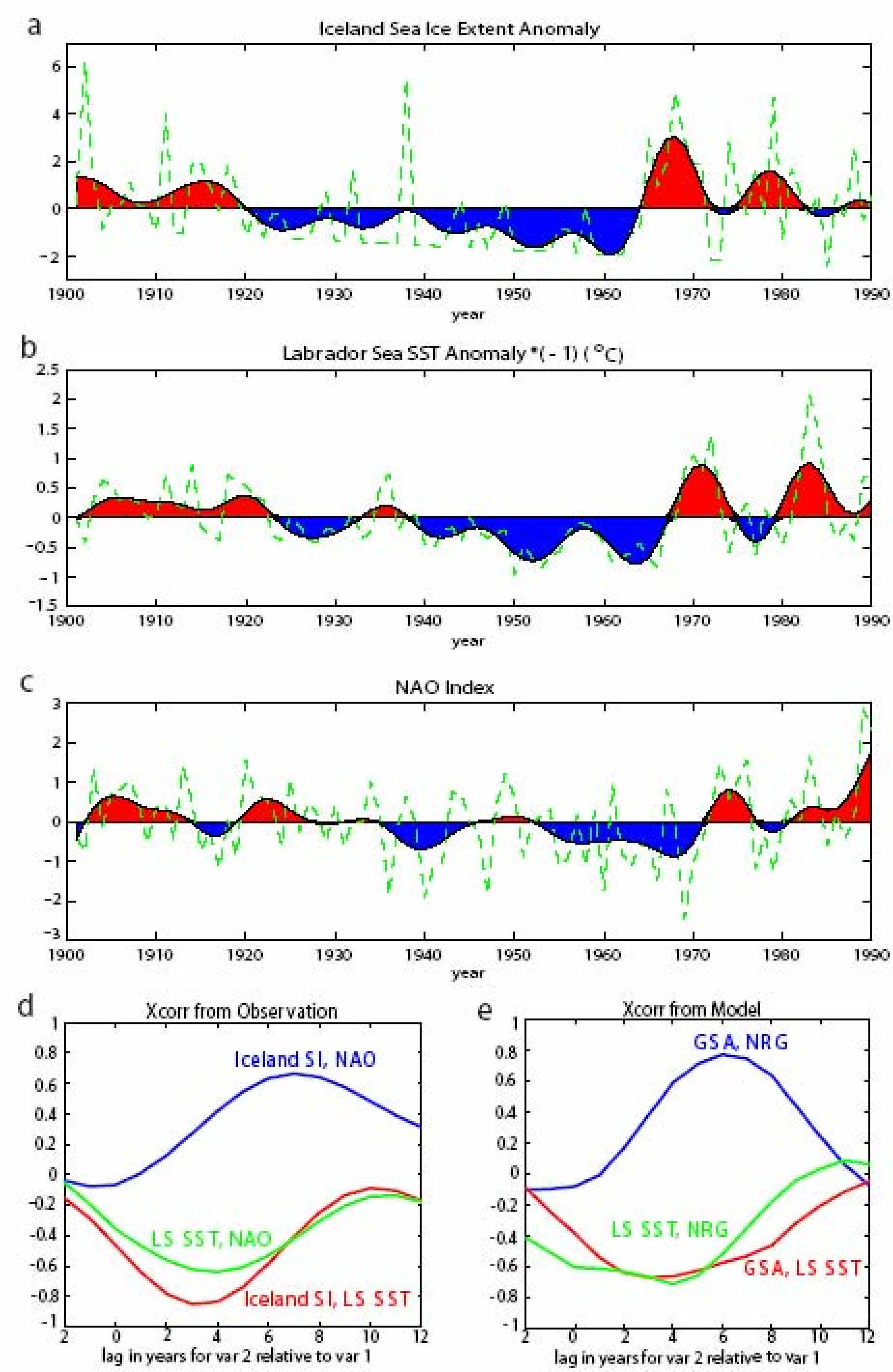


Figure 2.2 Observed time series during the 20th century and their cross correlations in comparison with modeling results. In **a, b, c**, green dash line is the unfiltered data and color shade is the 8-yr low-pass filtered data. **a**, Iceland sea ice extent anomaly, the dataset is maintained by Iceland Meteorological Office **b**, Central Labrador Sea SST anomaly from HadISST dataset (inverted, Rayner et al., 2003) **c**, NAO Index (Hurrell, 1995). **d**, Cross correlations between above low-pass filtered observed variables. Iceland SI: Iceland Sea Ice extent anomaly; LS SST: Labrador Sea SST anomaly **e**, Cross correlations between the unfiltered modeling variables. GSA: Freshwater flux anomaly. NRG: Northern recirculation gyre anomaly. LS SST: Labrador Sea SST anomaly.

References:

Dengg, J.,A. Beckmann, and R. Gerdes, 1996. The Gulf Stream separation problem. *The Warmwatersphere of the North Atlantic Ocean,* W.Krauss, Ed., Gebr. Borntraeger, 253-290.

Hurrell J. W., 1995. Decadal Trends in the North Atlantic Oscillation: Regional Temperatures and Precipitation. *Science*, **269**, 676-679. NAO Index Data provided by the Climate Analysis Section, NCAR, Boulder, USA.

Levitus, S., J. I. Antonov, T. P. Boyer, C. Stephens, 2000. Warming of the world ocean. *Science,***287**, 2225-2229.

Rayner, N.A., D.E. Parker, E.B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E.C. Kent, and A. Kaplan, 2003: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res.* **108**, 4407.

***Publications**:*

Zhang, R. and G. K. Vallis, 2004. The Role of the Deep Western Boundary Current in the Gulf Stream Path and Northern Recirculation Gyre, Journal of Physical Oceanography, Revised.

Zhang, R. and G. K. Vallis, 2004. Impact of Great Salinity Anomalies on the Low Frequency Variability of the North Atlantic Climate. To be submitted to Journal of Climate.

Project Report: **Simulated Global Response to an Imposed Freshwater Forcing in the North Atlantic**

Principal Investigator: Rong Zhang(Princeton)

Other Participating Researchers: Tom Delworth (GFDL)

NOAA's Goal #2 - Understanding Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:
Studying the global responses to the substantial weakening of the Atlantic thermhaline circulation and exploring the mechanism of global-scale synchronization of abrupt climate change.

Methods and Results/Accomplishments:
In this study Zhang and Delworth use a newly developed coupled ocean-atmosphere model (GFDL CM2.0) to investigate the global scale response of the climate system to a sustained addition of fresh water to the model's North Atlantic, such as may have occurred during glacial periods. In response to this forcing, the model's thermohaline circulation weakens substantially, thereby reducing the oceanic meridional heat transport in the Atlantic, with a resultant cooling in the North Atlantic and warming the South Atlantic. The associated global response involves the enhanced atmospheric heat transport across the equator, a southward shift of the intertropical convergence zone (ITCZ) over both the Atlantic and Pacific sectors, an El Nino like condition and weakened Walker circulation in the southern tropical Pacific, a La Nina like condition, and strengthened Walker circulation in the northern tropical Pacific, a dipole subsurface temperature response, and more symmetric ocean circulation about the equator in the western tropical Pacific, and weakened Indian and Asian summer monsoons. The substantial weakening of the thermohaline circulation leads to a more symmetric annual mean zonally averaged ITCZ and zonally integrated Hadley circulation about the Equator. These responses are consistent with the global-scale synchronization of millennial-scale abrupt climate change as indicated by paleoclimate records (Wang, et al., 2001; Altabet et al., 2002; Stott et al., 2002).

References:
Altabet M. A., Higginson M. J., and D. W. Murray, 2002. The effect of millennial-scale changes in Arabian Sea denitrification on atmospheric CO2. *Nature*, 415, 159-162.

Wang Y. J., H. Cheng, R. L. Edwards, Z. S. An, J. Y. Wu, C.-C. Shen, J. A. Dorale, 2001. A High-Resolution Absolute-Dated Late Pleistocene Monsoon Record from Hulu Cave, China. *Science*, 294, 2345-2348.

Stott L., C. Poulsen, S. Lund, and R. Thunell, 2002. Super ENSO and Global Climate Oscillations at Millennial Time Scales. *Science*, 297, 222-226.

Publication:
Zhang, R. and T. L. Delworth, 2004. Simulated Global Response to an Imposed Freshwater Forcing in the North Atlantic. To be submitted to Journal of Climate.

Project Report: **Ming is GFDL's liaison to the Climate Process Team (CPT) on Low-Latitude Cloud Feedbacks on Climate Sensitivity [1]**

Principal Investigator: Ming Zhao(Princeton)

Other Participating Researchers: GFDL Scientists: Isaac Held (CPT leader), Leo Donner and V. Ramaswamy Outside GFDL: Chris Bretherton (CPT lead PI), Steve Klein, Brian Soden and many others from NCAR, NASA and several universities (see [1] for details)

NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:
The main goals of the CPT are:
(1) To fully understand the difference in the low-cloud trends in the NCAR and GFDL models when CO2 is doubled,
(2) To use observations and recent advances in understanding the component physical processes to improve both models,
(3) To thereby reduce, or at least better estimate, our uncertainty about the sensitivity of climate to low-latitude marine boundary layer clouds,
(4) To compare in details the representation of tropical deep convective clouds and their radiative effects in both models with observations, and suggest improvement
(5) To bound (with more certainty than at present) the likely feedbacks of these clouds on climate sensitivity.

Methods And Accomplishments:
Ming has provided the CPT both global monthly climatology (CESS, CMIP, AMIP and SOM) and full-time resolution column (AMIP, 19 locations at observational sites) model data sets from GFDL GCM integration. He has created and maintained a GFDL CPT webpage to assemble simulation data, display results and efficiently communicate with the CPT.

Ming has been investigating the column-oriented diagnostic and modeling strategies for model comparison, model improvement and diagnosis of cloud feedback on climate sensitivity, which are central to the CPT. His results show that, when carefully forced by the GCM extracted dynamical and boundary forcings, the GFDL SCM can produce solutions very close but not bit-wise identical to that of the full model. The tiny initial differences eventually drive the SCM solution to diverge completely from the full model, indicating a chaotic behavior of the SCM. This behavior appears to be primarily associated to the convection parameterization. Despite the noisiness of the SCM, the investigation indicates several utilities of the SCM in understanding and improving the full model physics. 1) When running in a semi-prognostic mode, SCM can provide very detailed diagnostic of individual parameterization schemes (which are not readily available from the full GCM) and how they may locally interact in the full model. 2) Semi-prognostic tests also allow to assess and qualitatively estimate how a change of parameter or parameterization scheme may instantaneously impacts the cloud distribution. 3) Fully-prognostic tests with periodically applied short periods may be used to understand and assess parameterization schemes in a fully coupled way (coupling both in time and space).

Ming has been working on a reconstruction of the GFDL Relaxed Arakawa-Schubert (RAS) convection scheme. The new convection code has the following features: 1) More diagnostics (e.g., cloud-base mass flux, cloud work function, cloud entraiment rate). 2) An option to use a monotonic advection scheme (PPM) in calculating subsidence-produced tendencies. 3) An option to numerically obtain cloud-base mass flux. 4) Better modularity, which includes using structures to organize variables, separating water and tracer convective-tendency calculation from individual cloud loop. These changes make the reconstructed code readily to incorporate new convection schemes. Ming has also devised a visualization tool to examine inside the individual cloud loop, the detailed decision variables, importance of possible nonlinearities (such as thresholds) and how local profiles of large-scale state variables are processed by individual clouds. This visualization tool may be extended to describe the whole chain of model physics process, facilitating particularly the goal of a CPT core PI (Brian Mapes). Ming also tested the GFDL RAS convection scheme in simulating an idealized case (GCSS BOMEX) of shallow cumulus convection over trade-wind ocean. His simulation indicates three major deficiencies in RAS representation of shallow convection. 1) No convective inhibition (CIN). This makes the simulated shallow cumulus clouds too high, potentially explaining the tropic-wide overestimate of cloud liquid water content at 600-800 mb as observed in our full model. 2) Cloud work function (CWF) determination of cloud-base mass flux. This mass flux closure tends to underestimate shallower cumulus effect since deeper, inversion-penetrating clouds always have larger CWF and therefore dominate the cloud population. 3) Using cloud-base air (instead of surface or sub-cloud air) to determine cloud properties. This eliminates the possibility of shallowest clouds (which root in surface layer) and their associated cooling and moistening effect near the cloud-base level.

Ming has also been working with Isaac Held on idealized simulations of radiative-convective equilibrium (RCE) and Walker circulation under various climate changes. We have finished some preliminary tests and are now focusing on specific scenarios (e.g., fixed SST variation). We will examine systematically the differences of modeled large-scale circulation, cloud fields and cloud radiative forcing among different climates. Through this process we try to understand the AM2 cloud feedback to climate sensitivity under idealized situations. We will further analysis more realistic climate-change simulations produced by the GFDL IPCC runs and look for consistencies and differences between them. We hope the idealized simulations capture the most essential cloud feedback in our coupled GCM. In collaboration with other CPT members, we intend to explain some of the differences between the climate responses to warmer SSTs among the three models taking part in this CPT (GFDL, NCAR and NASA/GMAO). These efforts will not only improve our understanding of low-latitude cloud feedback on climate sensitivity but also benefit the future development of cloud parameterization in AM2.

References:

[1] C. S. Bretherton 2003 Climate Process Team {(CPT)} on low-latitude cloud feedbacks on climate sensitivity.

Publications:

None (as yet).

Project Reports:

Biogeochemistry

Project Report: **Nitrate Dynamics in Seagrass Communities**

Principal Investigator: Anita Adhitya (Princeton graduate student)

Other Participating Researchers: Princeton Advisor: Bess Ward

NOAA's Goals #1 - Protect, Restore, and Manage the Use of Coastal and Ocean Resources Through Ecosystem-based Management (50%)
NOAA's Goal #2 - Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond (50%)

Objectives and Motivation:
One biogeochemically significant system of interest in the oceans is seagrass communities. These ecosystems have high productivity and the ability to act as natural sinks for atmospheric CO2. For example, seagrass ecosystems in carbonate sediment banks have been estimated to be responsible for as much as 10% of annual net CO2 uptake in the ocean and recent measurements have identified high density seagrass regions with a net primary productivity amongst the highest rates for ecosystems. Seagrass systems also contribute to maintenance of water quality by filtering nutrients from the water column, and act as sediment traps, habitats and food sources. Despite their importance, the contribution of seagrass communities to biogeochemical cycles has not been extensively studied. Adhitya and Ward are trying to understand the response of chemical uptake in seagrass communities in response to physical flow conditions.

The goal of this work is to understand nutrient uptake dynamics in seagrass communities. Adhitya and Ward seek to measure the effects of the physical flow environment on nitrate uptake activity of organisms in the community. This work consists of two parts: identification of the nitrate uptake community, and investigation of community activity in response to hydrodynamic conditions.

Methods and Results/Accomplishments:
This work uses molecular biolgoical techniques, focusing on the nitrate reductase gene as a means to probe nitrate uptake. A DNA-based approach is used to identify the nitrate uptake community; an RNA- study of gene expression will be used to measure the activity of the contributing organsims. Adhitya and Ward have established a suite of tools to study the first component of this project. Using this, they have retrieved fragments of the nitrate reductase gene from two components of the community. DNA sequencing of the gene fragments is currently underway. Preliminary results are promising; they indicate that the system will be amenable to study using techniques available for gene expression measurement and that it will be of interest to do so. Work is continuing on the first part of the investigation, and techniques for the second part of the experiment will be examined.

References:
Dierssen, H. and Zimmerman, R. (submitted). Benthic ecology from space: seagrass net primary production across the Bahamas Banks. Limnology and Oceanography.

Thomas, F., Cornelisen, C., and Zande, J. (2000). Effects of water velocity and canopy morphology on ammonium uptake by seagrass communities. Ecology, 81(10):2704â€“ 2713.

