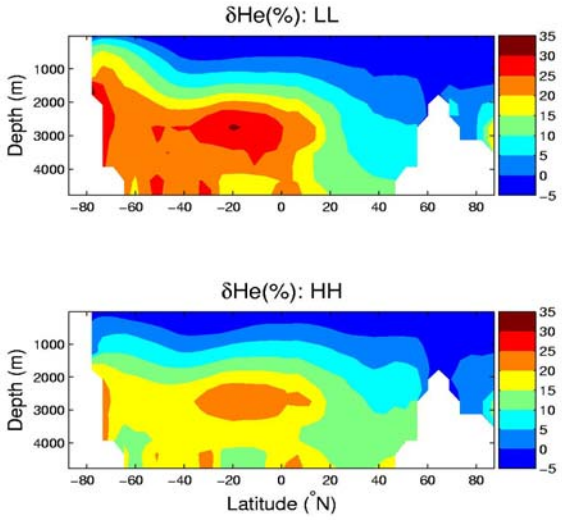
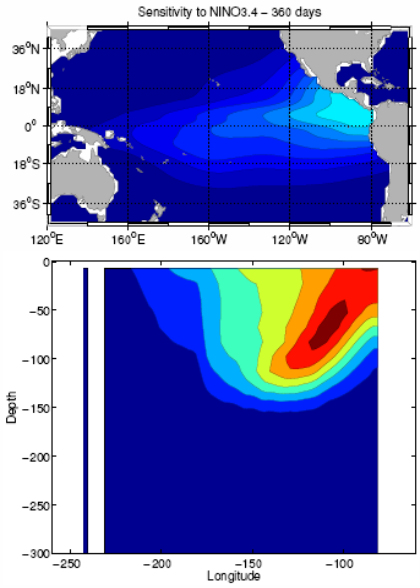


Annual Progress Report
July 1, 2005 – June 30, 2006

Cooperative Institute for Climate Science
at Princeton University
NOAA Cooperative Agreement NA17RJ2612



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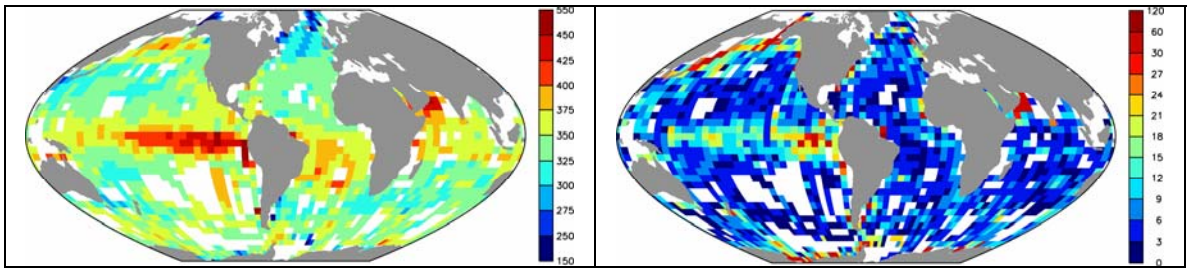


Table of Contents

Introduction **1**

Research Themes Overview **2-4**

Structure of the Joint Institute **5-6**

CICS Committees and Members **7**

Research Highlights

Earth System Studies/Climate Research **8-11**

Land Dynamics and Hydrology
Ocean Dynamics and Modeling
Large-Scale Atmospheric Dynamics
Climate Variability and Coupled Atmosphere-Ocean Modeling
Clouds and Moist Convection
Atmospheric Chemistry and Radiative Forcing

Biogeochemistry **11-14**

Land Ecosystem and Biogeochemistry Modeling
Ocean Biogeochemistry
Atmosphere and Ocean Inverse Modeling and Data Assimilation

Coastal Processes **14**

Paleoclimate **14**

NOAA Funding Tables **15**

Progress Reports **16-133**

Publications **134-138**

CICS Fellows **139**

CICS Administrative Staff **140**

Personnel Support Information **141-144**

CICS Project Awards **145**

Cooperative Institute for Climate Science
Princeton University

Annual Report of Research Progress under Cooperative Agreement NA17RJ2612
During July 1, 2005 – June 30, 2006

Jorge L. Sarmiento, Director
Geoffrey K. Vallis, Associate Director

Introduction

The Cooperative Institute for Climate Science (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. 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 all focused around the development and application of earth system models for understanding and predicting climate.

(1) **Earth System Studies/Climate Research.** Earth System modeling at GFDL and in CICS has emerged 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. These models are already producing useful products, but new and more sophisticated tools will continually be required for increasingly realistic representation of the processes and interactions in the Earth's climate system.

In addition to its model-development activities, CICS is also pursuing a number of topics in climate dynamics that will lead to both improved understanding of the climate system itself, and to improved models in the future. These topics include the parameterization of cloud-radiation-convection interactions and land-surface heterogeneity; investigations of regional climate changes to natural and anthropogenic forcings; hydrologic cycle-climate feedbacks; anthropogenic influence on modes of climate variability including, for example, the dynamics of the North Atlantic Oscillation; and various fundamental issues in the dynamics of the ocean and atmosphere. Included in this last category are investigations of the general circulations of the atmosphere and ocean themselves, and the investigation of the dynamical processes that give rise to climate variability on interannual to multi-decadal timescales and that might lead to potentially catastrophic *abrupt climate change* in the future. Investigators at CICS and GDFL are also pursuing holistic investigations of the climate system, to try to understand how the climate system operates as a whole. Such investigations are crucial if we are to properly simulate complex phenomena that defy simple explanations and that are not properly simulated with current models (such as the Intertropical Convergence Zone).

CICS is also continuing to pursue approaches to confronting models with observations in order to diagnose problems and judge reliability. The ability to simulate the observed climate, and its variability, with reasonable accuracy is a *sine qua non* of a sound climate modeling system. That variability arises from and is moderated by a host of factors, including ENSO, volcanic eruptions, the reddening by the ocean of weather variability in the atmosphere, 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. These all represent distinct challenges that must ultimately be addressed simultaneously by a successful Earth System model, and the research presented below describes some of the efforts along these lines.

Research in Earth System Studies/Climate Research within CICS generally takes place at two levels. At the individual or small-group level, scientists, sometimes with postdocs and graduate students, may investigate processes and dynamics and write research papers accordingly, and this activity is represented by the individual reports below. At the second level, these activities come together synergistically in model development activities in which larger groups and teams work together, bringing their various expertise together. It is more difficult to describe and categorize this activity, but it is an essential aspect of the CICS endeavor.

Finally, 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.

(2) **Biogeochemistry**. CICS is contributing to the development of the land and ocean biogeochemistry components of the Earth System model. The new model components are being used to study the causes and variability of land and oceanic carbon sinks and to develop a data analysis system for carbon that will provide improved estimates of the spatial distribution of carbon fluxes.

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 interannual 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 is performing 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 inversion 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, in order to provide ongoing estimates of the air-sea and land-atmosphere CO_2 fluxes particularly over North America.

(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, nor have they had the lateral resolution to fully represent physical, geochemical and biological processes on the narrow continental shelves. CICS has recently initiated a collaborative project with Rutgers University that will enable the development of tools that link coastal models to global climate models. These linked models will be used to provide the best scientific information possible to decision makers, resource managers, and other users of climate information. To address the specific research questions, the project will use a multi-disciplinary approach including analyses of *in situ* and remotely obtained data sets, circulation modeling, biogeochemical models with explicit carbon chemistry, and data assimilation techniques using dynamical and/or biological models.

(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 influence of tropical ocean-atmosphere states on climate, and the influence of freshwater fluxes and temperature changes on ocean circulation.

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 list which of the mission goals is addressed by each research project.

A key aspect of all four 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.

Education/Outreach

This year, CICS continued its collaboration with a Princeton University professional development institute for New Jersey teachers. This well-established summer program, QUEST, is led by Princeton University's Teacher Preparation Program. A two-week Weather and Climate unit for teachers in third through sixths grades, held this summer, offered a wide range of inquiry-based experiences through which the teachers could develop an understanding of atmospheric processes and learn methods to teach about weather and climate. The unit was developed and taught by Dr. Steven Carson, formerly a scientist and Outreach Coordinator at GFDL, and currently a middle school science teacher in Princeton. Twenty-one teachers from the Princeton region participated in the Weather and Climate unit, with 52% participation from the high poverty school district of Trenton and an additional 9% from the urban rim "blue collar" districts of Bordentown and Ewing.