Project Report: **Isoprene emissions and surface ozone trends over the eastern United States**

Principal Investigator: Arlene M. Fiore-Field (Princeton)

Other Participating Researchers: Drew Purves (Princeton) Larry Horowitz and Chip Levy (GFDL) Mat Evans (University of Leeds, UK), Yuxuan Wang and Robert Yantosca (Harvard) Qinbin Li (NASA JPL)

NOAA's Goal #2 - Understanding Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:

- Quantify contribution of reported changes in anthropogenic (NO_x, CO, and NMVOC) vs. biogenic emissions (isoprene) to observed ozone trends from the mid-1980s to the mid-1990s
- Examine sensitivity of surface ozone to uncertainties in (1) isoprene emissions and (2) isoprene-NO_x-ozone chemistry
- Compare plausible future biogenic scenarios for VOC emissions: from the eastern United States: "business-as-usual", and options for conversion of agricultural lands to biofuel production
- Examine impact of these future biogenic VOC changes on surface ozone in the eastern United States, and compare with predictions from commonly applied IPCC anthropogenic emissions scenarios

Methods and Results:

Reducing surface ozone to levels in compliance with the national ozone (O_3) standard has proven to be challenging, despite tighter controls on O_3 precursor emissions over the past few decades. New evidence indicates that biogenic volatile organic compound (BVOC) emissions changed considerably from the mid-1980s to the mid-1990s due to land-use changes in the eastern United States [*Purves et al.*, 2004]. Here, we apply two chemical transport models (GEOS-CHEM and MOZART-2) to test the hypothesis put forth by *Purves et al*. [2004], that the absence of decreasing O_3 trends over much of the eastern United States may reflect a balance between human-induced increases in BVOC emissions and legislated decreases in anthropogenic VOC emissions during this time period. While some compensation is evident in the most extreme events (O_3 > 90 ppbv) over eastern Texas (where isoprene increased O_3 but anthropogenic VOC, CO, and NO_x emissions decreased O_3), we find that the O_3 response is mainly driven by changes in anthropogenic NO_x emissions. Over most of the eastern United States, the data-derived changes in BVOC emissions have a small impact on surface O_3 concentrations (< 5 ppbv) compared to the impact from contemporaneous changes in anthropogenic NO_x emissions (up to 15 ppbv), although the O_3 response to anthropogenic emission changes is sensitive to the isoprene emission inventory. Furthermore, the reported anthropogenic plus biogenic emission changes from the mid-1980s to the mid-1990s in the eastern United States are insufficient to explain observed changes in mean July afternoon (1-5 p.m.) surface O_3 concentrations, although our study does not consider the influence of meteorological variability, changes in hemispheric background O_3, or plume chemistry. We show that substantial uncertainties in isoprene emissions and chemistry preclude an accurate quantification of the present-day contribution of biogenic or anthropogenic emissions to surface O_3 concentrations. For example, simulations with two commonly used isoprene emission inventories yield July mean surface O_3 concentrations that differ by -15 to +4 ppbv over the eastern United States. An additional 4-12 ppbv uncertainty in surface O_3 stems from the chemical fate of organic isoprene nitrates. These uncertainties in isoprene emissions and chemistry are most pronounced in the high-isoprene southeastern United States, where they influence both the sign and magnitude of the surface O_3 response to emission changes. One set of modeling assumptions shows that direct reaction with isoprene may be an important loss pathway for O_3 in this region. In all cases, controls on anthropogenic NO_x emissions would amplify the importance of this O_3 loss pathway in the southeastern states and decrease high-O_3 events (O_3 >70 ppbv) throughout the eastern United States.

Purves has developed projections of BVOC emissions for 2030 based upon recent observed changes in forest structure and composition from the 1980s to the 1990s. These changes are considered to be “business-as-usual” and are contrasted with BVOC emissions that would result from plausible biofuel scenarios described by *De La Torre Ugarre et al*. [2004], which Purves is in the process of obtaining. Fiore is applying these projected changes to the GEOS-CHEM 3-D model of ozone-NOx-CO-VOC chemistry. Simulations are also being conducted with anthropogenic emissions projected to 2030 according to the IPCC A1 (pessimistic) and B1 (optimistic) scenarios. This study allows us to compare scenarios with plausible future “natural” (though human-induced) VOC emissions with the commonly used anthropogenic IPCC scenarios. The influence of these processes on vegetation and the associated BVOC emissions are presently neglected in simulations of future atmospheric chemistry and climate; this study will determine whether such changes merit consideration.

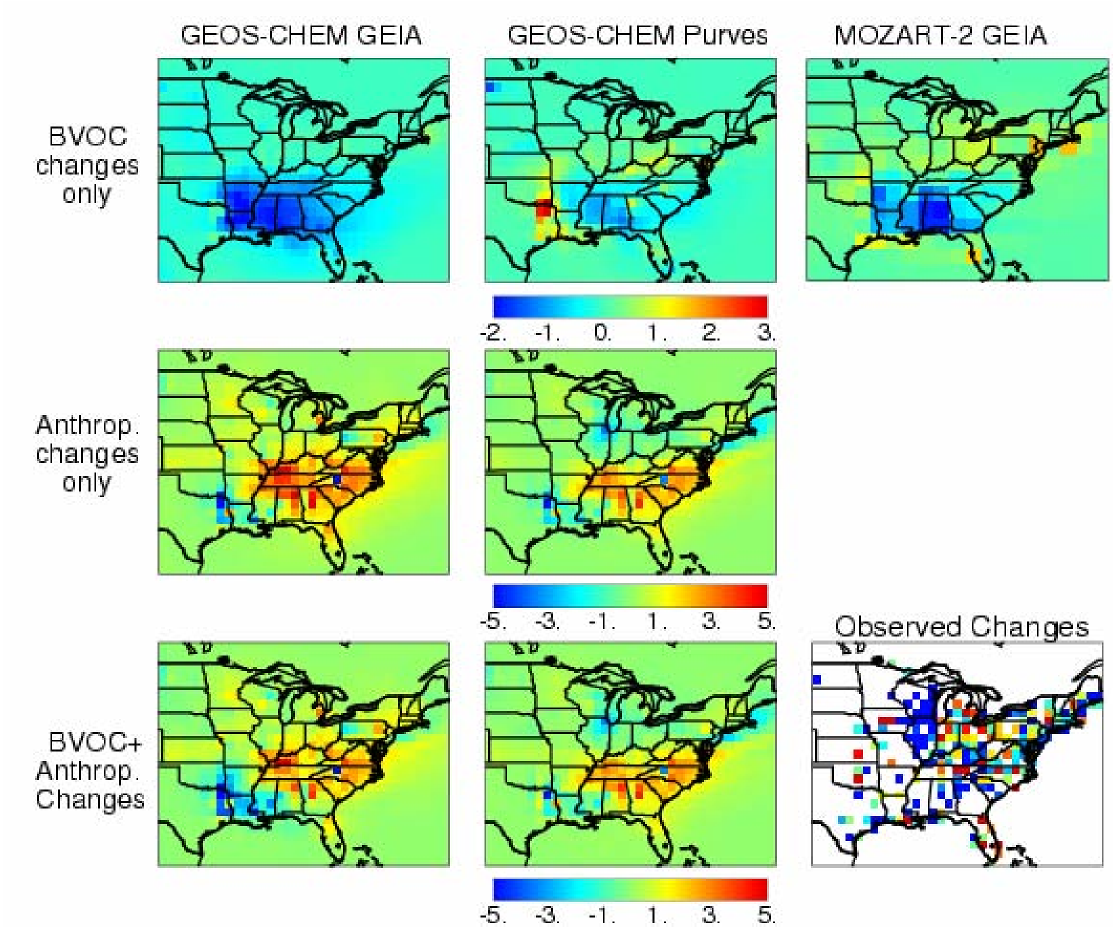


Figure: Change in mean July afternoon (1300-1700 LT) surface O_3 concentrations (ppbv) from the 1980s to the 1990s over the eastern United States resulting from changes in biogenic isoprene (top row), anthropogenic NO_x, CO, and VOC (middle row) emissions, in GEOS-CHEM for the GEIA (left) and Purves (middle) isoprene inventories, and in MOZART-2 for the GEIA inventory when isoprene nitrates are converted directly to nitric acid (upper right). The bottom panels show the surface O_3 response to the combined anthropogenic plus biogenic emissions changes in GEOS-CHEM, as well as the observed change in surface O_3 as recorded by the EPA AIRS network. The observations likely reflect a combination of processes such as meteorological variability, global emission changes, urban plume chemistry, not considered in the model simulations. The color bar saturates to emphasize regional patterns rather than extreme values.

References:

Purves, D.W., J.P. Caspersen, P.R. Moorcroft, G.C. Hurtt, S.W. Pacala, Human-induced changes in U.S. Biogenic VOC emissions: evidence from long-term forest inventory data, *Global Change Biology*, in press, 2004.

Forthcoming Publications:

Fiore, A.M., L.W. Horowitz, D.W. Purves, H. Levy II, M. Evans, Y. Wang, Q. Li, and R.M. Yantosca, Evaluating the contribution of changes in isoprene emissions to surface ozone trends over the eastern United States, manuscript in preparation for *J. Geophys. Res.*

Project Report: **Ozone studies**

Principal Investigator: Arlene M. Fiore-Field(Princeton)

Other Participating Researchers: PI: Randall Martin (Dalhousie University)
Aaron Donkelaar (Dalhousie University), Larry Horowitz, Bud Moxim, Chip Levy (GFDL), Daniel Jacob (Harvard), Dylan Jones (University of Toronto)

NOAA's Goal #2 - Understanding Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:

- Demonstrate utility of space-based NO2 and CH2O measurements to identify NO_x-sensitive vs. NO_x-saturated ozone production regimes.
- Determine why models disagree in predictions of stratospheric contribution to surface ozone despite similar skill in capturing total observed surface ozone.
- Improve accuracy of labeling stratospheric ozone in off-line atmospheric chemistry models
- Models disagree in their predictions of the stratospheric contribution to total surface ozone, even though they tend to capture the total surface ozone well when compared with observations. Quantifying the stratospheric component in the troposphere is crucial to our understanding of natural vs. anthropogenic influence on tropospheric ozone (an air pollutant at the surface, and greenhouse gas in the upper troposphere). At GFDL we now have three state-of-the-art atmospheric chemistry models that we are using to investigate this problem: MOZART- 2, GEOS-CHEM, and the GCTM.

Methods and Results (published abstract):

The question of stratospheric vs. other natural vs. anthropogenic contributions to surface ozone is central to the ongoing debate surrounding a quantitative definition of U.S. background ozone in surface air. A quantitative definition is necessary for (1) the health risk analyses conducted by the U.S. EPA as part of its process in setting the national ozone standard, and (2) to ensure that the EPA does not set a standard that is too close to background levels and thus unattainable via domestic emissions reductions.

We present a novel capability in satellite remote sensing with implications for air pollution control strategy. We show that the ratio of formaldehyde columns to tropospheric nitrogen dioxide columns is an indicator of the relative sensitivity of surface ozone to emissions of nitrogen oxides (NO_x = NO + NO2) and volatile organic compounds (VOCs). The diagnosis from these space-based observations is highly consistent with current understanding of surface ozone chemistry based on in situ observations. The satellite-derived ratios indicate that surface ozone is more sensitive to emissions of NO_x than of VOCs throughout most continental regions of the Northern Hemisphere during summer. Exceptions include Los Angeles and industrial areas of Germany. A seasonal transition occurs in fall when surface ozone becomes less sensitive to NO_x and more sensitive to VOCs.

Publications:

Martin, R.V., A.M. Fiore, and A.Van Donkelaar, Space-based diagnosis of surface ozone sensitivity to anthropogenic emissions , *Geophys. Res. Lett. 31*, L06120, doi:10.1029/2004GL019416, 2004.

Fiore, A.M., D.J. Jacob, H. Liu, R.M. Yantosca, T.D. Fairlie, Q. Li, Variability in surface ozone background over the United States: Implications for air quality policy, J. Geophys. Res., 108, 4787, doi:10.1029/2003JD003855, 2003.

Contributing Author to Chapters 2 and 3 of the Air Quality Criteria Document for Ozone and Related Photochemical Oxidants for the Environmental Protection Agency, March 2003-present.

Project Report: **Air Pollution and Linkages with Climate, and biogenic emissions in LM3**

Principal Investigators: Arlene M. Fiore-Field(Princeton), Tracey Holloway (Univ Wisconsin-Madison)

Other Participating Researchers: Tracey Holloway (Univ Wisconsin-Madison) (objective 1); J. Jason West (U.S. EPA) (objective 2); Meredith Hastings (Princeton), Christine Wiedinmyer and Alex Guenther (NCAR), Dorian Abbott and Paul Palmer (Harvard), Steve Pacala and Drew Purves (Princeton)

NOAA's Goal #2 - Understanding Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:

- Synthesize linkages between air pollution and climate for various emission control strategies
- Review evidence and mechanisms for intercontinental transport of pollution and examine the potential for international agreements to address growing hemispheric pollution levels
- Add capability to predict emissions (VOC, and eventually soil NO, and CH4 on a longer time scale) from the land model
- Apply this version of LM3 in coupled chemistry-climate model to examine interactions among climate, natural emissions, and air quality

Methods and Results (abstracts excerpted from publications)

From *Fiore et al*. [2003]: Linkages between climate and the intercontinental transport (ICT) of ozone and aerosols offer opportunities for coordinated mitigation of air pollution and global warming. This article considers the ICT of ozone and aerosols among Asia, Europe, and North America, and highlights linkages between air quality and climate that might benefit future emissions control strategies.

From *Holloway et al*. [2003]: We examine the emergence of InterContinental Transport (ICT) of air pollution on the agendas of the air quality and climate communities, and consider the potential for a new treaty on hemispheric air pollution. Intercontinental Transport is the flow of air pollutants from a source continent (e.g. North America) to a receptor continent (e.g. Europe). ICT of air pollutants occurs through two mechanisms: (1) episodic advection, and (2) by increasing the global background which enhances surface concentrations. We outline the current scientific evidence for ICT of aerosols and ozone, both of which contribute to air pollution and greenhouse warming. The growing body of scientific evidence for ICT suggests that a hemispheric scale treaty to reduce air pollutant concentrations may be appropriate to address climate and air quality concerns simultaneously. Such a treaty could pave the way for future climate agreements.

Fiore is incorporating the global MEGAN isoprene inventory of Alex Guenther and Christine Wiedinmyer (NCAR), just officially released this month, into the LM3 land model being developed at Princeton/GFDL. Her future plans in this direction include the incorporation of soil NO emissions, and possibly species-specific information on isoprene & monoterpene emissions in collaboration with Pacala (Princeton), and ultimately methane as well. Satellite data of formaldehyde (a product of isoprene oxidation) columns and NO_2 in conjunction with (limited) *in situ* data, will be used in evaluating the biogenic emissions modules.

Publications:

Fiore, A.M., T. Holloway, M.G. Hastings, A Global Perspective on Air Quality: Intercontinental Transport and Linkages with Climate, *EM*, December, 2003.

Holloway, T., A.M. Fiore, M.G. Hastings, Intercontinental Transport of Air Pollution: Will emerging science lead to a new hemispheric treaty?, *Environ. Sci. & Technol., 37*, 4535-4542, 2003.

Progress Report: **Carbon Observing System**

Principal Investigator: Manuel Gloor and Jorge L. Sarmiento(Princeton)

Other participating researchers: Andrew Jacobsen(Princeton), Larry Horowitz(GFDL)

NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Methods and Results:
The purpose of the research is to estimate and understand carbon sources and sinks using atmospheric concentration data mainly from CMDL in conjunction with atmospheric transport models and CO_2 flux estimates derived with independent approaches. We have worked on this problem in three ways. First is the development of a spatial high-resolution atmospheric modeling capability for analysis of upcoming spatial and temporally highly high-resolved data for North America as part of the North American Carbon Plan. Our efforts towards estimating sources and sinks with atmospheric transport inversions include

(1) the simulation of monthly flux pulses for a large number of regions using the model Mozart of Larry Horowitz (Horowitz et al. 2003) for estimating CO_2, CO, and CH_4 sources and sinks,
(2) model transport validation using SF_6 forward predictions with the MOZART model and comparably recent observations by CMDL/NOAA,
(3) inverse methods development using existing monthly flux pulses for comparably large regions simulated as part of the TRANSCOM3 experiment (Gurney et al. 2002). Besides establishing existing approaches (recursive and one-step inversion of the Greens-function based integral solution to the partial differential equation governing atmospheric transport) a prospective Post-doctoral student from geophysics is currently testing and implementing a geostatistical approach.

These activities are currently in progress.

A second effort has focused on analyzing the continental source / sink signal to noise problem for Eurasia using highly resolving regional atmospheric models and land biosphere fluxes with realistic diurnal cycle. This is an important problem as it is not quite clear to what extent it is possible to estimate carbon sources and sinks from atmospheric data at all and, if possible, what data density would be needed to constrain fluxes for example for a region like North America. It would in particular be more satisfying if atmospheric data based flux estimation approaches would become independent of "ad hoc" regularizing methods. A main result of the study is the determination of the "effective" signal/to noise ratio for a 20% increase of a land biosphere uptake across Eurasia during June 1998 with two high resolution regional models (Figure 1). "Effective" refers to taking into account the autocorrelation of simulated time-series via "effective sample size" (Zwiers & Storch 1995). The effective signal to noise ratio is calculated for hourly afternoon sampling (one sample every hour from 11 to 17 o'clock local time). It is apparent that over regions with large fossil fuel emissions a 20% increased biosphere sink cannot be detected while frequent sampling (between daily to a few days sampling) is needed to capture the signal more to the east of the continent. The results also indicate that signals above the mixed layer are so tiny that with the current obtainable measurement precision and accuracy they are too small to be helpful on their own (Figure 2). Thus high-density sampling is needed and should concentrate on the mixed portion of the planetary boundary layer. A manuscript summarizing the results has been prepared and will be submitted soon (Karstens et al., in prep.).