Structure of the Joint Institute

Princeton University and NOAA's Geophysical Fluid Dynamics Laboratory have a successful 40-year history of collaboration that has been carried out within the context of the Atmospheric and Oceanic Sciences Program (AOS). The Cooperative Institute for Climate Science (CICS) builds and expands on this existing structure. The CICS research and education activities are organized around the four themes discussed previously in the Research Themes Overview. The following tasks and organizational structure have been established to achieve the objectives:

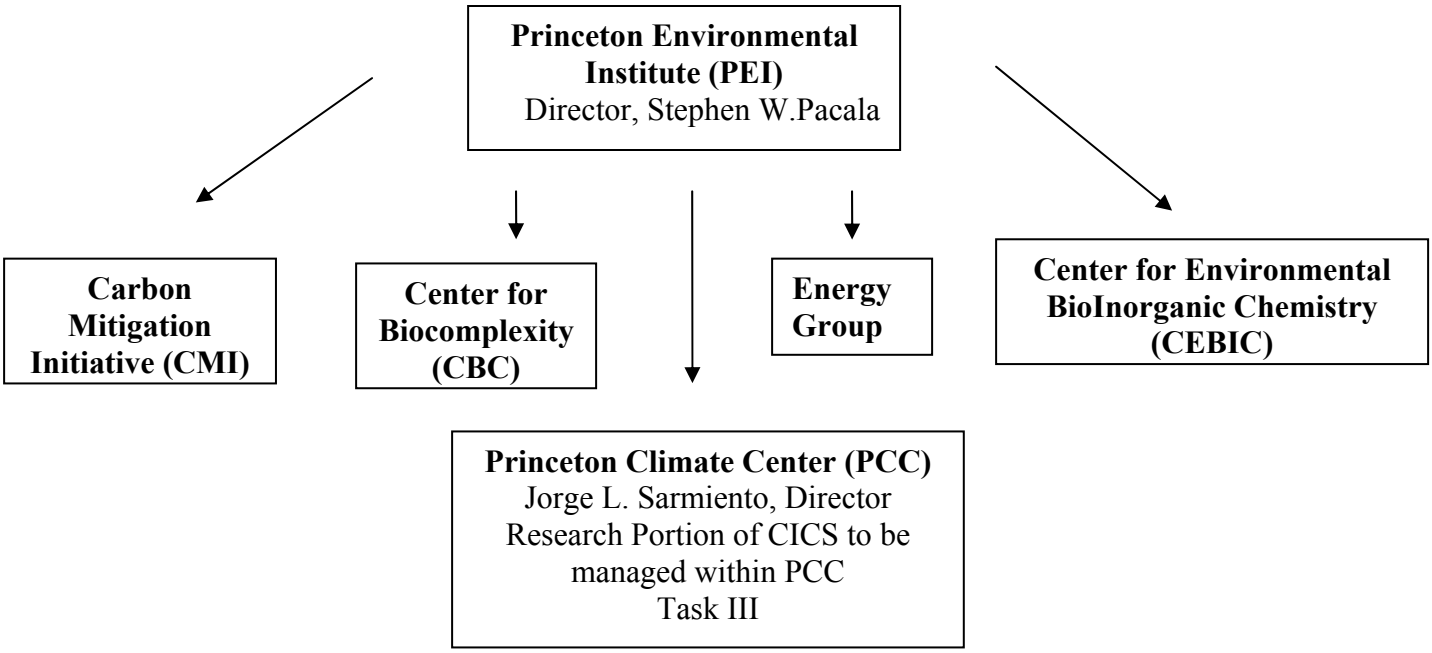
I. Administrative Activities including outreach efforts, are carried out jointly by the AOS Program and Princeton Environmental Institute (PEI).

II. Cooperative Research Projects and Education are carried out jointly between Princeton University and GFDL. These will continue to be accomplished through the 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 many 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.

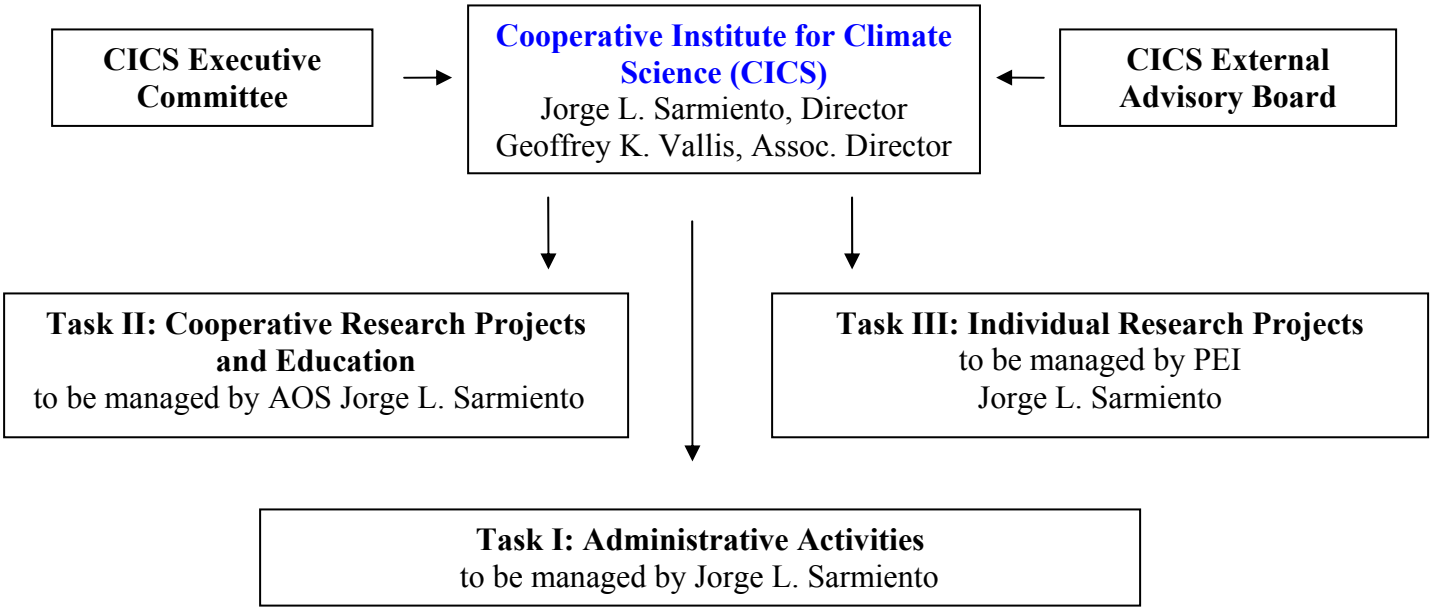
III. Principal Investigator led research projects supported by grants from NOAA that comply with the themes of CICS. These all occur within the newly formed Princeton Climate Center (PCC) of the Princeton Environmental Institute (PEI) and may also include subcontracts to research groups at other institutions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

The CICS Director, currently Jorge Sarmiento, is 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.

Princeton Environmental Institute Structure



Cooperative Institute for Climate Science Structure



CICS Committees and Members

PEI's Princeton Climate Center (PCC) Advisory Committee
Jorge L. Sarmiento – Director of CICS and Professor of Geosciences
Stephen W. Pacala – Director of PEI, Professor of Ecology and Evolutionary Biology
Michael Oppenheimer - Professor Geosciences and International Affairs
Ignacio Rodriguez-Iturbe – Professor Civil and Environmental Engineering
Denise Mauzerall – Associate Professor of Public and International Affairs

Executive Committee
S. George H. Philander – Professor of Geosciences
Issac Held – GFDL Senior Research Scientist
Hiram Levy – GFDL Senior Research Scientist
V. Ramaswamy – GFDL Senior Research Scientist
Geoffrey K. Vallis – Associate Director of CICS and Senior Research Oceanographer
Plus PCC Advisory Committee
Jorge L. Sarmiento – Director of CICS and Professor of Geosciences
Stephen W. Pacala – Director of PEI, Professor of Ecology and Evolutionary Biology
Michael Oppenheimer - Professor Geosciences and International Affairs
Ignacio Rodriguez-Iturbe – Professor Civil and Environmental Engineering
Denise Mauzerall – Associate Professor of Public and International Affairs

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

External Advisory Council
Jeffrey T. Kiehl – Director of NCAR's Climate Modeling Section
A.R. Ravishankara – Acting Director of NOAA's Chemical Sciences Division
Ants Leetmaa – Director of NOAA's Geophysical Fluid Dynamics laboratory
Dave Schimel – Senior Scientist at NCAR's Terrestrial Sciences Division
Peter Schlosser – Professor at Columbia University's Earth and Environmental Science Dept.
Chet Koblinsky – Director of NOAA's Climate Program Office

Research Highlights

The following highlights ongoing research in the major research and education themes we identified in the Research Themes Overview.

Earth System Studies/Climate Research

Research in Earth System Studies/Climate Research may be divided into Land Dynamics and Hydrology, Ocean Dynamics, Large-Scale Atmospheric Dynamics, Chemistry and Radiative Forcing, Climate Variability and Coupled Atmosphere-Ocean Modeling, and Clouds and Moist Convection. Research in all areas involves cooperative activities between the University and GFDL, in particular post-doctoral fellows and research students working with GFDL staff, as well as University researchers and faculty whose activities are funded through CICS. In the paragraphs below we summarize and highlight some of the activities going on in these areas. There is an entire spectrum of fascinating and important activities, from fundamental to quite applied; the Earth System, as complex as it is, demands such a wide range of activities. However, these activities also provide the essential building blocks for understanding the system and come together in a coherent mosaic, so enabling us to build better models of the system and, ultimately, to better predict it.

Land Dynamics and Hydrology

Land dynamics and hydrology plays an important role in climate simulations and projections, and this is reflected in the range and depth of the activities funded through CICS. In particular, the physical and biological components of the land model in GFDL's climate modeling system have been largely developed through CICS. One major, long term objective of this research is to develop and improve the land-surface parameterizations in the model, and this activity continues through the continued support of postdoctoral fellows and junior scientists who are physically located at GFDL. In addition to this activity, CICS also funds Professor Eric Wood with support for a postdoc for research in understanding the predictability and variability of hydrologic variables on seasonal-to-interannual timescales, and in the development of a ensemble statistical forecast system for the Eastern US. As well as its basic importance, this study will lead to very practical improvements in forecast skill on these timescales. In a related effort, Professor Ignacio Rodriguez-Iturbe is funded to develop a theoretical framework for modeling the space-time variability of soil moisture; this is basic research with a practical pay-off, namely an understanding of the processes necessary to properly measure soil moisture content by sparse sampling.. Finally, a quite applied effort to develop a real-time national streamflow information system has been successfully undertaken.

Ocean Dynamics and Modeling

The ocean plays a key role in determining the nature of climate variability on timescales from the interannual to the millennial. It also plays a key role in sequestering both heat and carbon dioxide, and therefore in determining the response of the climate system to increasing amounts of carbon dioxide in the atmosphere. Thus, a number of postdocs and students are studying varying aspects of the circulation. CICS is participating heavily in two 'Climate Process Teams' (CPTs) These activities are jointly funded by NOAA and NSF, and specifically call for an interaction between government laboratories and universities. One CPT is on 'overflows' and the

other on eddy-mixed-layer interactions. Overflows are notoriously difficult to simulate, yet they are the means whereby deep water is communicated from marginal seas into the general circulation, and thus potentially greatly impact the general circulation, and recent efforts show some progress in improving their representation in coarse-resolution ocean climate models. The 'eddy–mixed-layer' CPT seeks to understand how mesoscale eddies interact with the oceanic mixed layer, and to parameterize this interaction in climate models. It is, of course, the surface of the ocean that interacts with the atmosphere. Activities in this area include the development of new parameterizations of entrainment in overflows and for eddy–mixed-layer interactions, and setting up and using eddy-resolving numerical models to provide a 'ground truth' for parameterizations. Notable recent advances include the development of a new parameterization for the effects of submesoscale eddies in the mixed layer, the introduction of a 'residual' framework for parameterizing mesoscale eddies in ocean models, the investigation of the importance of tidal mixing and the development of new parameterizations of shear-driven turbulence.

Work is also underway on numerical model development topics. Notably, an ambitious effort has begin to develop the next generation of ocean models at GFDL — models with arbitrary or hybrid vertical coordinates. Similarly ambitious is the continuing development of four-dimensional data assimilation schemes and adjoint models for understanding parameter sensitivity. These are all described in more detail in the individual reports.

Large-Scale Atmospheric Dynamics

Atmospheric dynamics is at the core of the large-scale circulation of the atmosphere. Work in this area within CICS has proceeded through the support of graduate students and postdocs working with GFDL staff, with the goals of increasing our understanding of the large-scale circulation and improving our numerical models of the atmospheric circulation. That improving the models depends upon a better understanding of the dynamics has been demonstrated repeatedly when a model fails to agree with observations: Improving the parameterizations or the model resolution will necessarily ultimately provide the needed model improvement, but realizing which parameterizations are crucial, and how they might interact with the large-scale circulation, necessitates an understanding of the dynamics themselves.

Some students are focusing their work on fundamental aspects of the large-scale circulation. One student is trying to understand why the westerly winds move poleward if surface friction is reduced. The dynamics of this are undoubtedly linked to the very important topic of why the westerly winds seem to change latitude in simulations of global warming. By posing a related problem in a simpler context, we can hope to understand better the real-world but terribly complex problem of the changing winds in a warmer world. Another student is looking at the mechanisms that determine the location of the Intertropical Convergence Zone (ITCZ). The ITCZ is typically rather poorly similated in numerical models — many models produce two ITCZ's straddling the equator, instead of the one that is observed. Again by posing the problem in a more idealized framework, the essential dynamics of the phenomena are made more transparent. Understanding the effects of moisture is one of the biggest challenges in understanding the general circulation, and is the region of the biggest disconnect between comprehensive modeling and conceptual understanding, and a recently graduated student has constructed and used an idealized moist general circulation model and this model is now being

used to simulate and understand a variety of topics, including the impact of moist convection on the general circulation.

Other notable highlights include the investigation of the Brewer-Dobson circulation (the overturning circulation in the stratosphere) and how it might be affected by climate change, and investigating the effects of gravity wave parameterization schemes.

Climate Variability and Coupled Atmosphere-Ocean Modeling

Climate varies on timescales from the inter-annual to the millennial and beyond, and this variability typically involves interactions between the atmosphere and the ocean; both systems are important — it is sometimes said that the ocean is the pacemaker of the variability and the atmosphere is the agent of the variability. Studies within CICS have occurred both via researchers employed by CICS and via postdocs and students working with Princeton University and GFDL scientists. In one notable CICS investigators explored the impact of Atlantic multidecadal oscillations on Sahel rainfall and on Hurrican activity, finding a coherent and statistically significant relationship. In a related study, it was found that variability in the Atlantic can be induced by so-called Great Salinity anomalies at high latitudes. Taken together, these studies highlight the interconnectivity of the climate system.

These studies also highlight the complexity of climate, and the difficulty of making accurate numerical models that simulate the climate system appropriately. In an attempt to understand the coupled system better, and so to potentially improve future models, CICS scientists and postdocs are involved in trying to understand the fundamental dynamics of climate variability, In particular, by constructing somewhat simpler models of coupled ocean-atmosphere-land interaction, we hope to isolate essential mechanisms and better understand what key processes — and therefore what key parameterizations — the climate system and climate variability depends upon. This effort will be closely linked to the development and use of the full, state-of-the-art, climate system model at GFDL.

Clouds and Moist Convection

Moisture produces clouds. Clouds affect the radiation budget, and they also transport heat and (to a lesser extent) momentum vertically, in convection. The uncertainty involved in predicting clouds and their associated effects is the single greatest cause of uncertainty in our global warming projections. We have a number of postdocs and students working in related areas, generally with members of the GFDL scientific staff. These continuing activities range from trying to understand cloud microphysical properties better, to trying to better parameterize the macroscopic effects of convection. Regarding the former, one of our postdocs is working on nucleation processes in cloud ensembles with the goal of developing a more sophisticated and more accurate treatment of cloud microphysics for use in new deep convection and large-scale cloud parameterization schemes. At a more macroscopic level, another postdoc has been developing single-column models; these are models that contain all the parameterizations of a GCM, and that can be forced with observations to simulate actual events, and herby provide a

real-world test of the parameterizations. Finally, and linking with the activities in large-scale dynamics, CICS is involved in simulations with three-dimensional cloud resolving models. CICS investigators have investigated novel parameterizations of convection, paramaterizations that change the scale of the convection in order that it may resolved by the model. They then compare very high-resolution models with lower resolution, `parameterized' models to understand better the influence of convection on the large-scale circulation. They have also explored the behaviour of *global* models of the circulation that incorporate novel parameterizations of convection.