The third effort focused on analyzing recent air-sea flux estimates obtained with inverse methods in the light of ocean process model predictions (McKinely et al. submitted). The main results of the comparison are that for 1983-1998 both inversion results and biogeochemical models place the primary source of global CO_2 air-sea flux variability in the Pacific Ocean. Both methods also indicate that the Southern Ocean is the second-largest source of air-sea CO_2 flux variability, and that variability is small throughout the Atlantic, including the North Atlantic in contrast to previous studies.

References:

L. Horowitz et al., A global simulation of tropospheric ozone and related tracers: Description and evaluation of MOZART, version 2, J. Geophys. Res., 108, No. D24, 4784, doi:10.1029/2002JD002853, 2003.

G. A. McKinley, C. Rödenbeck, M. Gloor, S. Houweling and M. Heimann, Pacific Dominance to Global Air-Sea CO_2 Flux Variability: Predictions of a High-Resolution Atmospheric Inversion Agree with Ocean Models, in press *Geophys. Res. Lett.*.

M. Heimann, M. Gloor and C. Rödenbeck (2004), Spatial and Temporal Distributions of Sources and Sinks of Carbon Dioxide, In "The Global Carbon Cycle", Island Press, Washington, Eds. C. B. Field and M. Raupach, 187-204, 2004.

C. Rödenbeck, S. Houweling, M. Gloor, and M. Heimann (2003). CO_2 flux history 1982-2001 inferred from atmospheric data using a global inversion of atmospheric transport. *Atm. Chem. Phys*., **3**, 1919-1964.

M. Gloor, N. Gruber, J. L. Sarmiento, C. Sabine, D. Feely and C. Rödenbeck (2003). A first estimate of present and preindustrial air-sea CO_2 flux patterns based on ocean interior carbon measurements and models. *Geophys. Res. Lett.*, Vol. 30, No. 1 10.1029/2002GL015594 .

U. Karstens, M. Gloor, C. Rödenbeck, M. Heimann, Insights from simulations with high-resolution transport models on sampling the atmosphere for constraining mid-latitude carbon sinks, In prep. for submission to *J. Geophys. Rev.*

S. Houweling, F.-M. Breon, I. Aben, C. Rödenbeck, M. Gloor, M. Heimann, and P. Ciais (2004), Inverse modeling of CO_2 sources and sinks using satellite data: a synthetic inter-comparison of measurement techniques and their performance as a function of space and time, Atmos. Chem. Phys., 4, 523-538,

Gurney, K. R., R. M. Law, A. S. Denning, P. J. Rayner, D. Baker, P. Bousquet, L. Bruhwiler, Y.-H. Chen, P. Ciais, S. Fan, I. Y. Fung, M. Gloor, M. Heimann, K. Higuchi, J. John, T. Maki, S. Maksyutov, K. Masarie, P. Peylin, M. Prather, B. C. Pak, J. Randerson, J. Sarmiento, S. Taguchi, T. Takahashi, and C.-W. Yuen, (2002) Towards more robust estimates of CO_2 fluxes: control results from the TransCom3 inversion intercomparison. *Nature*, **415**: 626-630.

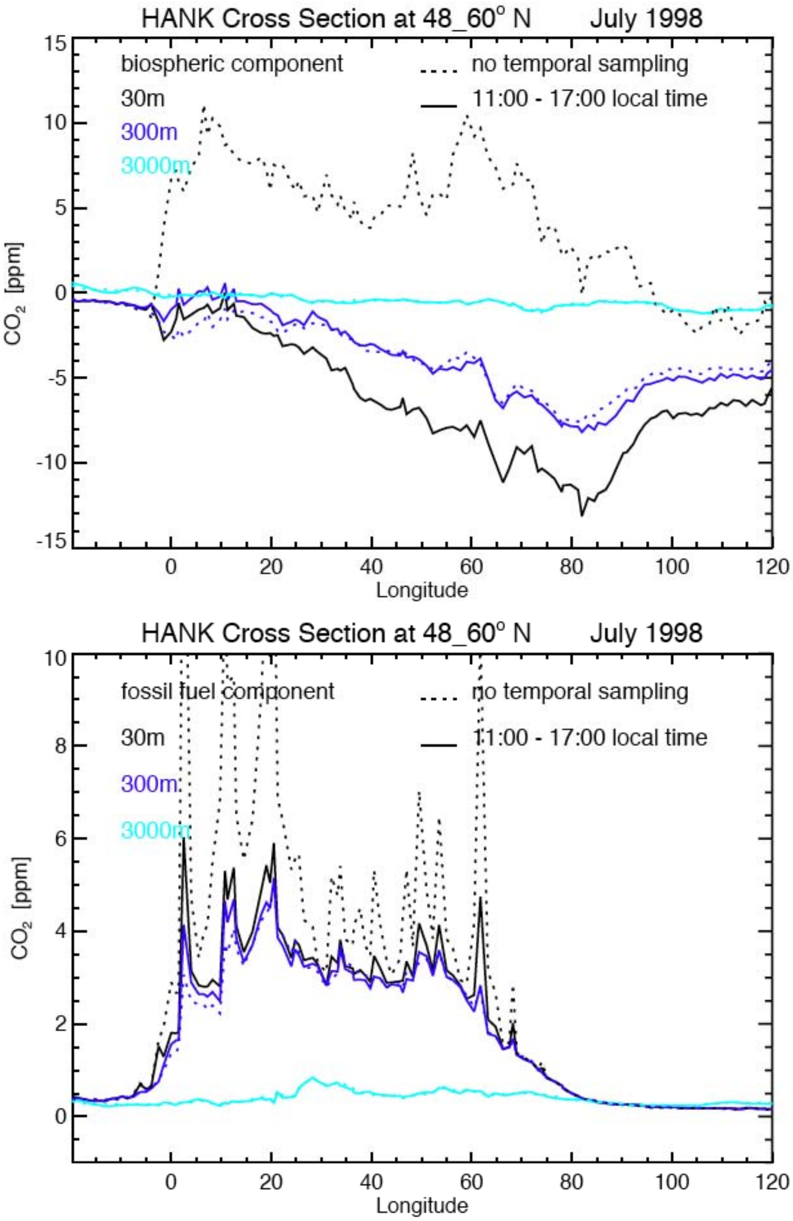


Figure 1: Simulated monthly mean biosphere (upper panel) and fossil fuel (lower panel) atmospheric CO_2 concentration in July 1998 across Eurasia (along redline in Figure 2, upper panel). The simulations use the HANK regional transport model (Hess et al. 2001) with biosphere surface fluxes from the TURC model (Ruimy et al. 1996) and fossil fuel emission from energy statistics (Andres et al. 1998). CO_2 signals at 30m, 300m and 3000m above ground and sampled either all day or selectively during afternoon only (dotted lines) are displayed.

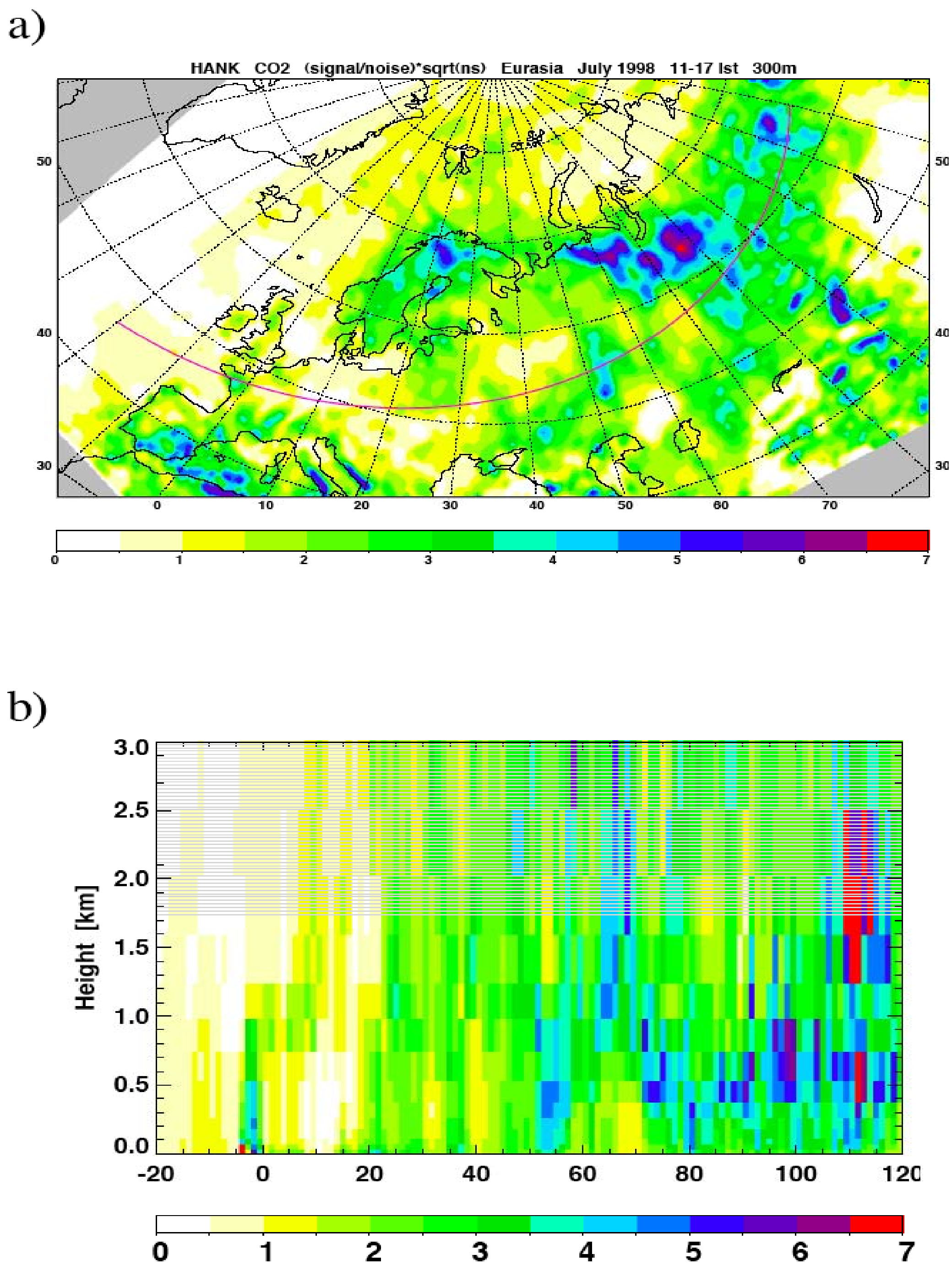


Figure 2: Effective signal to noise ratio for detecting a 20 % increased biosphere sink(~1.5PgCyr) at 300m above ground across Eurasia during July 1998 (upper panel) and from the surface to 3km height (lower panel) along the red line in the upper panel. The effective signal to noise ratio is based on hourly afternoon sampling every day in July. An effective signal to noise ratio less than one means the signal cannot be detected with daily afternoon sampling at the one sigma level while values larger that one indicate that daily afternoon sampling is sufficient to detect the 20% increased sink.

Project Report: **Terrestrial Nitrogen Cycle**

Principal Investigators: Lars Hedin and Michael Oppenheimer(Princeton)

Other participating researchers: Stefan Gerber and Simon Donner(Princeton)

NOAA's Goal #2 - Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:
The primary goal of this project is to evaluate the response of global nitrogen (N) cycling to climate variability, climate change and land use change, through the application of existing modeling tools and development of the nitrogen component of the GFDL land model. This effort will also create a strong community of N expertise at Princeton and GFDL.

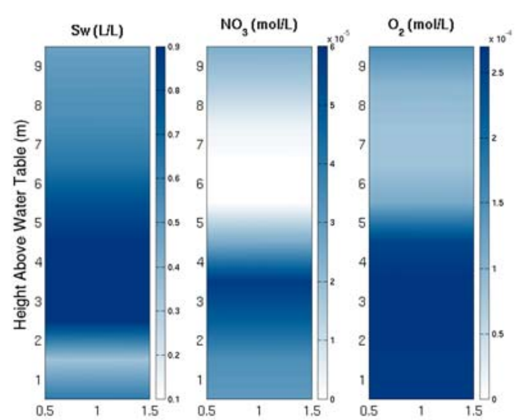
Methods and Results/Accomplishments:
Over the previous fiscal year, research has been conducted in three areas:

1. Implementation of the terrestrial N cycle into the GFDL land model
(Lars Hedin, Michael Oppenheimer, Stefan Gerber, Simon Donner)

The central objective of this work has been the integration of the terrestrial N cycling processes – including links between C, N and P cycles, trace gas emissions (N_2O, NO_x) and N losses to groundwater and streams – into the GFDL land model. Hedin and Oppenheimer formulated the initial plan for the N component of the land model, based upon existing models and Hedin's research on stoichiometric ratios. The careful search for a postdoctoral associate (Gerber) delayed the beginning of model development until later in the year.

To date, model development has focused on the linkage of soil N with the existing C cycle in the land model. In other models, litter and soil organic matter pools are each assigned a distinct C:N and N mineralization and immobilization occurs during C mineralization and organic matter transfer between the pools. This approach requires maintaining several litter and soil organic matter pools with similar decomposition rates are often similar. We are instead developing a new representation of N immobilization and mineralization, where C:N in the soil organic pools are variable, but critical ratio. The current work is focusing on the competition for mineral N between plants and heterotrophs.

2. Development of a generic model of denitrification and N cycling in unsaturated soils (Peter Jaffe, Andrew Altevogt)



We developed a 2D numerical model to simulate chemical transport and transformation in unsaturated soils. The model describes the simultaneous flow of both gas and liquid and chemical reactions in the aqueous phase. It is currently configured to simulate the response of O_2 and NO_3

concentrations due to changes in soil moisture, key to simulating denitrification.

The major thrust of the work has been an examination of the chemical speciation after soil saturation. The figure (above) presents the water saturation (Sw), NO_3 and aqueous O_2 profiles 30 minutes after the end of a 30 minute rainfall event.

The model is being further enhanced through including the soil heterogeneities, which lead to complex distribution of areas of denitrification, and testing with field measurements (in collaboration with Hedin).

3. Evaluation the impact of climate variability and land use on N export by large rivers (Simon Donner, Michael Oppenheimer).

We used existing modeling tools and agricultural inventory data to conduct two separate analyses of the impact of climate and land use on N export by Mississippi River.

The first study (Donner et al., subm.) used the IBIS land surface model and HYDRA transport model to examine the sensitivity on in-stream removal of N via benthic denitrification to inter-annual climate variability. We found a two-fold range in the fraction of N removed from the Mississippi River system each year, and a three-fold range in the associated N_2O emissions, with the lowest N removal (10-33%) and highest N_2O emissions (15.5–26.0 10^6 kg N) occurring in the wet years. The results show the importance of considering climate variability and change in the management of N export by large rivers.

The second study (Donner, in prep) used agricultural inventory data and two nutrient cycling models to investigate the contribution of feed cultivation to the N exported to the Gulf of Mexico. The study found that a shift to only vegetable, dairy and poultry production from Mississippi Basin crops could produce the same amount of dietary protein with less than half the current land and nutrient demands. The shift would reduce the annual NO_3 export by the Mississippi to a level at which Gulf hypoxic zone is historically small or non-existent.

Future plans

Over the next year, we will continue nitrogen model development land (including integrating the model of N transport and transformation in unsaturated soils). To this end, we have initiated bi-weekly nitrogen group meetings, in which the project scientists and others from the Princeton-GFDL community review key findings from the literature and further discuss model development. We will also continue analysis of the response of N export by rivers to climate variability and future climate scenarios, using the available modeling tools and chemistry data for the world's largest rivers.

Publications/References

Donner, S,D. Surf or Turf: How shifting from feed to food production could reduce nutrient loading from the Mississippi River to the Gulf of Mexico. In preparation

Donner, S,D., Kucharik, C.J. and Oppenheimer, M. The influence of climate on in-stream removal of nitrogen. Submitted to *Geophysical Research Letters*.

Project Report: *SUBCONTRACT:* **Modeling Land-Use Dynamics in the Earth System**

Principal Investigator: George Hurtt (University of New Hampshire)

Other participating researchers: Steve Frolking and Changsheng Li (UNH)

NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:
Our overall objective is to work with Princeton and GFDL scientists to study important human alterations to the land surface and their consequences in the Earth System. For 2004, we proposed to focus on the patterns of land use, and initiate work with Princeton/GFDL scientists on developing submodels of the relevant biogeochemical cycling. We also proposed to work with Princeton/GFDL scientists to support the integration of products, and to pursue scientific applications using them. Specifically, we proposed to produce and implement:

1. *A set of land-use change drivers for use in the ESM*

and to begin development and parameterization of other key land-use phenomena needed for ESM applications:

i. Patterns of fire management/fire risk
ii. Maps of agricultural management
iii. Fate of agricultural products
iv. Biogeochemical dynamics

Methods and Results/Accomplishments:
To meet our primary objective (1) of producing a set of land use change drivers for use in the ESM, we developed a Global Land-Use Model (GLM) (Hurtt et al In Prep, Hurtt et al 2004, Hurtt et al 2003). The model consists of gridded (1°x1° global) annual estimates of land-use transition rates that collectively specify the fraction of each grid cell that is modified by humans through time (e.g. crop, pasture, logging, recovering lands, …) and is consistent with available historical records and remote sensing estimates. For input, GLM is based on the HYDE (Goldewijk 2001) and SAGE (Ramankutty and Foley 1999) gridded global land cover estimates for 1700-1990, and FAO (FAOSTAT 2004) national wood harvesting statistics 1961-1990. Pre-1961 national wood harvest totals are estimated from per capita wood harvest rates during the period of FAO record and estimates of historic population density. These inputs have been extended in GLM to 2000 using relevant FAO data and other information. In addition, a scenario approach has been used to produce an ensemble of products with which to assess the sensitivity of important unknowns. Our analysis differs from previous global gridded land-use history products (e.g., HYDE and SAGE) in three ways: (1) it includes wood harvest as a land use; (2) it calculates annual land-use transitions to track land use evolution; and (3) it generates annual, global estimates of secondary land area. All products follow required formats for incorporation into the GFDL LM models and these applications are underway at GFDL/Princeton. In addition, the 1850-2000 subset has been assembled and used in CM2 IPCC simulations.

To meet our secondary objectives (i-iv) of beginning the development and parameterization of other key land-use phenomena needed for ESM applications, we have done the following. First, to address patterns of fire management/risk, we built on the regional fire modeling in Hurtt et al (2002) by beginning work to develop and parameterize explicit patterns of fire suppression over the US (Girod et al In prep), and by producing and implementing a modified regional fire model for application in the tropics (Amazon) (Cardoso et al 2003, Cardoso et al 2003a, Cardoso et al 2003b). For global studies, we initiated the development of a global fire model and demonstrated that our initial prototype captures important global patterns spatially, and temporally in response to climate variability (Girod et al 2004). We also contributed to a global analysis of fire risk/mitigation (Bravo et al In review). To address items (ii-iv, i.e. maps of agricultural management, fate of agricultural products, biogeochemical dynamics) we have initiated the assembly of needed global statistics on: agricultural management, crop type, crop characteristics, trade etc… spatially and aggregated by importance/area. To address biogeochemical dynamics on agricultural lands, we have initiated studies to bridge the advanced parameterizations for agricultural soils the widely applied DNDC model (e.g. Li et al 2002) with the developing parameterizations in the LM/ED models. These studies are ongoing.

In addition to these specific contributions, PI Hurtt has continued to serve on the USGS/NOAA/GFDL Land Model Development Team. As a member of that team, Hurtt has contributed to the development of the LM3 model (Shevliakova et al In prep, Shevliakova et al 2003). Hurtt has also contributed to the assessment of US land use changes on climate and air quality (Roy et al 2003, Purves et al 2004), and contributed to NAS workshop on global carbon (Hurtt et al 2003a).

By contributing crucial information/parameterizations to the developing Earth System Model, this research contributes to NOAA Goal 2: Understand Climate Variability and Change to Enhance Societies Ability to Plan and Respond.

References:

FAOSTAT. 2004. Statistical Database of the United Nations Food and Agricultural Organization, http://apps.fao.org/, visited Feb. 2004.

Goldewijk, K.K. (2001). Estimating global land use change over the past 300 years: The HYDE ddatabase, Global Biogeochemical Cycles 15(2), 417-433.

Hurtt, G. C., S. W. Pacala, P. R. Moorcroft, J. Caspersen, E. Shevliakova, R. Houghton, B. Moore. 2002. Projecting the future of the US carbon sink. *Proceedings of the National Academy of Sciences of the United States (PNAS), 99*(3): 1389-1394.

Li C., et al (2002) Reduced methane emissions from large-scale changes in water management of China's rice paddies during 1980-2000. Geophysical Research Letters 29, 20, 1972, doi:10.1029/2002GL015370.

Ramankutty, N., and J.A. Foley (1999). Estimating historical changes in global land cover: croplands from 1700 to 1992, Global Biogeochemical Cycles 13(4), 997-1027.

Presentations at Professional Meetings:

Girod G, King T, Hurtt G (2004) Global Fire Patterns and Trends from ENSO Events Estimated Using an Enhanced Ecosystem Model, AGU Fall Meeting, San Francisco. Pending.

Hurtt G, Frolking S, Fearon M, Moore B, Shevliakova E, Malyshev S, Pacala S,

Houghton RA (2004) Three centuries of gridded, global land-use transition rates and wood harvest statistics for Earth System Model applications, LUCC: Integrated assessment of the land system: The future of land use, Amsterdam. Pending.

Hurtt G, Frolking S, Fearon M, Moore B, Shevliakova E, Malyshev S, Pacala S (2003) Estimating the Uncertainty of Land-use History Reconstructions in the Global Carbon Balance. AGU Fall Meeting, San Francisco.

Shevliakova E, Pacala S, Hurtt G, et al. (2003) Carbon Cycle and Vegetation Dynamics in the GFDL-Princeton University Coupled Atmosphere-Biosphere Model. AGU Fall Meeting, San Francisco, Poster.

Cardoso M, Salas B, Hurtt G, Hagen S, Keller M, Fearon M (2003a) Land-Cover Transitions as Predictors of Fire Activity in Amazonia. AGU Fall Meeting, San Francisco, Poster.

Hurtt G (2003a) Direct and Indirect Human Contributions to Terrestrial Greenhouse Gas Fluxes: Consideration for Differing Spatial and Time Scales. Presentation to the \ National Academy of Sciences, Washington, DC.

Cardoso M, Hurtt G, Moore B, Nobre C, Prins E, Setzer A (2003b) Use of satellite fire products in large-scale models. 9th Brazilian Remote Sensing Symposium, Brazil.

Publications and Papers in Preparation/Review:

Hurtt GC, Frolking S, Fearon M, Moore B, Shevliakova E, Malyshev S, Pacala S, Houghton RA. The underpinnings of human land-use activities: three centuries of global land-use transitions and wood harvest statistics for Earth System Science studies. In prep.

Bravo L, et al. Protection from Flooding, Erosion, Storms, and Fire, Ch 17 In: *The Mellinium Ecosystem Assessment*. In Review.

Purves D, Caspersen J, Moorcroft P, Hurtt G, Pacala S. (2004) Human-induced changes in U.S. biogenic VOC emissions. *Global Change Biology* 10:1-19 doi:10.1111/j.1365-2486.2004.00844.x.

Cardoso M, Hurtt GC, Moore B, Nobre C, Prins E. (2003) Projecting future fire activity in Amazonia. *Global Change Biology* 9: 656-669.

Roy SB, Hurtt GC, Weaver CP, Pacala SW. (2003) Impact of historical land cover change on the July climate of the United States. *Journal of Geophysical Research* 108, D24, 4793, doi:10.1029/2003JD003565.

Project Report: **Understanding North Pacific Carbon-Cycle Changes**

Principal investigator: Robert M. Key(Princeton)

Other Participating Researchers: C. Sabine and R. Feely(NOAA/PMEL)

NOAA's Goal #2 - Understanding Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:
Funding from this grant provided the support needed to prepare for and to carry out a workshop designed to investigate evidence for changes in hydrographic properties related to the carbon cycle in the North Pacific Ocean. The parameters studied included temperature, salinity, density, oxygen, nutrients, alkalinity and total inorganic carbon. Preparatory work focused on collection and analysis of recent and historical data from cruises in the North Pacific. The data analysis used classical techniques. First the quality of the various measurements was determined and then data from measurements in the same general area were compared to determine if differences existed beyond what might be expected from the data precision and accuracy. Any significant differences found were investigated to determine whether they might be ascribed to biogeochemical change or physical change.

Methods and Results/Accomplishments:
Both national and international oceanographers were contacted for cruise data which could be used in this study. New data sets were subjected to the same quality control procedures developed for the WOCE program. Parameter accuracy was estimated by comparison of deep water values to values obtained as part of WOCE. The precision of new data was estimated by visual examination of deep water properties within each data set. Property change was determined by comparing distributions in potential density space along sections with multiple occupations at different times. This procedure yielded a time series for the 152W section from Hawaii to Alaska with four occupations and a few shorter sections with two occupations in the far northwestern Pacific. Coomparison was limited to samples having a density greater than the densiest surface which outcropped in the winter in the North Pacific and having a depth significantly deeper than the deepest mixed layer found for the region.

Comparisons were made for nutrients, oxygen and carbon parameters, but the primary focus was on oxygen since this measurement had the greatest signal to noise ratio. All comparisons were made relative to WOCE cruises. Very significant trends were identified for both the eastern and western North Pacific. The oxygen change along 152W was found to be even greater than discussed by Emerson et al. (2001) who used some of the same data. The difference between this comparison and Emerson derived from minor differences in technique.

At the workshop the changes in data properties with time were compared to numerical ocean model results, primarily presented by C. Deutsch. In discussions which followed, the conclusion was that the differences were all attributable to changes in physical ocean circulation.

One additional result derived from the workshop was much more open data sharing agreements between the U.S. and Japan. Subsequent to the meeting we now have access to a large new data set which includes numerous time series stations and sections in the Northwest Pacific. Preliminary investigation indicates that significant effort will be required to configure the Japanese data into a better format, but once this is accomplished, the merged Pacific data available for climate changes including carbon will be much improved.!

References:

Emerson, S., S. Mecking and J. Abell, The biological pump in the subtropical North Pacific Ocean: Nutrient sources, Redfield ratios, and recent changes, Global Biogeochem. Cycles, 15(3), 535-554, 2001.

Publications:

No publications have yet resulted from this work. Results are expected to be presented at the next PICES meeting.

Progress Report: **Land carbon sink modeling**

Principal Investigator: Stephen W. Pacala (Princeton)

Other participating researchers: Elena Shevliakova and Sergey Malyshev (Princeton)

NOAA's Goal #2 - Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:
To continue the development of new models of the land surface, with an emphasis on terrestrial carbon sources and sinks.

Methods and Results/Accomplishments:
1. Land model development:
A comprehensive land model has been implemented and is undergoing an evaluation. The model is capable of simulating global distribution and functioning of terrestrial carbon sources and sinks as well as the exchange of water and energy between land, vegetation, and atmosphere. The carbon acquired through photosynthesis is balanced by plant respiration and carbon accumulation in leaves, roots, sapwood, and wood. In addition, model simulates soil carbon pools processes. The land model allows to track carbon dynamics of vegetation and soil in response to environmental conditions, ambient concentration of CO2, natural disturbances (e.g. fire), and anthropogenic land use changes (e.g. deforestation and agricultural cropland abandonment). Additionally, changes in distribution of vegetation structural characteristics are affecting key land surface parameters such as albedo and surface roughness. The land model has undergone a series of experiments with prescribed climate and coupled to GFDL atmospheric model. Additionally, a number of improvements to river routing model and soil hydrology and physics have been implemented. Ongoing work is focusing on improvements in simulation of regional distribution of carbon fluxes and their interannual variability. A number of experiments of land model coupled to climate model are underway, including an interactive CO2 fluxes.
2. IPCC climate scenario simulations.
Implemented 1850-2000 historical land cover dataset for LM2 was assembled and used in CM2 IPCC simulations.
3. Participation in Global Land-Atmosphere Coupled Experiment.
We have also participated, together with Dr. C. T. Gordon (GFDL), in collaborative Global Land-Atmosphere Coupled Experiment (GLACE, http://glace.gsfc.nasa.gov/). The purpose of this project is to establish the coupling strength between land and atmosphere components in a number of GCMs, to improve understanding of land processes in general, and understanding of differences among models in particular. We have submitted results of GFDL model runs; currently our results and the results of other modeling groups are being analyzed by the project team, and detailed paper is going to be published as soon as the analysis is done. First results of the study have been recently published in Science (see reference below). A manuscript describing GLACE results in details is in preparation
4. Study of the influence of large-scale wind-power on global climate.

This is also a collaborative effort by Princeton University, GFDL, Carnegie-Mellon University, and National Center of Atmospheric Research (NCAR). The results of this study have shown that the influence of massive amount of wind farms (about 10% of land surface, sufficient to satisfy energy needs of humankind by year 2100 without fossil fuels) on climate is not negligible in some regions. Both GFDL and NCAR models have shown consistent and detectable response to the wind farms, which, however, is much smaller that the effect of corresponding carbon emissions would be if all the energy came from fossil fuels. The results of the GFDL model have been presented at the 2003 Fall AGU Meeting, December 8-12, San Francisco, CA. A paper describing the results of the entire collaborative study has been submitted to PNAS and accepted, currently in press.

Publications:

Randal D. Koster, Paul A. Dirmeyer, Zhichang Guo, Gordon Bonan, Edmond Chan, Peter Cox, C. T. Gordon, Shinjiro Kanae, Eva Kowalczyk, David Lawrence, Ping Liu, Cheng-Hsuan Lu, Sergey Malyshev, Bryant McAvaney, Ken Mitchell, David Mocko, Taikan Oki, Keith Oleson, Andrew Pitman, Y. C. Sud, Christopher M. Taylor, Diana Verseghy, Ratko Vasic, Yongkang Xue, Tomohito Yamada, 2004: Regions of Strong Coupling Between Soil Moisture and Precipitation, Science, 305, 1138-1140

David W. Keith, Joseph F. DeCarolis, David C. Denkenberger, Donald H. Lenschow, Sergey L. Malyshev, Stephen Pacala and Philip J. Rasch, 2004: The influence of large-scale wind-power on global climate, accepted to Proc. Nat. Academy of Science.

Shevliakova, E., S.W. Pacala, S. Malyshev, G.C. Hurtt, and J.P. Caspersen. 2003 "Carbon Cycle and Vegetation Dynamics in the GFDL-Princeton University Coupled Atmosphere-Biosphere Model",Eos Trans. AGU, 84(46), Fall Meet. Suppl., Abstract B41C-0899A.

Shevliakova, E., S.W. Pacala, S. Malyshev, G.C. Hurtt, J. P. Caspersen, P.C.M. Milly, & L.Thompson "LM3 – Terrestrial Component of the GFDL/Princeton University Coupled Atmosphere-Biosphere Model. Model Design and Evaluation." (In preparation).

Project Report: **Workshop on policy and carbon and aerosols**

Principal Investigator: V. Ramaswamy (GFDL)

Other Participating Researchers: M. Oppenheimer (Princeton University), A. Leetmaa (GFDL)

NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives: Investigations of the inputs of carbon dioxide and aerosols into the atmosphere upon air quality and climate, the global and regional impacts, and how the quantitative determinations can be used to provide improved inputs into policy-making decisions.

Methods and Results/ Accomplishments:
This project will consist of convening a Workshop to go over the issues mentioned above and come forth with a set of recommendations. Preparations have involved discussions with a select number of scientists from various institutions including Princeton/ GFDL as to the aspects that require the most attention. Concerns have been raised as to how the focus needs to be a tight one in order to avoid a shallow exercise. To this effect, a set of questions have been drafted and are undergoing scrutiny by scientists before the agenda is set and official invitations are prepared. The Workshop to discuss the issues will be a limited participation event; we are hoping to get experts in a diverse set of the relevant disciplines - climate change modeling, air quality and pollution experts, impacts analysts, economics. Owing to our desire to get top-notch experts, we have been constrained to defer the date of the meeting to Spring of next year in order to avoid conflicts with other major meetings.

So far, there is a broad agreement that the issues to be discussed should include the following: global versus regional changes over the past century and those anticipated over the next century by the IPCC- class models; focus on temperature, precipitation, heat index, soil moisture; uncertainties in forcings and feedbacks that lead to uncertainties in responses; natural variability; air quality evolution around the globe, contrasting Europe and Asia; technology in play in various countries to control pollution; if possible, devise metrics that quantitatively link climate impacts with air pollution effects; factors emanating from the scientific studies that are key as inputs into policy decisions. Some specific issues concerning economic aspects have yet to be formulated. The target date for completion of the drafting is Fall 2004.