Atmospheric Chemistry and Radiative Forcing

The atmosphere is forced by radiation from the sun, and so it is crucial to accurately calculate that radiative forcing. Aspects of this forcing are well understood; for example, highly accurate calculations are available for clear sky absorption if the atmospheric composition is given. However, other aspects are less clear, even aside from clouds effects. The prediction and effects of aerosols remain a significant source of uncertainty in modeling efforts. Research continues both in understanding the effects of aerosols on the radiation budget, and in understanding the factors that determine the global distribution of aerosol. Typically, this research involves students, postdocs and junior research scientists working with GFDL scientists. For example, in one study CICS researches explored the interaction of aerosols with parameterized deep cumulus clouds in the GFDL general circulation model. And in another study, a Princeton graduate student investigated the distribution of dust in the southern hemisphere oceans.

Biogeochemistry

CICS research in "Biogeochemistry" explores the links between changes in the physical climate and the potential impacts on natural ecosystems and human institutions, and feedbacks between these factors and climate. Biogeochemistry research in CICS has three components: (1) development of land ecosystem and biogeochemistry models and implementation of these in coupled climate models; (2) development of ocean carbon sink/ecosystem models and implementation of these in coupled climate models; and (3) inverse modeling and data assimilation of atmospheric, oceanic, and terrestrial carbon observations with the goal of determining the large scale distribution of carbon sources and sinks around the world and contributing to the ongoing national effort to determine the spatial and temporal distribution of the North American carbon sink.

Land Ecosystem and Biogeochemistry Modeling

The land carbon modeling group led by Pacala has been working with the land model in three broad areas, including improvement, scientific applications, and the development of new components including land use dynamics and fires, freshwater biogeochemistry, and nitrogen cycling.

Various versions of the land model have already been implemented in an assortment of GFDL atmosphere and coupled climate models and much of the focus this year has turned to comparing these versions with each other as well as testing and improving their ability to simulate annual temperature and rainfall. New model development efforts have been aimed at enhancing model

capabilities such as facilitating the coupling of land with atmospheric components in the GFDL Flexible Modeling System. Scientific applications of the land model include a demonstration that land use changes over the past 300 years have had only a modest effect on global climate but large regional effects. In addition, numerous tests have been made to investigate how the land model affects atmospheric model performance, including seasonal forecasts.

A major focus of land model development efforts continues to be land use and its impact on the physical properties, biogeochemical cycles and hydrology of the land. Hurtt of the University of New Hampshire is being funded by CICS to address this issue. During this past year, his group completed the development of the new global gridded synthesis model of land-use changes for the period 1700-2000 that was used in the 300-year climate impact study. Additional work focused on enhancing agricultural land use parameterizations, including information on multiple crop types (e.g., C3 annual, C3 perennial, C4 annual, and N fixers) and rice agriculture in Asia. Another major focus of land model development efforts by Hurtt has been on the development of fire models, including new components such as the first parameterization of the effect of fire suppression in the U.S., and improved tropical fire dynamics. Crevoisier, a post-doc in Sarmiento's group, has contributed to this overall effort with the development of a prognostic model of boreal fire frequency. The first version of this will be implemented in the land model over the next year.

Understanding the cycling of nutrients like nitrogen in natural and managed ecosystems is crucial for assessing the impact of global change on areas of vital environmental and economic concern, including forest carbon balances, agricultural productivity, eutrophication of coastal ecosystems and nitrous oxide emissions to the atmosphere. Hedin's group has added vegetation and soil nitrogen dynamics to the land model and begun to perform model simulations. Vörösmarty of the University of New Hampshire has been funded by CICS to develop add a freshwater component to the land biogeochemistry model. During the past year, his group familiarized themselves with the GFDL model and began preliminary implementation of the N-cycle in the GFDL river component, as well as providing information to GFDL on the delivery of nitrogen to the ocean by rivers that could be used in the ocean biogeochemistry model. Hurtt is examining the impact of humans on the land N-cycle.

Ocean Biogeochemistry

The CICS ocean biogeochemistry group led by Sarmiento has made progress in three areas: the combined analysis of existing models and observations to study interannual variability and detect trends in ocean biogeochemistry, model simulations of the potential impact of climate change on ocean biogeochemical processes, and the continued development and improvement of models of ocean biogeochemistry.

As regards model and observational analysis, Key has been involved in several programs to analyze historical data and contribute towards the synthesis of new data being gathered as part of CLIVAR with the goal of quantifying the accumulation of anthropogenic carbon and changes in ocean biogeochemistry over time. The data sets that result from his ongoing efforts play a central role in the development and testing of GFDL and Princeton's ocean biogeochemistry models. In closely related modeling studies, Rodgers has been using ocean simulations to analyze the causes of the complex patterns of observed changes in oxygen and dissolved inorganic carbon

distribution that are starting to show up in the new CLIVAR repeat sections. In a separate but related study to develop an optimal network design for surface pCO_2 measurements, Russell has assembled a global pCO_2 database that she is using in combination with GFDL earth system model simulations to begin analyzing the spatiotemporal variability of pCO_2.

Sarmiento's group has contributed to the development of the ocean biogeochemistry model at GFDL, now in its final stages, by implementing tracers in the most recent ocean model and implementing multiple tracers in the flux coupler that allows for exchange of tracers between models in the Flexible Modeling System. While the final steps of implementing the ocean biogeochemistry model take place at GFDL, Sarmiento's group has initiated a first set of climate-biogeochemistry feedback simulations in the CM2.1 climate model using a simplified ocean carbon model that was used in earlier studies, and including tracers such as chlorofluorocarbons and radiocarbon. The code for these simulations has been completed and have a series of tests to determine how to initialize the model and how long it must be run before doing climate perturbations simulations. The model simulations will be carried out over the next few months. These simulations will allow direct comparison with earlier climate model simulations carried out at Princeton and will prepare the way for simulations using the new GFDL ocean biogeochemistry model. In a parallel effort, Sarmiento's group has been leading an effort in collaboration with investigators at GFDL to develop a coarse resolution coupled climate model that could be used for longer and more numerous simulations than are possible with the existing higher resolution model.

Finally, the ocean carbon modeling group has continued its research on evaluating how well the ocean circulation models simulate processes of particular importance to ecosystem and carbon cycle dynamics in order to lay the groundwork for improving them. Earlier work has shown the critical importance of Southern Ocean processes in the air-sea balance of CO_2, anthropogenic CO_2 uptake, and the supplying of nutrients for biological production through Southern Ocean upwelling which feeds into the base of the main thermocline as Subantarctic Mode Water. These processes are now beginning to be analyzed in the GFDL coupled climate models. A new project involves the combined use of the mantle helium-3 tracer together with radiocarbon to elucidate the pathways by which the nutrient and carbon rich waters of the deep ocean upwell to the surface.

Atmosphere and Ocean Inverse Modeling and Data Assimilation

The purpose of this component of the project, which is taking place jointly between Sarmiento and Pacala's groups, is the analysis of carbon system observations to determine the spatial and temporal distribution of carbon sources and sinks. Three separate tasks have been undertaken during the past year. The first of these was the completion of a series of papers by Mikaloff Fletcher et al. and Jacobson et al. on a new ocean only inverse model as well as ocean-atmosphere "joint inversions," all of which are now in press. These effort combined large scale atmospheric as well as oceanic observations to determine the spatial distribution of carbon sources and sinks on a continental and ocean basin scale. The oceanic observations provide extremely tight constraints on air-sea fluxes. When combined with atmospheric observational constraints, a major finding from this research is that there appears to be no need for a large CO_2 fertilization sink in the tropics to balance the deforestation source. This has significant

implications for future predictions by terrestrial biosphere models, which up to now have included a major CO_2 fertilization sink.

A second task was completion of a study by Crevoisier to examine the feasibility of doing a control volume carbon budget over North America based on the tall tower data that will soon become available across the United States. Results from this research, described in a paper that is now in press, show that the borders of the United States will be well represented by the tall tower data over most of the country except in the southwest. The analysis framework is now prepared for when the data become available.