Reference:
Intergovernmental Panel on Climate Change (2001), Cambridge University Press.

Project Report: **Optical properties of organic aerosol and consequences for climate**

Principal Investigator: Cynthia Randles (Princeton graduate student)

Other Participating Researchers*:* Advisors: V. Ramaswamy (GFDL), L. M. Russell (Princeton, now at UCSD/Scripps Institution of Oceanography)

NOAA's Goal #2 - Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:

The purpose of this research is to investigate the role organic carbon plays in optical extinction and to try and reduce the uncertainties in the optical properties associated with organic carbon. Different organic compounds will have different effects on the hygroscopic growth properties of aerosol, and different organic compounds will have differing absorption properties. The goal is to link growth properties of a particular subset of organic compounds to reasonable ranges of optical properties in order to obtain a reasonable range of extinction associated with organics.

Methods and Results/Accomplishments:

Scattering of incoming solar radiation by sea salt aerosol is strongly dependent on relative humidity (RH) since hygroscopic particles take up water at high RH. Organic compounds may constitute up to 50% of marine aerosol mass in internal mixtures. We used a detailed thermodynamic and optical model to calculate hygroscopic growth and extinction of sea salt aerosol internally mixed with a soluble organic compound. Increasing organic content from 10 to 50% suppresses growth at high RH compared to a pure NaCl particle by 4 to 20%. For a mildly absorbing organic, the scattering increase with RH is reduced by up to 32% for these mixtures, consistent with observations. Internal mixtures of 90% NaCl and 10% non-absorbing organics cause 3% less cooling than 100% NaCl particles in the visible spectrum over the clear-sky oceans. For a mildly absorbing organic compound, 10% organic content reduces radiative cooling substantially compared to 100% NaCl aerosol [Randles et. al., 2004].

From the results of Randles et. al. [2004], absorbing organic compounds on sea salt change the direct radiative forcing of aerosols, possibly even from cooling to warming when the surface albedo is very reflective. This effect is primarily due to assumed absorption properties of the OC, although hygroscopicity also has a significant effect. It is important to improve our understanding of absorption by OC for the particle concentrations and sizes assumed in this study. This study motivates the assessment of the probability and loading of OC with imaginary refractive indices as high as 10^{-3} in actual field conditions. Organic functional group composition sampled at Appledore Island, ME during ICARTT 2004 will be used to determine realistic representative organic compounds that vary in both optical and hygroscopic properties. Using concurrently sampled size distributions, Mie calculations will be performed to assess the variability in extinction as a function of organic hygroscopicity and absorption.

Publications/References

Randles, C. A., L. M. Russell, and V. Ramaswamy (2004), Hygroscopic and optical properties of organic sea salt aerosol and consequences for climate forcing, *Geophys. Res. Lett.*, 31, L16108, doi:10.1029/2004GL020628.

Project Report: **Quantifying The Control That The Position Of The Southern Hemisphere Westerlies Exerts On The Partition Of CO_2 Between Atmosphere And Ocean**

Principal Investigator: Joellen L. Russell(Princeton)

Other Participating Researchers: J.R. Toggweiler(GFDL), J. M. Wallace (U. Washington)

NOAA's Goal # 2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond.

Objectives:
Dr. Russell is quantifying the control that the position of the Southern Hemisphere westerlies exerts on the partition of CO_2 between atmosphere and ocean. This work has implications for the global carbon cycle in both the past (i.e. glacial- interglacial) and the future (as a response to increased greenhouse gas loading). There are significant observed trends in Southern and Northern Hemisphere zonal winds, with a tendency in recent years for more positive Northern and Southern Annular Mode (NAM and SAM) indices, corresponding to a poleward displacement of the mid-latitude westerlies.

Methods and Results / Accomplishments:
Dr. Russell has simulated glacial/interglacial changes in atmospheric carbon dioxide by varying the wind over the Southern Ocean to produce changes in the rate of deep water upwelled to the surface, using a model constructed from an energy balance atmospheric model (EBM) coupled to a 3x3 degree ocean model (MOM4 -Khartoum), an ice model (SIS) and land model (LAD), and running with chlorofluorocarbons and the OCMIP2 carbon cycle tracers. She has simulated the effect of the modern circulation trends by imposing wind anomalies in the shape and magnitude implied by the NAM and SAM trends from NCEP data. Russell presented results from these simulations at an invited talk at the Goldschmidt Conference in Copenhagen, Denmark in June, 2004 and the paper is in preparation. Russell is currently conducting simulations of future impacts of the poleward shift of the westerlies by increasing the atmospheric load of CO_2 in $2XCO_2$ and $4XCO_2$ simulations while forcing the model with the winds from the same runs of CM2.0 and CM2.1.

Dr. Russell is a co-author on the three papers documenting GFDL's CM2 climate models in preparation for the Journal of Climate. She is also contributing a paper titled "The Impact of the Poleward Shift of the Westerly Winds on the Southern Ocean Circulation in GFDL's CM2 Climate Models" for the same issue of the Journal of Climate.

Dr. Russell also continues her collaboration with Prof. Mike Wallace (Dept. of Atmospheric Sciences, University of Washington) with a new paper on the impact of tropical biomass burning on global carbon dioxide growth rates and the oxidizing potential of the atmosphere. In addition, Russell has developed a version of the energy balance model for the next FMS release and is documenting that configuration in collaboration with Rong Zhang.

Publications:
Russell, J.L., & J.M. Wallace (2004). Tropical Biomass Burning on Global Carbon Dioxide Growth Rates and the Oxidizing Potential of the Atmosphere. In prep. for Global Biogeochem. Cycles.

Russell, et al. The Impact of the Poleward Shift of the Westerly Winds on the Southern Ocean Circulation in GFDL's CM2 Climate Models. In prep for J. of Climate.

Russell, J.L. and J.R. Toggweiler. The Position of the Westerly Winds Determines the Partitioning of Carbon Between Atmosphere and Ocean. In prep for Paleoceanography.

Russell and R. Zhang. FMS MOM4-EBM-SIS Coupled Model Documentation. In prep.

Delworth et al. GFDL's CM2 Climate Models- Part 1: Overall description. In prep. for J. of Climate.

Griffies et al. GFDL's CM2 Climate Models- Part 2: Ocean model formulation. In prep. for J. of Climate.

Gnanadesikan et al. GFDL's CM2 Climate Models- Part 3: The Ocean Simulation. In prep. for J. of Climate.

Project Report: **Development of a joint ocean-atmosphere inversion**

Principal Investigator: Jorge L. Sarmiento (Princeton)

Other Participating Researchers: Andrew Jacobson (Princeton)

NOAA's Goal # 2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:
A new estimation methodology that couples an inversion of atmospheric concentration time-series from the 75 longest-term Globalview-CO_2 stations to an ocean inversion of the GLODAP anthropogenic and pre-industrial carbon tracers has been developed.

Methods and Results/Accomplishments:

The new approach exploits for the first time in a consistent manner the large ocean carbon data set with atmospheric CO_2 concentrations to constrain land-air and air-sea carbon fluxes at the same time. The approach uses annual mean atmospheric concentration "footprints" (sensitivities of concentrations to surface fluxes) from the Transcom3 experiment and ocean footprints simulated with a suite of ocean models including the GFDL/NOAA MOM3 ocean model. First results of new joint inversions indicated considerable sensitivity of the footprint simulations to the use of different ocean and atmosphere transport models. Thus, we have decide to use an entire suite of 16 atmospheric and 10 oceanic transport model versions are used to make a robust, spatially-resolved estimate of air-sea and air-land carbon fluxes.

Interesting results include a very substantial reduction in uncertainty of oceanic surface fluxes with flux results of out-gassing in both the tropics and the Southern Ocean that are significantly lower than when using atmospheric data alone. This pinning-down of southern hemisphere and low-latitude air-sea fluxes combined with the atmospheric signals provides strong evidence for tropical and southern land CO_2 emissions to be significantly larger than estimated with previous inversions (Figure 1).

Publications:

Andrew R. Jacobson and Jorge L. Sarmiento (2004) On the Need for Regularization in Atmospheric Inversions of Surface Carbon Fluxes, In prep. for submission to *Geophys. Res. Lett.*

Andrew R. Jacobson, Nicolas Gruber, Jorge L. Sarmiento, and Sara Mikaloff Fletcher (2004), A Joint Atmosphere-Ocean Inversion for Surface Fluxes of Carbon Dioxide, In prep. for submission to *Global Biogeochemical Cycles.*

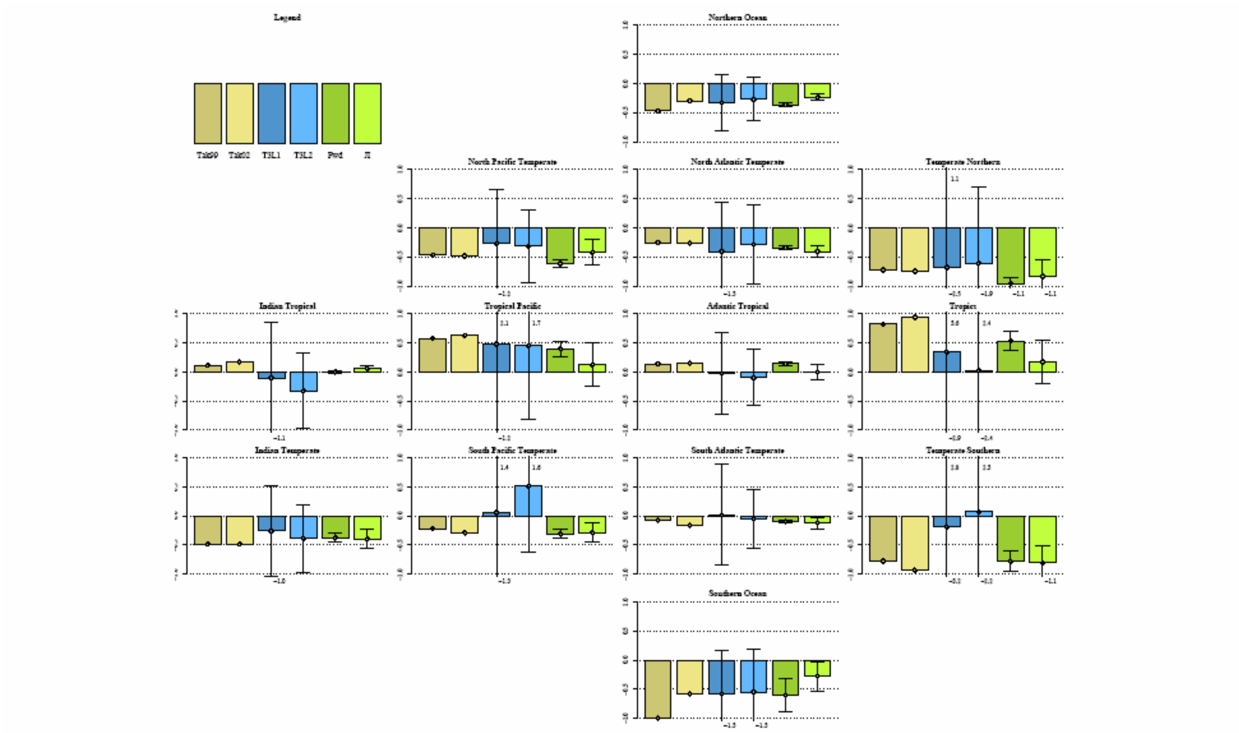


Figure 1 shows first results of this analysis for a meridional section across the Southern Ocean extending from South Africa to Antarctica, at about 20E.

Project Report: **Reanalysis of ocean Redfield ratios using new data and a Monte Carlo estimation technique**

Principal Investigator: Jorge L. Sarmiento (Princeton)

Other Participating Researchers: Andrew Jacobson and Robert M. Key (Princeton), Ben McNeil (University of New South Wales, Australia)

NOAA's Goal # 2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:
Analyses to improve our understanding of functioning and controls of the ocean carbon cycle

Methods and Results/Accomplishments:

Andy Jacobson, in collaboration with GLODAP author Robert Key and Australian colleague Ben McNeil, has developed a new inversion technique for water mass analysis using non-conservative tracers. In this inversion, biogeochemical tracer concentrations in a given sample are interpreted as a mixture of contributions from discrete end-members, modified by microbial remineralization. The system of equations being considered is nonlinear, and solutions are obtained using a global nonlinear optimization scheme based on simulated annealing. Previous attempts to solve systems like this one have involved either a regretful linearization or the use of non-global nonlinear optimizers which are susceptible to the problem of getting stuck in local minima. For this reason alone, the retrieved parameters are likely to be more robust. The fundamental problem of water mass analysis remains, however: the characterization of the chemical properties of end-members is subject to biases and uncertainties that propagate through the system in complicated ways. This new inversion technique performs "geographic" Monte Carlo analysis with end member properties chosen randomly for each inversion trial from the distribution of the wintertime surface expression of each water mass. In this manner, an explicit estimate of the uncertainty due to end member characterization uncertainties is obtained. Retrieved quantities include not only the fractions of major water masses composing some 70,000 samples in the world ocean, but also the stoichiometry of aggregate remineralization undergone by the mixture.

Spatial gradients and mean values of the new stoichiometric ratios disagree to varying extents with the commonly-used constant values established by Redfield (1934) and refined by Anderson and Sarmiento (1994).

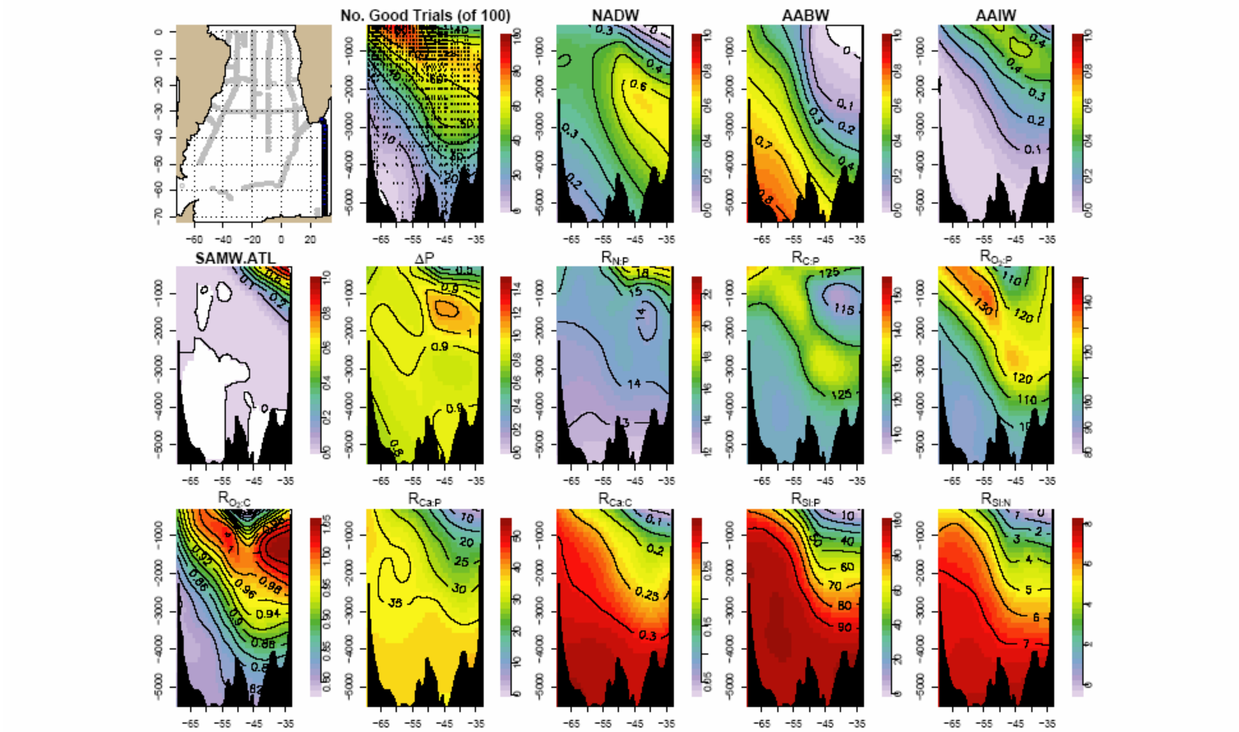


Figure 2. Comparison of ocean flux estimates. In this tableau, discrete flux regions are depicted in correspondence to their approximate geographic location. Each bar represents an estimate of the air-sea CO_2 flux from a different source. They are: T99-Takahashi (1999), Tak02--Takahashi (2002), T3L1-TransCom3, Level 1 atmospheric inversions, T3L2-TransCom3, Level 2 atmospheric inversions, Fwd-the five-configuration MOM3 suite forward simulations using OCMIP2 protocols, and JI--the current joint inversion estimate. Units are PgC/yr and error bars extend to one standard deviation.

Publications:

Andrew R. Jacobson, Benjamin I. McNeil, Robert M. Key, and Jorge L. Sarmiento (2004),Water Mass Analysis using Nonconservative Tracers Part I: Methods and Evaluation, In prep. for submission to *Global Biogeochemical Cycles.*

Andrew R. Jacobson, Benjamin I. McNeil, Robert M. Key, and Jorge L. Sarmiento (2004),Water Mass Analysis using Nonconservative Tracers Part II: South Atlantic Case Study, in prep. for submission to *Global Biogeochemical Cycles.*

Figure 3. Nonlinear water mass analysis for section depicted with dark blue circles in map in upper left-hand corner.

Project Report: **Sensitivity-Analysis of low-latitude productivity to sub-antarctic mode water formation rate and sub-antarctic mode water pathways**

Principal Investigator: Jorge L. Sarmiento (Princeton)

Other Participating Researchers: Jennifer Simeon(Princeton)

NOAA's Goal # 2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:
Analyses to improve our understanding of functioning and controls of the ocean carbon cycle

Methods and Results/Accomplishments:
Changes of ocean circulation in the near future as a result of global warming are likely. In order to understand the possible consequences on ocean carbon cycling and thus carbon uptake an understanding of the main controls of ocean productivity is needed. Sarmiento et al., (2004), demonstrated the prevalence of Sub-antarctic Mode Water (SAMW) in the thermocline, indicating that SAMW water renewal rate is a major control to low-latitude biological productivity. The present research extends this study by illustrating the pathways of SAMW from the base of the thermocline to the ocean surface, quantifying the SAMW contribution to above thermocline waters and their renewal rate, and finally estimating the response time of above thermocline waters to potential changes of SAMW production and pathways.

To address the research questions we utilize a novel dye tracer to track the dispersion of surface waters originating from the SAMW outcrop in combination with an idealized age tracer. Both tracers are used in a suite of simulations with general circulation models (GCM). Three GCM versions are employed to represent a broad range of plausible global circulations. The three versions differ by the return pathways of high-latitude waters. Ultimately, the relevance of the SAMW circulation with respect to the dispersion of pre-formed Southern Ocean nutrients in the global ocean is examined using a correlation analysis between SAMW water mass fraction and nutrient concentrations.

In more detail we released dye tracer from four source regions: (1) SAMW outcrop, (2) Antarctic Intermediate Water outcrop, (3) entire ocean surface north of 40N and (4) approximately 1000 m deep (□=27.4 isopycnal), low-latitude region extending from 30 S and 40 N. At steady state dye values equal the fractional contribution of source region waters to specific water volumes like upper thermocline water (Figure 4). The idealized age tracer tracks the age of a water parcel as it moves away from any one of the four source regions. The age tracer, in conjunction with the dye tracer, provides an estimate of the thermocline's response time to changes in the source regions. Lastly, float trajectory simulations reconstruct where SAMW waters enter the main thermocline and through which processes.

Results show that the upper thermocline is predominantly comprised of SAMW (~60%), even for the GCM circulation with strong low-latitude upwelling (SAMW composes ~46%). Age tracers indicate the relative speed with which water parcels originating from the SAMW outcrop propagate through the Atlantic and the global oceans. Given the volume of SAMW occupying the upper thermocline and the speed with which it penetrates the global oceans a response time can be calculated by scaling the respective age tracers with the source fractions (i.e. the dye tracer concentration) . This, in theory, represents the time it would take for source region waters to entirely flush the volume of the upper thermocline. Preliminary analyses indicate that the global thermocline will begin to ``feel'' the changes in SAMW production rate on a timescale of approximately 270 years or less.

Float trajectories indicate two general pathways for northward SAMW to enter the main thermocline. One pathway is ``fast", O(10 years), where SAMW follows eastern boundary currents. This path is impacted by near surface buoyancy fluxes resulting in relatively fast transformations from heavy to light waters. The second pathway is slow, O(100 years), and follows the geostrophic gyre transport pathway. These parcels tend to follow isopycnals and remain enclosed in the ocean interior.

The different pathway timescales have implications on the SAMW's maintenance of pre-formed versus remineralized nutrients. The dye tracers and nutrients are examined along selected, representative float trajectory paths. Correlation analyses of the dye tracers and various nutrients along these paths indicate that the integrity of nutrients originating from the SAMW outcrop is preserved fairly well in the South Pacific gyre, while in the South Atlantic gyre, nutrients are not well preserved. One can speculate that this is due to biological activity or that, given that the float analyzed remained in the near surface waters much of the time, the physical dynamics rapidly de-couple from the nutrient dynamics.

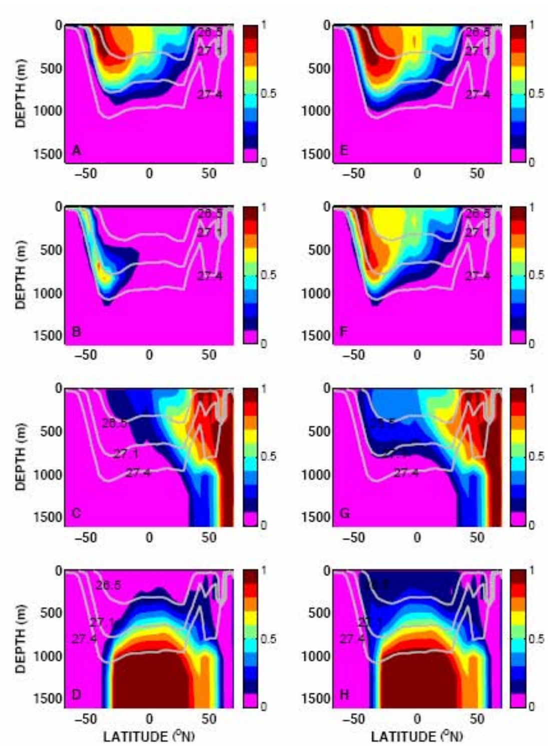


Figure 3: Dye tracer simulation results. Dye is released in four source regions, from top, SAMW, AAIW, Northern and Deep,Low-Latitude. A value of 1 indicates dye release region. In the upper thermocline, dye is allowed to propagate freely, varying in magnitude from 0 to 1. The dye then becomes representative of the fractional contribution from the source region. For areas denser than the 27.4 isopycnal, dye is removed from the system. Simulations on the left column are cases when the SAMW

and/or the AAIW outcrop regions are excluded from the "free" region. Panels on the right show cases when the outcrop regions are included in the "free" region.

Publications:

Sarmiento, J.L., N. Gruber, M.A. Brzezinski and J.P. Dunne, High-latitude controls of thermocline nutrients and low latitude biological productivity, Nature, 427, 56-60, 2004.

Sarmiento, J.L. and J. Simeon, Quantification of the SAMW influence and climate sensitivity timescale over the thermocline, (in preparation).

Project Report: **Development of Gas-exchange component of GFDL Earth-System Model**

Principal Investigator: Jorge L. Sarmiento (Princeton)

Other Participating Researchers: Richard D. Slater and Sergery Malyshev (Princeton), John Dunne (GFDL)

NOAA's Goal # 2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:
Development of a Earth-System Model

Methods and Results/Accomplishments:
A generalized coupling of gas fluxes between the ocean and atmosphere in the context of the FMS is under development. Thus far, a framework has been developed and implemented which allows an arbitrary number of gasses to be transferred across the ocean-atmosphere interface based on user-specifiable gas flux schemes based on wind speed, Schmidt number, solubility and oceanic and atmospheric concentrations. Carbon dioxide and oxygen have been implemented within our ocean biogeochemistry models. Work is progressing to merge this scheme with that developed by the land modelers.

Project Report: **The Effects Of Adding Chlorophyll A To The MOM4 om2.**

Principal Investigator: Colm Sweeney(Princeton)

Other Participating Researchers: Anthony Rosati(GFDL)

NOAA's Goal # 2 – Understanding Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:
Understanding the effects of adding chlorophyll a to the MOM4 om2.

Methods and Results/Accomplishments:
In this project I have been looking at the effects due to difference parameterizations of shortwave irradiance in the water column on ocean circulation and heat transport. The results of this study show that parameterizations which prescribe more absorption of shortwave irradiance at the surface tend to stratify the waters in the subtropical and tropical gyre regions. The effect of this stratification actually results in small increases in heat transport due to a shallower Ekman layer and greater surface divergence. The resulting effect at the equator is lower sea surface temperatures. While the addition to chlorophyll-a fields to the MOM4 ocean model has added another level of realism our parameterization of shortwave radiation, the overall effects to circulation are second order.

Publications

Sweeney, C., A. Gnanadesikan, S. M. Griffies, M. J. Harrison, A. J. Rosati, and B. L. Samuels, 2004: Impacts of shortwave penetration depth on large-scale ocean circulation and heat transport. *Journal of Physical Oceanography*, **Accepted**.

Project Report: **Estimation of pCO2 in the equatorial Pacific Using Rosati Assimilation Model and Feely pCO2 data.**

Principal Investigator: Colm Sweeney(Princeton)

Other Participating Researchers: John Dunne(GFDL), Richard Feely(PMEL), Manuel Gloor (Princeton), Andy Jacobson(Princeton), Anthony Rosati(GFDL), Jorge Sarmiento(Princeton) and Rik Wanninkhof (AOML)

NOAA's Goal # 2 – Understanding Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:
Estimation of pCO2 in the equatorial Pacific using Rosati assimilation model and Feely pCO2 data.

Methods and Results/Accomplishments:
About a year ago GFDL hosted the PMEL/GFDL/AOML ocean CO_2 data assimilation workshop which had the following goals. From that meeting a set of questions were identified to guide our research over the next three years:

1) What is the magnitude of the air-sea CO_2 flux over the world oceans?
2) What is the natural variability in the air-sea gas exchange of CO_2?
3) What are the mechanisms driving variability in air-sea gas exchange of CO_2?
4) How will air-sea gas exchange change in the future?

With the ongoing development of a biogeochemical model for MOM4 and a 4-D variational assimilation model at GFDL over the past year, it seemed appropriate to focus on two goals. The first would be a short-term goal appropriate to the datasets and modeling products that are ready for use. The second was longer-term goals which would have a global focus and utilize datasets and models that were still being developed. Since that meeting a lot of progress has been made both in model development at GFDL and data acquisition and analysis at PMEL and AOML. In particular, I wanted to update you on the our progress merging the GFDL data assimilation model with data acquisition and analysis at PMEL and AOML.

In several recent papers Dick Feely and others (i.e. Cosca, et al. 2003; Feely, et al. 2004; Takahashi, et al. 2003; Obata and Kitamura 2003; Le Quere, et al. 2000; McKinley, et al. 2004) have demonstrated that a major source of inter annual variability in air-sea CO2 fluxes occurs in the Equatorial Pacific. In order to correctly quantify this variability we have focused on finding empirical relationships between surface ocean pCO2 and other non-CO_2 data products that can be are easily measured or predicted over many time and space scales. Because the surface concentration of CO2 and the consequential air-sea flux is primarily constrained by circulation and biology, our focus has been to identify datasets that are most likely to indicate changes in circulation or biology. While satellite data is often cited as the answer to our inability to be at all places at all times, we believe that GFDL data assimilation model maybe yet another important tool for interpolating between measurements to predict the inter annual variability in air-sea CO2 fluxes. In this regard Dick Feely has identified a strong relationship between the 20C isotherm depth and surface ocean pCO2 in the Equatorial Pacific. Over the next six months we plan to use this empirical relationship between surface pCO2 and the 20C isotherm to predict the magnitude of variability air-sea fluxes from 1980-2000 in the Equatorial Pacific. The emphasis of this short-term study will be to test how far off the equator this relationship holds. With the recent completion of GFDL prognostic biogeochemical model we hope to be able to compare and contrast measurements of surface pCO2 at the equator with the 43 year re-analysis run that is now being set up by John Dunne. Further work will also be done to compare the 43 re-analysis run with a steady state run enabling us to identify dominant processes responsible inter-annual changes in surface ocean pCO2 and the resulting air-sea flux. Ultimately, we strive to assimilate the data collected at PMEL and AOML into the models at GFDL. This will evolve as the GFDL ocean adjoint model becomes available.

Anticipating the value of high frequency non-remotely sensed salinity and mixed layer depth measurements to improve both the circulation through data assimilation and estimates of CO2 air-sea flux, AOML is producing seasonal mixed layer depth and surface salinity fields based on the ARGO profiling float array. This data will be used in conjunction with surface water pCO2 levels obtained from the NOAA COSP program to determine the use of MLD and SSS in creating pCO2 algorithms other parts of the ocean that can be used in the assimilation routines.

References:

Cosca, C. E., R. A. Feely, J. Boutin, J. Etcheto, M. J. McPhaden, F. P. Chavez and P. G. Strutton. 2003. Seasonal and interannual CO2 fluxes for the central and eastern equatorial Pacific Ocean as determined from fCO(2)-SST relationships. Journal of Geophysical Research-Oceans 108.

Feely, R. A., R. Wanninkhof, W. McGillis, M. E. Carr and C. E. Cosca. 2004. Effects of wind speed and gas exchange parameterizations on the air-sea CO2 fluxes in the equatorial Pacific Ocean. Journal of Geophysical Research-Oceans 109.

Le Quere, C., J. C. Orr, P. Monfray, O. Aumont and G. Madec. 2000. Interannual variability of the oceanic sink of CO2 from 1979 through 1997. Global Biogeochemical Cycles 14: 1247-1265.

McKinley, G. A., M. J. Follows and J. Marshall. 2004. Mechanisms of air-sea CO2 flux variability in the equatorial Pacific and North Atlantic. Global Biogeochemical Cycles 18: GB2011.

Obata, A. and Y. Kitamura. 2003. Interannual variability of the sea-air exchange of CO2 from 1961 to 1998 simulated with a global ocean circulation-biogeochemistry model. Journal of Geophysical Research-Oceans 108.

Takahashi, T., S. C. Sutherland, R. A. Feely and C. E. Cosca. 2003. Decadal variation of the surface water PCO2 in the western and central equatorial Pacific. Science 302: 852-856.

Project Report: **Design and Construction Of Atmosphere And Coastal Ocean CO_2 Measurement Platform – SABSOON**

Principal Investigator: Colm Sweeney(Princeton)

Other Participating Researchers: Wade McGillis(WHOI)

NOAA's Goal # 2 – Understanding Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:
Design and construction of atmosphere and coastal ocean CO_2 measurement platform-SABSOON

Methods and Results/Accomplishments:
A combination of resources including both time series stations and ship surveys of sea surface and atmospheric CO_2 on the continental margins are required to properly assess the coastal carbon component of the NACP. The objective of this project is to design and build a prototype CO_2 measurement system on a ocean tower on the southeastern continental shelf of the United States. This pCO_2 system will be capable of making calibrated atmospheric CO_2 measurements comparable to ***CMDL island stations*** in addition to in situ sea surface CO_2 concentrations. In addition to high-quality (0.2 ppm) and high-frequency CO_2 measurements taken every ½ hour, monthly CMDL flask analysis of CO_2, N_20, SF_6, CO, and CH_4 will allow us to quantify and understand the sources of variability in the atmosphere while continuous measurements of dissolved O_2 and monthly measurements of total CO_2 will allow us to quantify and understand sources of variability in the ocean.

Publications:

Sweeney, C., T. Newberger, and W. McGillis, 2005: Remote-high precision measurements of atmospheric and ocean pCO2. *Ocean Engineering*, **In prep**.

Sweeney, C., T. Newberger, and T. Takahashi, 2004: Mechanisms driving meso-scale, regional and annual variability of surface ocean pCO2 in the Drake Passage . *Deep Sea Research*, **In prep**.