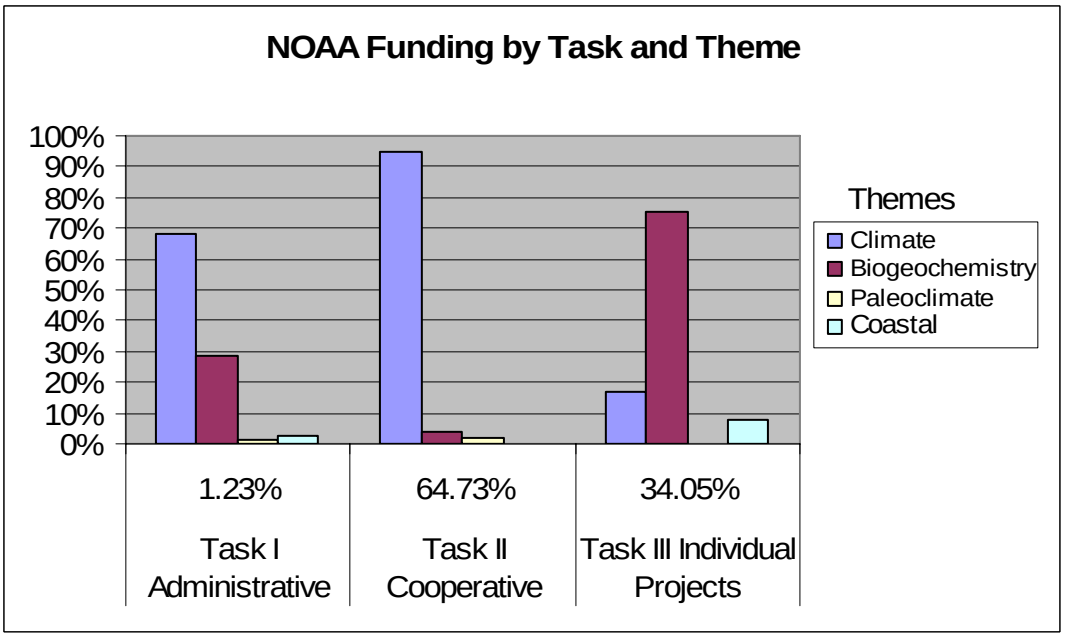
The third task is a preliminary inverse model analysis of combined atmospheric observations of O_2 and CO_2 to constrain air-sea fluxes in a study led by Crevoisier. In related work, Mikaloff Fletcher and Crevoisier are continuing their efforts to develop a framework for the combined analysis of atmospheric measurements as well as satellite based estimates of CO_2, CO, and CH_4.

Coastal Processes

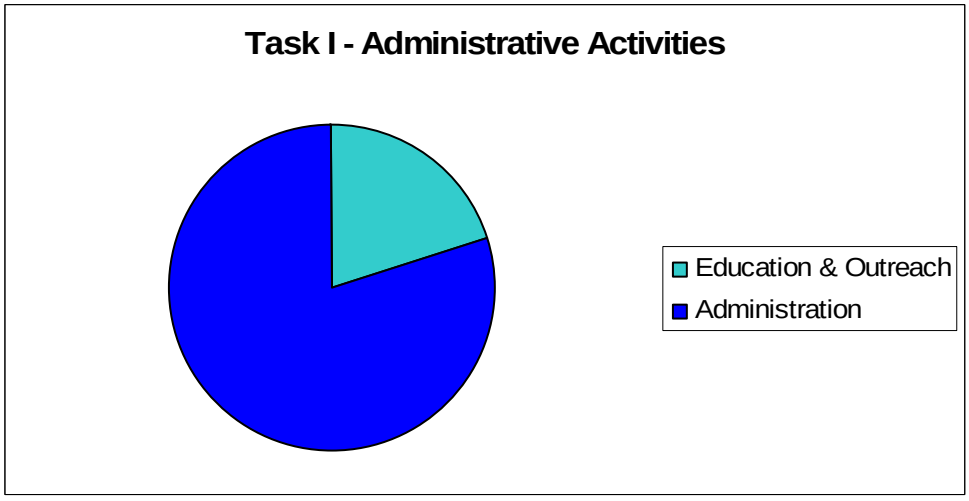
The overall objective of this theme is to establish a Princeton/Rutgers collaboration for the purpose of linking the advanced coastal modeling and observing capabilities at IMCS with the global climate modeling activities at Princeton/GFDL. This research theme was initiated a year ago with the funding of a proposal from Professor Dale Haidvogel of the Institute of Marine and Coastal Sciences (IMCS) of Rutgers University. The Rutgers group has a state-of-the-art, end-to-end modeling system for the coastal zone, a world class observing network in the Middle Atlantic Bight, and expertise in the simulation and understanding of coastal ocean (physical and biogeochemical) processes. During the first year, the Rutgers group used their existing model of the Middle Atlantic Bight to study response of the biogeochemistry to the North Atlantic Oscillation, particularly how it influences the air-sea flux of CO_2, and they carried out a series of development studies on how to embed their high resolution coastal model in a coarse resolution large scale model.

Paleoclimate

Due to limited funding over the past year, CICS was only able to fund one post-doc in this area despite the high priority that we place on this topic. We hope to be able to devote more attention to this in the near future, particularly as the new climate models at GFDL are used more and more to examine past climates, and also as the new coarse resolution climate models that are being developed at CICS and GFDL come to fruition. The post-doc funded under this topic was Agatha de Boer, who worked with CICS Fellow Sigman to investigate the causes of reduced high latitude overturning during the last ice age, which they believe may have been caused by the differing effects of salinity and temperature in glacial versus interglacial climates due to the non-linearity of the equation of state.



Task I - Administration covers the administrative activities of the cooperative institute and support of outreach activities. Funding during the past year included minimal support for the CICS Director and Administrator and full support for the part-time administrative assistant. Funding was also provided for QUEST, a well-establish summer program for elementary teachers in New Jersey.



Progress Reports:

Earth System Studies/Climate Research

Progress Report: **Hybrid Ocean Model Development**

Principal Investigator: Alistair Adcroft (Princeton Research Oceanographer)

Other Participating Researchers: Whit Anderson (Princeton), Robert Hallberg (GFDL), Stephen Griffies (GFDL), V. Balaji (GFDL), Zhi Liang (GFDL)

Theme #1: Earth System Studies/Climate Research

NOAA's Goal #1: Protect, Restore, and Manage the Use of Coastal and Ocean Resources through Ecosystem-based Management (35%)
NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond (60%)
NOAA's Goal #3: Serve Society's Needs for Weather and Water Information (5%)

Objectives:
Develop the foundations of the next generation ocean model at GFDL/NOAA

Methods and Results/Accomplishments:
The main development thrust for the next generation began in 2006 with a major overhaul of the HIM code. The underlying infrastructure has been revised to support the symmetric array concept that will facilitate nesting and novel horizontal grids. The model is now under-going rapid development to implement new features, principally implicit large-eddy simulation (ILES) capability and arbitrary lagrangian-eulerian (ALE). These will be at the heart of the next significant ocean climate model at GFDL.
Substantial research went into advection schemes and the piecewise-parabolic method (PPM). The two principle results of this activity are i) the implementation of PPM in the MOM4 code and ii) the development of a new, very high-order monotonicity preserving, finite volume advection scheme (OSMP7 and FCT-OSMP7-TVD3). The results are unprecedented for ocean models and the impact on the "spurious diabatic" problem being assessed.
Further research into the representation of topography was presented at a CPT workshop on overflows and gravity currents. The concept of thin walls and porous barriers generated much excitement and is a major improvement on the representation of bathymetry in z-ocean models.

Publications:
A. Adcroft and R. Hallberg, 2006: On methods for solving the oceanic equations of motion in generalized vertical coordinates. Ocean Modelling. 11, 224-233.

G. Boccaletti, R. Ferrari, A. Adcroft, D. Ferreira and J. Marshall, 2005: The vertical structure of ocean heat transport. Geophys. Res. Lett. 32 (10), L10603 [10.1029/2004GL022189]

D. Menemenlis, C. Hill, A. Adcroft, J.-M. Campin, B. Cheng, B. Ciotti, I. Fukumori, P. Heimbach, C. Henze, A. Kohl, T. Lee, D. Stammer, J. Taft and J. Zhang, 2005: NASA Supercomputer Improves Prospects for Ocean Climate Research. EOS, Transaction, American Geophysical Union. 86 (9) 1 March 2005, 95-96.

Progress Report: **Flexible Modeling System (FMS)**

Principal Investigator: V. Balaji, (Princeton Senior Technical Staff)

Other Participating Researchers: Alistair Adcroft (Princeton), Isaac Held (GFDL), Keith Dixon (GFDL), Karl Taylor (DoE/PCMDI), Max Suarez (NASA/GMAO), Steve Hankin (NOAA/PMEL). Tony Rosati (GFDL), S-J Lin (GFDL), Steve Pacala (Princeton), Jorge Sarmiento (Princeton).