Project Report: **Estimation of Global Gas Exchange Coefficient for CO_2 and Other Trace Gases**

Principal Investigator: Colm Sweeney(Princeton)

Other Participating Researchers: Manuel Gloor(Princeton), Andy Jacobson(Princeton), Anthony Rosati(GFDL), Jorge Sarmiento(Princeton) and Rik Wanninkhof (AOML)

NOAA's Goal # 2 – Understanding Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:
Estimation of global gas exchange coefficient for CO_2 and other trace gases

Methods and Results/Accomplishments:
Wind-speed dependent bulk formulations of gas transfer velocity have traditionally been scaled to the oceanic inventory of bomb ^{14}C (Wanninkhof 1992, Wanninkhof and McGillis 1999). The recent advances in our ability to estimate both the first two moments of global wind-speeds and the inventories of bomb ^{14}C inventories call for a reanalysis of this anchor point as well as an exploration of its implications on oceanic carbon uptake. We present a reanalysis of ^{14}C flux estimates which proceeds from global to regional scales using both the traditional global inventory approach directly from data as well as inverse calculations of oceanic transport which permit us to resolve atmosphere-ocean ^{14}C flux in 10 regions. Using a best fit, in a least squares sense, between 8,000 measurement-based estimates of bomb ^{14}C in the upper 1500 m of the water column and three different configurations of a GCM we see a discrepancy between our inventory and the Broecker et al. (1985 and 1995) bomb ^{14}C inventories used by Wanninkhof (1992) and Wanninkhof and McGillis (1999). Our preliminary results suggest that the average global piston velocity may be over estimated by as much as 25%. However, large discrepancies between data and model-based inversions in surface waters of the high latitudes will need to be further investigated. A regional analysis shows that while total world ocean inventories are similar, there is a large model dependent variation in the location of the bomb ^{14}C surface fluxes. In particular, average surface fluxes of bomb ^{14}C from 1954-1994 are extremely dependent on the model parameterizations picked in the Southern Ocean.

Publications:
Sweeney, C., E. M. Gloor, A. R. Jacobson, R. M. Key, G. Mckinley, J. L. Sarmiento, 2004: Inverse estimates of the Bomb ^{14}C inventory and gas exchange coefficient in the world oceans. *Geophysical Research Letters*, **In prep**.

References:
Broecker, W. S., T. H. Peng, G. Ostlund and M. Stuiver. 1985. The Distribution of Bomb Radiocarbon in the Ocean. Journal of Geophysical Research-Oceans **90:** 6953-6970.

Broecker, W. S., S. Sutherland, W. Smethie, T. H. Peng and G. Ostlund. 1995. Oceanic Radiocarbon - Separation of the Natural and Bomb Components. Global Biogeochemical Cycles **9:** 263-288.

Wanninkhof, R. 1992. Relationship between Wind-Speed and Gas-Exchange over the Ocean. Journal of Geophysical Research-Oceans **97:** 7373-7382.

Wanninkhof, R. and W. R. McGillis. 1999. A cubic relationship between air-sea CO2 exchange and wind speed. Geophysical Research Letters **26:** 1889-1892.

Project Report: **Aerosol impact on tropospheric photochemistry from the viewpoint of radiative transfer.**

Principal Investigator: Huiyan Yang (Princeton graduate student)

Other participating researcher: Advisor: Hiram Levy II(GFDL)

NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:
To understand the aerosol impact on tropospheric photochemistry from the viewpoint of radiative transfer.

Methods:
The aerosol optical parameters were calculated with Wiscombe's Mie code (http://climate.gsfc.nasa.gov/%7Ewiscombe/Home.html). The photodissociation coefficients (J's) were calculated with the NCAR Tropospheric Ultraviolet & Visible (TUV) radiation model (Madronich and Flocke, 1998) (http://acd.ucar.edu/models/UV/TUV/index.html), version 4.0a. Actinic flux was calculated with the 8-stream DISORT radiative transfer scheme in TUV. Daily averaged O_3 tendencies and OH concentrations were calculated with a background photochemical box model (Klonecki and Levy II, 1997, Klonecki, 1999), which was coupled to TUV.

Results/Accomplishments:
Clouds and BC aerosols are found to be the most important. A comparison between the sensitivity study and some representative observations showed that the global average cloud reduction of DIPR at the surface level is about 20%, and is about 30% in storm-track zones. At the surface level, the average negative BC impact is about 10% in urban areas, and could reach about 40% in some heavily polluted urban areas. Mineral-dust aerosol, which is the next most important, can reduce the photochemistry at the surface level by over 17% in some seasons over the desert or along its long-range transport paths. The negative impact of sulfate aerosols is around 2% at the surface level, and the impact is as positive as 4% at the top of the sulfate aerosol layer in some urban areas. BC, sulfate, and mineral-dust all have much smaller impacts away from their source regions. The impact of sea-salt aerosol is generally less than 1%. The fractional impacts on O_3 chemical tendency and OH concentration don't depend much on NO_x, but the magnitude of the impact depends strongly on the concentration of NO_x: when NO_x is very low, the impacts are also very small even if DIPRs are strongly affected. By studying different mixing states of absorbing and scattering aerosol components, it is found that the external mixing state produces the weakest impact while the internal mixing state produces the strongest impact. Coating has almost the same impact as internal mixing. There is very little synergy between cloud and absorbing aerosols when clouds are located above the aerosol layer or when they are located in the same layer. The synergy is strong when clouds are located below the absorbing aerosol, where the impact of absorbing aerosol dominates.

References:

Klonecki, A. and H. Levy II, Tropospheric chemical ozone tendencies in CO-CH4-NOy-H2O system: their sensitivity to variations in environmental parameters and their application to global chemistry transport model study, J. Geophys. Res., 102, D17, 21,221-21,237, 1997.

Klonecki, A., Model study of the tropospheric chemistry of ozone, PhD thesis of Princeton University, 1999.

Publications:

Sensitivity of photodissociation rate coefficients and O3 photochemical tendencies to aerosols and clouds, Huiyan Yang and Hiram Levy II, accepted by *J. Geophys. Res.*, 2004

Progress Report: **Aspects of Dimethyl ether (DME) as a clean household cooking fuel for China.**

Principal Investigator: Eric Larson (Princeton University)

Other participating researcher: Huiyan Yang (Graduate Student)

NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives: To understand different aspects of Dimethyl ether (DME) as a clean household cooking fuel for China.

Methods: Paper reading and compilation, data collection and analysis

Results/Accomplishments:
Dimethyl ether (DME) has characteristics similar to liquefied petroleum gas (LPG) as a household cooking fuel. As such, DME is an attractive fuel for clean cooking. DME can be made from any carbonaceous feedstock, including natural gas, coal, or biomass using established technologies. Given China's rich coal resources, the production and use of coal-derived DME as a cooking fuel in China could be attractive. We reviewed characteristics of DME and technology for making DME from coal. Conditions under which coal-derived DME in China would be cost-competitive with imported LPG in different regions of China are analyzed.

Publications:
DME from coal as a household cooking fuel in China, Eric Larson and Huiyan Yang, accepted by *Energy for Sustainable Development*, 2004.

Progress Report: **Transformation of black carbon aerosol from hydrophobic to hydrophilic.**

Principal Investigator: Huiyan Yang(Graduate Student)

Other participating researcher: Hiram Levy II(GFDL)

NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:
To understand the transformation of black carbon aerosol from hydrophobic to hydrophilic.

Methods:
A box model was set up in the study of the role of H2SO4 vapor in the transformation of black carbon aerosol from hydrophobic to hydrophilic. The model has four species: H2SO4 vapor, sulfate nuclei, hydrophobic black carbon aerosol (BC1), and pre-existing water-soluble aerosols. The production rate of H2SO4 vapor by SO2 oxidized by OH is the input of the model. There are nucleation and condensation of H2SO4 vapor, self-coagulation of sulfate nuclei, and coagulation of sulfate nuclei on BC1 and water-soluble aerosols. The number density of BC1 and water-soluble aerosols are kept constant in the simulation, while the concentrations of H2SO4 vapor and sulfate nuclei vary with time. There is also a prescribed deposition rate of H2SO4 vapor and sulfate nuclei.

Results/Accomplishments:
The condensation of H2SO4 vapor is found to be the most important mechanism in the transformation. The representative transformation time by this mechanism ranges from about 4 hours (by including the nucleation of H2SO4 vapor) to 40 hours in urban and remote oceanic areas respectively. The coagulation of hydrophobic black carbon aerosol with pre-existing water-soluble aerosols is important only in urban and urban influenced rural areas, while the coagulation with cloud droplets is important in remote areas.

Publications:
Study of the transformation of black carbon aerosol from hydrophobic to hydrophilic, in preparation.

Project Reports:

Paleoclimate

Project Report: **Exploring The Dynamics Of The Tropical Oceans**

Principal Investigator: Marcelo Barreiro(Princeton)

Other participating researchers*:* George Philander (Princeton)

NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objective:
The eastern tropical Atlantic and Pacific oceans are generally considered to behave similarly, with the SST variability dominated by dynamical ocean-atmosphere interactions. An interesting difference has been found in their response to orbital forcing. Paleoclimate records show that during the past the tropical Pacific SST variability has been dominated by the obliquity (41kyr) cycle, while the tropical Atlantic presents a stronger response to the 23kyr precessional cycle. This project investigates the dynamical reasons for this difference.

Methods and Results: To address this issue I am currently in the process of coupling a simplified atmospheric general circulation model to a 1-1/2 reduced gravity model of the global tropical oceans. This coupled model will be relatively fast to run allowing us to explore a large spectrum of possibilities by changing the physical parameters of the model.

In addition, as part of the community effort to evaluate the coupled model's performance I am analyzing the simulation of the model in the tropical Atlantic. The focus is on the simulated mean state, climatological cycle and interannual variability and its comparison with observations.

Project Report: **Factors that may affect polar stratification during glacial climates.**

Principal Investigator: Agatha M. de Boer(Princeton)

Other Participating Researchers: Daniel Sigman (Princeton)

NOAA's Goal # 2 – Understanding Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:
This research question concerns the factors that may affect polar stratification during glacial climates. Sigman et al. (2004) have recently proposed that the ocean may have been significantly more stratified in fresh polar regions during colder climates because of the non-linearity of the equation of state. They base their suggestion on ocean cores in the sub polar Pacific and the SO (south of the polar front) which display a sharp drop in opal (SiO_2 formed by Diatoms) during the late Pliocene transition (2.7 Million years ago) to colder ice-age climates. The opal decrease, together with a sharp increase in delN15 indicate that surface ocean was depleted in nutrients. Higher stratification could have inhibited the supply of nutrients from below. We would like to test the hypothesis in the same model in which we will perform the wind experiments. The purpose of this is to be able to compare the relative effects of colder climates and winds in the meridional overturning and ocean stratification.

Methods and Results/Accomplishments:
The project question is addressed by adjusting the equation of state in MOM4. Temperatures and salinities are kept constant but the density is calculated after the temperature is increased or decreased (only in the density calculation) by a constant value. Final conclusions will follow the completion of the revised set of experiments mentioned above.

References:
Sigman et al., 2004. Polar ocean stratification in a cold climate. *Nature,* 428, 59-63

Project Report: **Role of the Tropics in the Early Pliocene**

Principal Investigator: S. George H. Philander(Princeton)

Other participating researchers*:* Marcelo Barreiro (Princeton), Ronald Pacanowski (GFDL), Alexey Fedorov (Princeton, now at Yale).

NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objective: Paleoclimate reconstruction have shown that permanent El Nino conditions prevailed in the tropical Pacific 3Ma (Ravelo et al. 2004). Here we investigate the role of the tropics at that time. We want to answer the question: Can the tropical conditions be at least partially responsible for the warm climate during the early Pliocene?

Methods and Results:

As a first step toward addressing this issue I have run atmospheric general circulation models forced with different boundary conditions in the tropics to determine the response and their ability to reproduce key aspects of the atmospheric circulation 3Ma. I have compared simulated surface temperature, hydrological cycle, wind stress and albedo, with those of today's climate. Initial results show that permanent El Nino conditions can account for a portion of the warm climate present 3Ma.

The next step will be to look into the possibility that changes in surface atmospheric fluxes (of freshwater, heat and momentum) may in turn force the ocean generating a response that feeds back onto the atmosphere consistent with the boundary conditions, maintaining the climate. To investigate this possibility we plan to run experiments in which an ocean general circulation model is forced with fluxes taken from the AGCM runs.

References:

Ravelo, A. C., D. H. Andreasen, M. Lyle, A. Olivarez Lyle, and M. W. Wara, 2004: Regional Climate Shifts caused by gradual global cooling in the Pliocene epoch. Nature, 429, 263-267.

Project Report: **The Pliocene Paradox**

Principal Investigator: S. George H. Philander (Princeton)

Other Participating Researchers: The number of participants will be on the order of 15.

NOAA's Goal #2 - Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:
The first of these workshops will be in Princeton on October 21 and 22, 2004 to discuss:
Conditions during the early Pliocene (3 to 5 million years ago approximately) amount to a paradox: the world was much warmer then than it is now even though the same sunlight was incident on essentially the same global geography, and even though the atmospheric concentration of carbon dioxide was essentially the same as today. This paradox implies that climatic conditions then, and those of today, are two very different responses to essentially the same external forcing. The critical questions are therefore: What disturbances can cause a transition from one state to the other? Can the current rise in atmospheric CO^2 cause a transition?

Methods and Results/Accomplishments:
The purpose of the meeting is to discuss the observational and theoretical studies that can help answer these questions. The final ½ day of the meeting will be a presentation, to a public audience, of the main results from the workshop.

The Pliocene Paradox
GFDL & Guyot Hall/October 21-23, 2004

THURSDAY	**GFDL, Forrestal Campus**	
9:00 AM	Introductory remarks(Empirical Information)	Philander
9:20 AM	Warm Surface Waters in Upwelling Zones	Ravel et. al.
10:00 AM	High Latitude Changes in Oceanic Stratification	Sigman, Huag
10.50 AM	The Response to Obliquity Variations	Herbert et. al.
11:30 AM	Nonlinear Aspects of the Obliquity Response	Huybers, Wunch
	LUNCH	
1:30 PM	The Atlantic - Theorectical Considerations	deMenocal
2:15 PM	The Atmospheric Response to a Permanent El Nino	Barreiro
2:50 PM	Conditions That Can Maintain a Permanent El Nino	Fedorov
3:15 PM	Response to Milankovitch in a Climate Model	Broccoli
3:45 PM	The Response of Various Climate Models to Higher CO_2	Ramaswamy et. al.
FRIDAY	**Guyot Hall, Main Campus**	
9:00 AM	Response to Milankovitch in a Climate Model	Broccoli
	Summary of Results/Discussion of projects	
	LUNCH	
2:00 PM	Empirical Information	Ravelo, Huybers, Wunsch
3:30 PM	Theoretical and Modeling Considerations	Fedorov, Delworth
	Discussion	Herbert, Molteni
	RECEPTION	

Project Report: **Paleoclimate**

Principal Investigator: Daniel M. Sigman(Princeton)

Other Participating Researchers: Agatha DeBoer, (Princeton-AOS Postdoc)

NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives:
Our objective is to perform model experiments to test hypothesized mechanism for the link between climate warming and polar ocean destratification that is evident in paleoclimate reconstructions. We specifically wish to test the non-linearity of the seawater equation of state as a mechanism for changing the vertical density gradient in the polar ocean.

Methods and Results/Accomplishments:
The needed experiments must be run for hundreds of model years. Since the coarse-resolution version of MOM4 had not yet been developed, DeBoer updated Dr. J.R. Toggweiler's "water planet" model with the MOM4 code. Experimentation with the model is now underway. One set of experiments "tricks" the seawater equation of state in the model, calculating ocean density for 2 degrees C warmer and colder than is actually the case in the model. These experiments confirm a cooling/stratification link in the North Pacific, but the changes in the Antarctic require further analysis and the implementation of a ventilation age tracer. The experiments have also led to the recognition of a supporting mechanism for polar stratification under cold climate that involves meridional gradients in upper ocean density. This research is proceeding roughly according to plan, although difficulties with the model development have led to a later start with the experiments than might have been hoped.

References:
None.

Publications:
None; manuscript pending.

2003-2004 CICS Publications

Refereed Journals:

Cardoso M, **Hurtt GC**, Moore B, Nobre C, Prins E. (2003) Projecting future fire activity in Amazonia. *Global Change Biology* 9: 656-669.

Fiore, A.M., T. Holloway, M.G. Hastings, A Global Perspective on Air Quality: Intercontinental Transport and Linkages with Climate, *Environmental Management*, December, 2003.

Fiore, A.M., D .J. Jacob, H. Liu, R. M. Yantosca, T. D. Fairlie, Q. Li, Variability in surface ozone background over the United States: Implications for air quality policy, *J. Geophys. Res.*, 108, 4787, doi:10.1029/2003JD003855, 2003.

Fox-Kemper, B., J. Pedlosky: 2004, Wind-driven barotropic gyre I: Circulation control by eddy voriticity fluxes to an enhanced removal region. *Journal of Marine Research,* 62(2), 169-193.

Fox-Kemper, B.: 2004, Wind-driven barotropic gyre II: Effects of eddies and low interior viscosity. *Journal of Marine Research*, 62(2), 195-232.