Theme #1: Earth System Studies/Climate Research

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

Methods and Results/Accomplishments:

- Development of Flexible Modeling System (FMS) and FMS Runtime Environment (FRE) in support of Earth system modeling activities at PU/GFDL.
- Delivery of CM2.0 and CM2.1 models and model results for IPCC via GFDL Data Portal.
- Development of FMS infrastructure and modeling components for next generation physical climate model CM3 and Earth system model ESM3.
- Design of next-generation model and data frameworks (Earth System Curator project) in collaboration with the Earth System Modeling Framework (ESMF), Program for Integrated Earth System Modeling (PRISM) and Global Organization of Earth System Science Portals (GO-ESSP) groups, whose steering committees I serve on.

References:
FMS homepage: http://www.gfdl.noaa.gov/fms

Publications:
Delworth et al 2006: GFDL's CM2 global coupled climate models - Part 1: Formulation and simulation characteristics, *Journal of Climate*, (2006), **19**, No. 5, pages 643-674.

GFDL's CM2 global coupled climate models - Part 2: The baseline ocean simulation, Gnanadesikan et al., Journal of Climate, (2006), **19**, No. 5, pages 675-697.

Collins et al, 2005: Design and Implementation of Components in the Earth System Modeling Framework. *International Journal of HPC Applications*, **19**, 341—350.

Balaji et al 2005: The Exchange Grid: a mechanism for data exchange between Earth System components on independent grids, accepted for publication, Proceedings of Parallel CFD 2005.

Zhou et al 2006: Cross-Organization Interoperability Experiments of Weather and Climate Models with the Earth System Modeling Framework, accepted for publication to *Concurrency and Computation: Practice and Experience.*

Project Report: **Cooperative Institute for Climate Science Professional Development Summer Institute in Weather and Climate July 10-21, 2006**

Principal Investigator: Steve Carson (Princeton Regional School Chemistry Teacher)

Other Participating Researchers: 21 participants

Theme #1: Earth System Studies/Climate Research

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

Objectives:

In support of the Cooperative Institute for Climate Science's (CICS) intent to train the next generations to deal with the increasing complexity of understanding and predicting climate, the CICS collaborated with a Princeton University program called QUEST on a professional development institute for New Jersey teachers, July 10-21, 2006. QUEST is a long-standing summer program of Princeton University's Teacher Preparation Program. The two-week Weather and Climate unit in which CICS was involved was for teachers in third through sixth grades and offered a wide range of inquiry-based experience through which the teachers could develop an understanding of atmospheric processes and learn methods to teach about weather and climate. The unit was developed and taught by Dr. Steven Carson who was formerly a scientist and Outreach Coordinator at the Geophysical Fluid Dynamics Laboratory (GFDL) of CICS and is currently a middle school science teacher in Princeton, New Jersey.

Methods and Results/Accomplishments:

In the first week of the unit basic principles of weather and climate were explored by the participating teachers. Experiments and measurements involving pressure, temperature, heat transfer, and humidity laid the foundation. Those ideas were then brought together through exploration of the principles of cloud formation and the origin of wind. Experiments demonstrating the Coriolis effect served as a basis to understand global circulation of the atmosphere and the structure of tropical cyclones. A guest scientist from GFDL expanded on the topic of tropical cyclones by presenting background, research and modeling of tropical cyclones. To further expand understanding of storms, hands-on activities were used to develop explanations for lightning and tornadoes. A guest speaker from the Mount Holly Forecast Office of the National Weather Service provided further insight into principles of weather, data collection, and forecasting. A variety of activities were used to develop understanding of how energy from the sun is distributed over the earth, the cause of seasons, the basis and importance of the greenhouse effect, and optical phenomena in the atmosphere.

In the second week more quantitative approaches were used to expand on some of the previous topics and to introduce other new topics. The drawing of isotherms on maps of monthly average temperature was used to develop ideas of climate vs. weather and relate the patterns to principles introduced in the first week. Weather conditions and patterns were further explored through drawing isobars, plotting fronts, and examining a variety of maps and other resources available on the internet. More quantitative experiments were done with the distribution of light energy over the earth and with different ways to measure and express humidity. These were related to models of weather and climate. A second guest speaker from GFDL further drew on the topics studied to that point to discuss research and modeling concerning causes and consequences of global warming. An additional group of teachers studying the interdisciplinary curriculum of science, math, and literature joined the session to explore snow crystals and the reasons for their patterns.

The program gave teachers an understanding of the basic principles behind weather and climate and the integration of those principles with other dimensions of climate change.

PARTICIPATING SCHOOL DISTRICTS

Weeks One and Two – 21 teachers in grades 3-6 from the following school districts:

1 from Bordentown
1 from Ewing
3 from Lawrence Township
1 from Montgomery Township
1 from South Brunswick
11 from Trenton
1 from Washington Township
1 from West Windsor-Plainsboro
1 from an Independent School

52% participation from high poverty school district (Trenton) and an additional 9% from urban rim/"blue collar" districts (Bordentown and Ewing)

FEEDBACK FROM TEACHERS:

"I gained tremendous content knowledge, practical tips, and ideas that I can use in my classroom. The experience underscored, for me, the importance of varying methods of instruction, activities, locations, etc. in a classroom setting."

"QUEST gives one the opportunity and time to really/effectively learn about a subject taught by someone who really cares."

"I knew very little about weather coming into the program. My hope was to learn enough about the subject that I could do a good job teaching it next year. I definitely feel as though I gained not only significant amount of content knowledge, but also a wealth of practical teaching ideas. "

"Steve is very knowledgeable about this topic and enjoys sharing what he knows. He is the best! He taught at a great pace and always made sure we understood."

Progress Report: **What Determines The Location Of Surface Westerlies?**

Principal Investigator: Gang Chen (Princeton AOS graduate student)

Other Participating Researchers: Isaac Held (GFDL)

Theme #1: Earth System Studies/Climate Research

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

Objectives:
Understanding the factors that control the location of surface westerlies

Methods and Results/Accomplishments:

In response to global warming, the mid-latitude jet shifts poleward in the southern hemisphere (Kushner et al 2001). We study the nature of jet shift by analyzing one particularly simple case: as the surface friction is reduced, the mid-latitude jet and surface westerlies shift polewards (Robinson 1997).

We first examined the jet shift with the surface drag in an idealized dry GCM more comprehensively, particularly on the robustness of the results. Also, we compared the effects of surface drag with a constant torque computed from the effect of drag in the model. This similarity of the drag with the torque has implications for the orographic gravity wave drag parameterization. We have also confirmed this gravity wave drag effect in AM2, a more comprehensive GCM. This jet shift is also related to the annular mode that has been recently brought to great interest in climate research. It was also found that the response differs significantly to a torque in stratosphere than that in the troposphere.

Furthermore, we constructed a simple shallow water model to explain the jet shift with the surface drag. This simple model offers a qualitative approach to understand the nonlinear effect of midlatitude eddies on the surface westerly latitude.

References:

Robinson, W. A., 1997: Dissipation dependence of the jet latitude. J. Climate, 10, 176--182.

Kushner, P. J., I. M. Held, and T. L. Delworth, 2001: Southern hemisphere atmospheric circulation response to global warming. J. Climate, 14, 2238--2249.

Publications:

Chen, G., I. M. Held, and W. A. Robinson: Sensitivity of the Latitude of the Surface Westerlies to Surface Friction. Submitted to J. Atmos. Sci.

Progress Report: **The Dominance Of The North Atlantic In The Meridional Overturning Circulation**

Principal Investigator: Agatha M. de Boer (Princeton Research Associate)

Other Participating Researchers: J. Robert Toggweiler (GFDL) and Daniel M. Sigman (Princeton University)

Theme #1: Earth System Studies/Climate Research

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

Objectives:

The sinking of dense salty water in the North Atlantic is the main organizing feature of the ocean's deep circulation. The lack of a similar process in the North Pacific leads to a striking division of water properties between a salty, well ventilated Atlantic and a fresher, poorly ventilated Pacific. The overturning associated with the sinking in the North-Atlantic also leads to a large trans-equatorial heat flux from the Southern Hemisphere to the Northern Hemisphere, which exists despite the lack of any help from sinking in the Pacific. So, how does the Atlantic basin come to dominate the ocean's overturning and deep circulation? Common explanations involve the hydrological cycle and its interaction with the earth's topography which renders the North Atlantic more salty than the North Pacific. It is difficult to distinguish the effect of this forcing from the salinity gradients that result from the circulation itself. Paleo-observations suggest that the North Atlantic was more dominent during warm periods in the past. The North Atlantic was more dominant 20,000 years ago at the Last Glacial Maximum when sinking continued in the North Atlantic but was virtually absent in the Southern Ocean (McManus et al., Nature, 428, 834-837, 2004) The North Atlantic was less dominant during the early Pliocene (3.1-4.4 million years ago) when there appears to have been some sinking and ventilation in the North Pacific along with sinking in the Southern Ocean (Ravelo et al., 1999).

We thus investigate the hypothesis that the North Atlantic circulation's dominance is a result of global factors like the mean ocean temperature or the relative strength of the atmosphere's hydrological cycle or the strength of the wind-driven circulation rather than the effect of evaporation and precipitation over the North Atlantic.

Methods and Results/Accomplishments:

We examine the robustness of the NA dominance in an energy-driven meridional overturning circulation under different climatic forcings. Using an ocean general circulation model coupled to an energy moisture balance model, we first show that, as anticipated, the ocean does not support deep convection without winds or a high vertical diffusivity. Once deep convection and overturning set in, the distribution (or pattern) of convection is determined by the relative strength of the thermal and haline buoyancy forcing. In the most thermally dominant state (i.e., negligible salinity gradients), strong convection occurs in the North Atlantic (NA), North Pacific (NP) and Southern Ocean (SO) while in the most haline dominated state convection is restricted to the NA. We then test the effect of various forcing mechanisms on the strength and distribution of the overturning. A more vigorous hydrological cycle enforces stronger salinity gradients, favoring the haline state of NA dominance. On the other hand, a higher mean ocean temperature will increase the importance of temperature gradients because, alpha, the thermal expansion coefficient is higher in a warm ocean. Similarly, an increase in SO winds tends to neutralize the salinity gradients, pushing the ocean to the thermal state. In this framework, deep water formation in the NA is not driven by local buoyancy forcing but rather, responds passively to convection changes in the NP and SO. It follows that the inclusion of all deep convective basins are essential in a study of the meridional overturning in the Atlantic. Overall the experiments show that the mean ocean

temperature and wind field increase the dominance of the NA during warm periods, while the hydrological cycle works against this trend. Given the observations mentioned above, we conclude that the effect of changes in the hydrological cycle is smaller than that of the wind and mean ocean temperature on long timescale.

References:

1) Ravelo, A. C., and D. H. Andreasen, (1999) Using planktonic foraminifera as monitors of the tropical surface ocean, Reconstructing Ocean History - A window into the future, F. Abrantes and A. Mix (eds), Plenum Press, New York, 217-244

2) McManus et al (2004). Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes. Nature 428, 834.

Publications:

De Boer A. M., J. R. Toggweiler and D. M. Sigman. The dominance of the North Atlantic in the Meridional Overturning Circulation, in preparation.

Progress Report: **The Atmospheric Boundary Layer In The GFDL Climate Model**

Principal Investigator: John M. Edwards (Princeton Visiting Research Staff)

Other Participating Researchers: Host**:** Leo J. Donner (GFDL)

Theme #1: Earth System Studies/Climate Research

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

Objectives:
To improve the representation of the atmospheric boundary layer in the GFDL climate model.

Methods and Results/Accomplishments:

The atmospheric boundary layer plays a key role in the climate system, influencing surface fluxes, determining near-surface weather and controling the transport of atmospheric pollutants. Boundary layer parameterizations in climate models must therefore be physically based and realistic. Development of boundary layer schemes requires comparison with field data and simulations conducted with detailed process models. Initial work has centered on a mechanistic diagnosis of the performance of the boundary layer scheme in the GFDL model, using short integrations of the full and single-column versions of the model. The following two examples illustrate this approach.

The solid curves in figure 1 show the potential temperature, θ, at two-hourly intervals, starting from dawn, at a point in the southern US on a clear summer's day, obtained using the standard version of the AM2 model. Initially the atmosphere is stably stratified and θ increases with height. In response to solar heating an unstable layer grows from the surface, eventually becoming well-mixed. However, the unstable stratification is excessive duing the middle of the day. Including non-gradient fluxes (Holtslag and Boville, 1993), representing the effects of eddies with a depth comparable to that of the boundary layer, shown by the dashed curves, reduces the excessive stratification: the boundary depth then increases more rapidly during the late morning.

To investigate the stable boundary layer scheme, the single-column model has been set up to simulate the GABLS1 test case (Cuxart 2006), an idealized simulation which has been run by a number of large-eddy and single-column modelling groups. The initial profiles comprise a vertically uniform wind and a uniform potential temperature of 265 K in the lowest 75hPa of the atmosphere. A constant surface cooling is applied and a stable boundary layer develops. Figure 2 shows the profiles of wind speed and potential temperature from the single-column model at the end of the simulation. The model simulates a low-level jet, with a maximum in the wind speed at about 970 hPa, and a sigmoid profile of potential temperature in qualitative agreement with large-eddy models. However, as is the case for other operational forecasting and climate models, the simulated stable boundary layer is about twice as deep as predicted by large-eddy models.

References:

Holtslag, A. A. M. and B. A. Boville, 1993: Local versus nonlocal boundary-layer diffusion in a global climate model. J. Climate, vol. 6, pp. 1825-1842

Cuxart, J. and 23 others, 2006: Single-column model intercomparison for a stably stratified atmospheric boundary layer, Boundary-Layer Meteorol., vol. 118, pp. 273-303

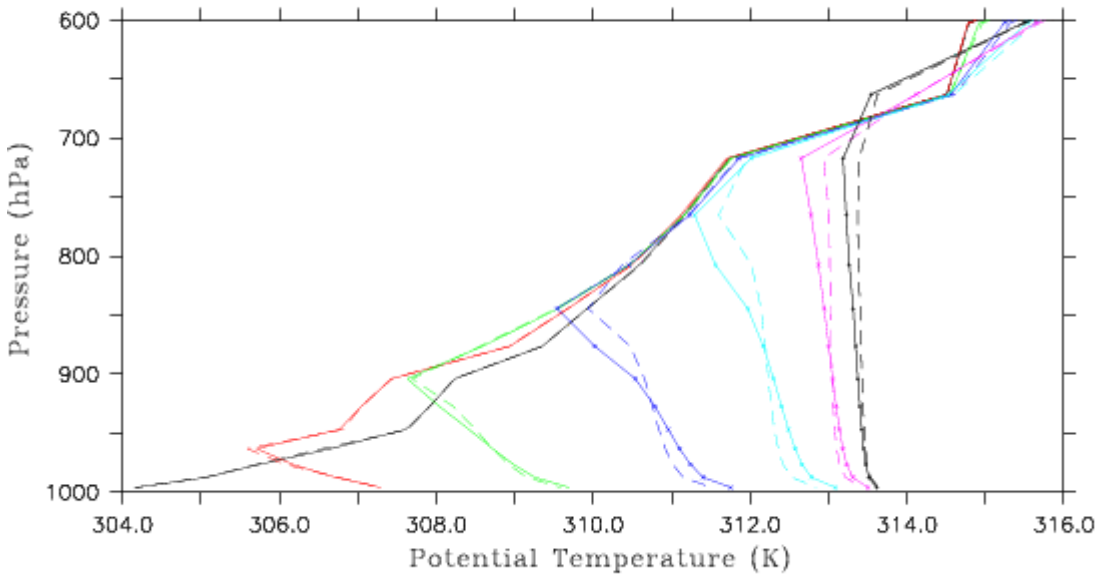


Figure 1: The evolution of the potential temperature in a developing convective boundary layer at 06 (thin black), 08 (red), 10 (green), 12 (blue), 14 (cyan), 16 (magenta) and 18 LST (thick black). Solid curves are for the standard version of AM2. Dashed curves show the effect of including non-gradient fluxes.