Hill, C., C. DeLuca, **V. Balaji,** M. Suarez, A. daSilva, January/February 2004. Architecture of the Earth System Modeling Framework, *Computers in Science and Engineering*, vol 6, No.1, 18-28.

Holloway, T., **A.M. Fiore,** M.G. Hastings, Intercontinental Transport of Air Pollution: Will emerging science lead to a new hemispheric treaty?, *Environ. Sci. & Technol., 37*, 4535-4542, 2003.

Houweling, S., F.-M. Breon, I. Aben, C. Rödenbeck, **M. Gloor,** M. Heimann, and P. Ciais (2004),

Inverse modeling of CO_2 sources and sinks using satellite data: a synthetic inter-comparison of measurement techniques and their performance as a function of space and time, *Atmos. Chem. Phys*., 4, 523-538,

Kim, B.G., S.E. Schwartz, M.A. Miller, and Q. Min, 2003: Effective radius of cloud droplets by ground-based remote sensing: Relationship to aerosol, *J. Geophys. Res.,* 108(D23), 4740, doi:10.1029/2003JD003721.

Martin, R.V., **A.M. Fiore**, and A.Van Donkelaar, Space-based diagnosis of surface ozone sensitivity to anthropogenic emissions , *Geophys. Res. Lett. 31*, L06120, doi:10.1029/2004GL019416, 2004.

Pauluis, Olivier, 2004: Boundary layer dynamics and cross-equatorial Hadley Circulation. *J. Atmos. sci*., **61**, 1161-1173.

Pauluis, Olivier, and Kerry A. Emanuel, 2004: Numerical instability resulting from infrequent calculation of radiative heating. *Monthly Weather Review*, **132**, 673-686.

Purves, D., J. Caspersen, P. Moorcroft, **G. Hurtt,** S. Pacala. (2004) Human-induced changes in U.S.biogenic VOC emissions. *Global Change Biology* 10:1-19 doi:10.1111/j.1365-2486.2004.00844.x.

Randal D. Koster, Paul A. Dirmeyer, Zhichang Guo, Gordon Bonan, Edmond Chan, Peter Cox, C. T. Gordon, Shinjiro Kanae, Eva Kowalczyk, David Lawrence, Ping Liu, Cheng-Hsuan Lu, **Sergey Malyshev**, Bryant McAvaney, Ken Mitchell, David Mocko, Taikan Oki, Keith Oleson, Andrew Pitman, Y. C. Sud, Christopher M. Taylor, Diana Verseghy, Ratko Vasic, Yongkang Xue, Tomohito Yamada, 2004: Regions of Strong Coupling Between Soil Moisture and Precipitation, *Science*, 305, 1138-1140

Randles, C., A., L. M. Russell, and V. Ramaswamy (2004), Hygroscopic and optical properties of organic sea salt aerosol and consequences for climate forcing, *Geophys. Res. Lett.*, 31, L16108, doi:10.1029/2004GL020628.

Riviere, G., Hua B. L. and Klein, P. 2004. Perturbation growth in terms of baroclinic alignment properties. *Quart. J. Roy. Meteor. Soc.* **130,** 1655-1673.

Roy, S. B., **G. C. Hurtt**, C. P. Weaver, S. W. Pacala. (2003) Impact of historical land cover change on the July climate of the United States. *Journal of Geophysical Research* 108, D24, 4793, doi:10.1029/2003JD003565.

Salzmann, M., Lawrence, M.G., **Phillips, V.T.J.** and L. J. Donner, 2004: Modelling tracer transport by a cumulus ensemble: lateral boundary conditions and large-scale ascent. *Atmos. Chem. Phys. Discuss.*, **4,** 3381-3418

Tian, B., B. J. Soden, and X. Wu, 2004: Diurnal cycle of convection, clouds, and water vapor in the tropical upper troposphere: Satellites versus a general circulation model. *J. Geophys. Res.*, **109**, D10101, doi:10.1029/2003JD004117.

Vallis, G. K., **E. P. Gerber**, P. J. Kushner, and B. A. Cash, 2004: A Mechanism and Simple Dynamical Model of the North Atlantic Oscillation and Annular Modes, *Journal of Atmospheric Science*, 61, 264-280

Wittenberg, A. T., 2004: Extended wind stress analyses for ENSO. J. Climate, 17, 2526-2540.

Zhang, S., J. L. Anderson, A. Rosati, M. Harrison, **S. P. Khare**, and **A. T. Wittenberg**, 2004: Multiple time level adjustment for data assimilation. *Tellus* A, 56, 2-15.

Book Chapters:

Pauluis, Olivier, 2004: Chapter 9. Water vapor and entropy production in the Earth atmosphere. In Non-Equilibrium Thermodynamics and the Production of Entropy: Life, Earth, and Beyond, Kleidon and Lorenz Ed. Springer Verlag, for publication in Fall 2004

Fiore, A. M. Contributing Author to Chapters 2 and 3 of the Air Quality Criteria Document for Ozone and Related Photochemical Oxidants for the Environmental Protection Agency, March 2003-present.

Heimann, M., **M. Gloor** and C. Rödenbeck (2004), Spatial and Temporal Distributions of Sources and Sinks of Carbon Dioxide, In "The Global Carbon Cycle", Island Press, Washington, Eds. C. B. Field and M. Raupach, 187-204.

Ph.D. Thesis:

Tam, C-Y. 2003: The Impact of ENSO on Tropical and Extratropical Atmospheric Variability on Intraseasonal and Synoptic Time Scales as Inferred from Observations and GCM Simulations, Ph.D. dissertation, Princeton University, New Jersey, 197 pp.

Meeting Publications

Dery, Stephen J., Marc Stieglitz, E. McKenna and Eric F. Wood 2004 Recent trends and changes in freshwater discharge into Hudson, James, and Ungava Bays, *Eos Trans. AGU,85*(17), Jt. Assem. Suppl., Abstract H34A-03.

Luo, Lifeng, Andrew Wood, Eric F. Wood, Dennis P Lettenmaier 2004. An Experimental Seasonal Streamflow Prediction System and The Streamflow Predictability Over the Ohio River Basin, *Eos Trans. AGU,85*(17), Jt. Assem. Suppl., Abstract H33A-04.

Luo, Lifeng Eric F Wood, Tony Gordon and **Sergy Malyshev** 2004 Precipitation variability and predictability in the GFDL General Circulation Model, *Eos Trans. AGU,85*(17), Jt. Assem. Suppl., Abstract H31E-05.

Shevliakova, E., S.W. Pacala, **S. Malyshev, G.C. Hurtt,** and J.P. Caspersen. 2003 "Carbon Cycle and Vegetation Dynamics in the GFDL-Princeton University Coupled Atmosphere-Biosphere Model",*Eos Trans.* AGU, 84(46), Fall Meet. Suppl., Abstract B41C-0899.

Lead Author Publication Table

	JI Lead Author			NOAA Lead Author			Other Lead Author		
	FY01	FY02	FY03	FY01	FY02	FY03	FY01	FY02	FY03
Peer-reviewed	4	12		1			1	10	
Non Peer- reviewed	2	4							
Chapters in books		2						1	
Ph.D. Thesis		1							

CICS FELLOWS

The CICS Fellows will be principally responsible for carrying out the research proposed under this project. Fellows will be selected by the Executive Committee of the CICS. The present CICS Fellows include senior research staff at GFDL and the following faculty members at Princeton University:

Lars Hedin, Professor of Ecology and Evolutionary Biology, a biogeochemist who does research on the terrestrial nitrogen cycle.

Michael Oppenheimer, Professor of Geosciences and International Affairs, an atmospheric chemist who does research on the impacts of climate change and also the nitrogen cycle.

Stephen Pacala, Professor of Ecology and Evolutionary Biology, a biogeochemist who does research on the terrestrial carbon cycle and is co-Director of the Carbon Mitigation Initiative of Princeton University.

S. George Philander, Professor of Geosciences, who does research on ocean dynamics and paleoclimate and is Director of the Atmospheric and Oceanic Sciences Program.

Ignacio Rodriguez-Iturbe, Professor of Civil and Environmental Engineering, who does research on hydrology.

Jorge L. Sarmiento, Professor of Geosciences, a biogeochemist who does research on the ocean carbon cycle and biological response to climate change who is Director of CICS.

Daniel Sigman, Professor of Geosciences, a biogeochemist who does research on paleoceanography.

Eric Wood, Professor of Civil and Environmental Engineering, who does research on hydrology.

TASK I: Administrative Staff

<u>CICS Director</u>
Jorge L. Sarmiento
Professor of Geosciences
Princeton University
Phone: 609-258-6585
Fax: 609-258-2850
jls@Princeton.edu

<u>CICS Administrative and Financial Contact</u>
Laura Rossi
Manager, Program in Atmospheric and Oceanic Sciences
Princeton University
Phone: 609-258-6376
Fax: 609-258-2850
lrossi@Princeton.edu

<u>CICS Alternate Administrative and Financial Contact</u>
Stacey Christian
Finance/Grants Manager, Princeton Environmental Institute
Princeton University
Phone: 609-258-7448
Fax: 609-258-1716
smecka@Princeton.edu

TASK II: Cooperative Research Projects and Education Supported Personnel

NAME	DATES	RANK	Advisor
Adhitya, Anita	11/15/03-1/31/04	Graduate Student	Ramaswamy/Ward
Chen, Gang	7/1/03-6/30/04	Graduate Student	Held
Frierson, Dargan	7/1/03-6/30/04	Graduate Student	Vallis
Gerber, Edwin	7/1/03-6/30/04	Graduate Student	Vallis
Grianik, Nadjeda	7/1/03-6/30/04	Graduate Student	Vallis
Hammann, Arno	8/1/03-6/30/04	Graduate Student	Philander
Huang, Yi	8/12/03-6/30/04	Graduate Student	Ramaswamy
Khare, Shree	7/1/03-6/30/04	Graduate Student	Anderson
Lee, Seoung-Soo	7/1/03-6/30/04	Graduate Student	Donner
Randles, Cynthia	7/1/03-6/30/04	Graduate Student	Ramaswamy
Smith-Mrowiec, Aga	7/1/03-6/30/04	Graduate Student	Garner
Tam, Chi-Yung	7/1/03-10/31/03	Graduate Student	Lau
Yang, Huiyan	7/1/03-6/30/04	Graduate Student	Levy
Balaji, V.	3/1/04-6/30/04	Professional Technical	Leetmaa
Barreiro, Marcelo	1/1/04-6/30/04	Research Associate	Philander
deBoer, Agatha	7/1/03-6/30/04	Research Associate	Togweiller/Sigman
Field, Arlene Fiore	8/25/03-6/30/04	Research Associate	Levy
Fox-Kemper, Baylor	7/1/03-6/30/04	Research Associate	Vallis
Kim, Byung-Gon	7/1/03-6/30/04	Research Associate	Ramaswamy
Phillips, Vaughan	7/1/03-6/30/04	Research Associate	Donner
Reichler, Thomas	7/1/03-6/30/04	Research Associate	Kushner
Riviere, Gwendal	1/1/04-6/30/04	Research Associate	Orlanski
Tian, Baijun	7/1/03-6/30/04	Research Associate	Soden
Wittenberg, Andres	7/1/03-3/15/04	Research Associate	Rosati
Zhang, Rong	7/1/03-6/30/04	Research Associate	Vallis
Zhao, Ming	2/4/04-6/30/04	Research Associate	Klein/Vallis
Pauluis, Olivier	7/1/03-6/30/04	Research Staff	Held
Russell, Joellen	7/1/03-6/30/04	Research Staff	Toggweiler
Sweeney, Colm	7/1/03-6/30/04	Research Staff	Rosati/Sarmiento
Xia, Youlong	12/19/03-6/30/04	Research Staff	Milly
Vallis, Geoffrey	7/1/03-6/30/04	Senior Research Scholar	Leetmaa
Adcroft, Alistair	7/1/03-9/5/03	Visiting Research Scholar	Leetmaa
Wu, Chun-Chieh	1/1/04-6/30/04	Visiting Research Scholar	Milly

Departures

Thomas Reichler-6/30//04 Assistant Faculty at University of Utah
Baijun Tian-6/30/04 Postdoctoral Scholar at California Institute of Technology
Andrew Wittenberg-3/15/04 Physical Scientist at NOAA-GFDL

Ph.D. Defense – October 27, 2003
Student: Chi-Yung Tam/Advisor: Ngar-Cheung Lau
Dissertation: "The Impact of ENSO on Tropical and Extratropical Atmospheric Variability on Intraseasonal and Synoptic Time Scales as Inferred from Observations and GMC Simulations"
Present Affiliation: Postdoctoral Fellow at the School of Ocean And Earth Science and Technology, International Pacific Research Center, University of Hawaii

Task III: Individual Projects Supported Personnel

NAME	DATES	MONTHS SUPPORTED	RANK	ADVISOR
Altevogt, Andrew	5/1/04-6/30/04	2 mos.	Research Associate	Hedin
Dery, Stephen	1/1/04-6/30/04	6 mos.	Research Associate	Wood
Luo, Lifeng	7/1/03-6/30/04	12 mos.	Research Associate	Wood
Jacobson, Andrew	4/1/04-6/30/04	¾ mo.	Research Staff	Sarmiento
Malyshev, Sergey	7/1/03-6/30/04	12 mos.	Research Staff	Pacala
Shevliakova, Elena	9/1/03-6/30/04	10 mos.	Research Staff	Pacala
Gloor, Emanuel	9/15/03-6/30/04	9½ mos.	Research Scientist	Sarmiento
Key, Robert M.	10/1/03-12/31/03	2 mos.	Research Scientist	Sarmiento
Simeon, Jennifer	11/1/03-6/30/04	3¾ mos.	Professional Technical	Sarmiento
Slater, Richard	11/1/03-6/30/04	5½ mos.	Professional Technical	Sarmiento
Sarmiento, Jorge L.	7/1/03-8/15/03	1½ mos.	Professor	

Personnel Information Table

Category	Number	B.S.	M.S.	Ph.D.
Research Scientist	2			2
Visiting Scientist	2			2
Postdoctoral Fellow (Research Associate)	13			13
Professional Technical Staff	1			1
Research Staff	6			6
Administrative *	0			
Graduate Students	9	9		
Received less than 50% NOAA support	11	5		6
Total	**44**	**14**		**30**
Located at the Lab (include name of lab)	29-GFDL	4		25
Obtained NOAA employment within the last year	**1-GFDL			

* Administrative Staff: Jorge L. Sarmiento, Director, Laura Rossi and Stacey Christian, Administrative Support, devote significant time to Joint Institute work but receive total support from Princeton University for this work.

**Andrew Wittenberg, Physical Scientist
NOAA-Geophysical Fluid Dynamics Laboratory
Start Date: March 15, 2004

CICS FY'04 List of Awards

Amount	Investigator(s)	Project Title
$ 117,000	L. Hedin/M. Oppenheimer	Terrestrial Nitrogen Cycles (Task III)
$ 100,000	M. Oppenheimer/V. Ramaswamy	Workshops on policy, carbon and aerosols (Task III)
$ 50,000	S. G. H. Philander	AOS Workshops and Summer school (Task III)
$ 200,000	I. Rodriguez-Iturbe, P. Jaffe, E. Wood	Scaling of Space, Time, Heterogeneous Hydrologic Dynamics (Task III)
$ 50,000	M. Gloor	Carbon Observing System (Task III)
$ 100,000	S. G. H. Philander/D. Sigman	Paleoclimate Study (Task III)
$ 25,000	R. M. Key	Understanding North Pacific Carbon-Cycle Changes (OGP-Task III)
$ 468,650	J. L. Sarmiento/S. Pacala	Determination of Carbon Source and Sink Distributions and Development of Carbon Sink Models (Task III)
$ 83,425	E. Wood	The Influence of Surface Hydrological Processes on Climate (Task III)
$ 83,425	L. Hedin/M. Oppenheimer	Modeling terrestrial nutrient cycling (Task III)
$ 81,939	E. Wood	Land Surface Predictability Studies at GFDL (OGP-Task III)
$ 152,200	J. L. Sarmiento	Ocean and Atmospheric Inverse Modeling for Global Carbon Flux Determinations (OGP-Task III)
$1,415,459	S. G. Philander	The Atmospheric and Oceanic Sciences Research Program (Task II)

SUBCONTRACTS

Amount	Investigator	Project Title
$ 200,000	E. Tziperman/Harvard	Development of an experimental 4d assimilation and ENSO prediction system based on the latest MOM4 GFDL model (Task II)
$ 114,500	G. Hurtt/UNH	Modeling Land-Use Dynamics in the Earth System (Task III)
$ 32,447	T. Haine/John Hopkins	Development of Haine's Irminger Sea/Denmark Strait Regional Ocean Circulation Model And Data Assimilation System (Task II)