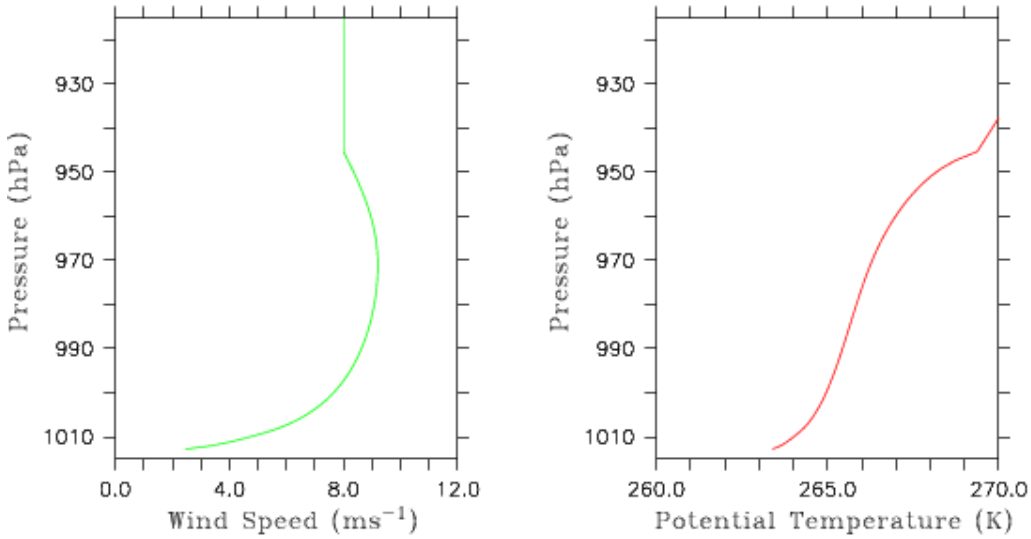


Figure 2: The profiles of the wind speed (left) and potential temperature (right) after 9 hours in the GABLS1 simulation.

Progress Report: **Atlantic Climate Variabilty and Predictability in a Simplified Coupled Model**

Principal Investigator: Riccardo Farneti (Princeton Research Associate)

Other Participating Researchers: Geoffrey Vallis (Princeton)

Theme #1: Earth System Studies/Climate Research

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

Objectives:
To develop an idealized climate model for the Atlantic sector and use this for studies of ocean-atmosphere interactions at decadal to centennial time scales.

Methods and Results/Accomplishments:
During the last few months, Farneti has been developing a simpified Ocean-Land-Atmosphere coupled model, derived from the GFDL CM2.0, where all its different components have been modified to focus on the simulation of Atlantic climate variability. The ocean model is the GFDL Modular Ocean Model (Griffies et al, 2004). The configuration consists of a single ocean basin (Atlantic-like) with an Antarctic Circumpolar Current. A second configuration differs in the southernmost part of the basin, where the Drake Passage is missing. Idealized initial temperature and salinity conditions are applied to the ocean at rest and the sea-ice model is coupled to the ocean. The atmospheric component is the AM2.0 B-grid model (The GFDL Global Atmospheric Model Development Team, 2005). The atmosphere has been configured to run as a 120 degrees wide zonal re-entrant channel. Additionally, simplified parameterizations of atmospheric processes have been implemented into the original model following Frierson (2005). Namely, the use of a simple grey-radiation, large-scale condensation and simplified Betts-Miller convection schemes. These changes imply a considerable computational gain, retaining a good representation of the atmospheric climate at both tropical and extra-tropical latitudes. Finally, the land model is reduced to a 'swamp bucket land', with nonzero evaporation and water availability everywhere, and a simple redistribution of precipitated water back into the ocean. The model components and new parameterizations retain the original modularity, in order to allow the coupled model to recover complexity in any of its parts. At this stage, the model development is completed and the ocean-atmosphere system is spinning-up. We anticipate to investigate multidecadal to centennial climate variability in the Atlantic region, decadal ocean-atmosphere modes of variability and the effects of ocean dynamics on the North Atlantic Oscillation. The idealized coupled model will allow also experiments on future climate change as well as paleoclimate studies.

References:
The GFDL Global Atmospheric Model Development Team, 2005. The New GFDL Global Atmosphere and Land Model AM2-LM2: Evaluation with Prescribed SST Simulations, J. Climate, 17, 4641-4673.

Frierson, D.M.W., 2005. Studies of the general circulation of the atmosphere with a simplified moist general circulation model, PhD Thesis, Princeton University.

Griffies, S. M., M. J. Harrison, R. C. Pacanowski, and A. Rosati, 2004: *A Technical Guide to MOM4*. GFDL Ocean Group Technical Report No. 5, Princeton, NJ: NOAA/Geophysical Fluid Dynamics Laboratory, 342 pp.

Progress Report: **Elements of the interaction between the Meridional Overturning Circulation (MOC) and the Antarctic Circumpolar Current (ACC)**

Principal Investigator: Neven-Stjepan Fučkar (Princeton AOS graduate student)

Other Participating Researchers: Geoffrey K. Vallis (Princeton Advisor), S. George H. Philander (Princeton), Anand Gnanadesikan and Isaac Held (GFDL)

Theme #1: Earth System Studies/Climate Research

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

Objectives:
To understand the dynamics and thermodynamics of the MOC-ACC connection and its climate relevance.

Methods and Results/Accomplishments:

The world's oceans exert a significant influence on the climate. The processes of lateral (primarily meridional) and vertical transport of heat, freshwater, and critical chemical constituents in the oceans and the atmosphere are responsible for the present habitable state of the Earth. In such a planetary scale mosaic, from the point of ocean role in climate dynamics, an interesting and not yet completely resolved question is the level of integration and nature of interaction between the ocean meridional overturning circulation (MOC) and the Antarctic Circumpolar Current (ACC). Particularly interesting is the possibility of the dependence of the ACC stratification and transport on remote surface conditions and MOC mechanisms (i.e. remote control via oceanic bridge).

Under the supervision of Prof. Geoffrey K. Vallis my recent research addresses the question of impact of interhemispheric surface forcing through the MOC on the ACC in an idealized coarse-resolution general circulation ocean model. At the nexus of this study presently is the Modular Ocean Model version 4.0c (MOM4) with analytically prescribed direct (wind stress) and restoring (temperature and virtual salinity) surface boundary conditions. We began working with a single-basin configuration that includes the Southern Ocean (SO) channel with a sill. A striking result in this setup is the substantial sensitivity of the ACC transport to the Northern Hemisphere (NH) meridional temperature gradient, i.e. to the change of the NH buoyancy forcing (besides previously established sensitivity to the SO winds and buoyancy forcing). As the NH thermal gradient decreases, the ACC transport increases primarily due to the increase of thermal wind shear component. Hence this research represents an opportunity to further understand and distinguish dynamical and thermodynamical mechanisms of the ACC transport and variability through the study of interhemispheric and subsequently interoceanic aspects. Ultimately, we plan to explore this point further with a hierarchy of ocean-only and coupled models depending on available computer resources and time.

Publications:

A paper on this subject is being written and it will be submitted soon.

Progress Report: **A Dynamical and Statistical Understanding of the North Atlantic Oscillation and Annular Modes**

Principal Investigator: Edwin Gerber, Princeton Graduate Student (currently a Postdoctoral Research Scientist at Columbia University)

Other Participating Researchers: Geoffrey Vallis (GFDL/Princeton)

Theme #1: Earth System Studies/Climate Research

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

Objectives:
To understand the dynamics of the North Atlantic Oscillation and annular modes.

Methods and Results/Accomplishments:

Gerber defended his PhD thesis in December, 2005. His thesis research on extratropical intraseasonal (10-100 days) variability was based a series of models of the extratropical atmosphere. In the 2005-6 year, his work focussed on the most complex model in the hierarchy, a dry primitive equation model of the atmosphere. This model is the GFDL spectral dynamical core, forced by an idealized scheme developed by Held and Suarez (1994).

A parameter study was completed to assess the impact of zonally asymmetric forcing on the spatial structure and timescale of extratropical intraseasonal variability. Such variability in the atmosphere is known to be organized in several patterns (or modes), the most dominant being the North Atlantic Oscillation (NAO) and the so-called annular modes. Annular mode-like variability is produced in the model with the standard Held-Suarez forcing. Realistic NAO-like variability is created with the addition of zonal asymmetries, idealized topography and thermal perturbations designed to approximate land-sea contrast.

The parameter study allowed Gerber to probe a feedback between the synoptic (2-10 day) variability with the intraseasonal variability that increases the power of the lower frequency patterns. As shown in Figure 1, the timescale of the annular mode in the model drops significantly as the forcing is made more asymmetric. It also becomes less sensitive to model parameters, such as the equilibrium temperature gradient which determines the thermal forcing in the model. With the most realistic forcing, the timescale is near 10 days, consistent with observations. The change in sensitivity to model parameters with zonal asymmetry suggest that the feedback depends on the structure of the model's storm track. Gerber developed an simple stochastic model to explain these changes. His results indicate the importance of interactions between synoptic variability in the North Atlantic storm track and NAO.

References:

I. M. Held and M. J. Suarez, 1994: A Proposal for the Intercomparison of the Dynamical Cores of Atmospheric General Circulation Models, Bulletin of the American Meteorological Society, **75**, 1825-1830.

Publications:

E. P. Gerber and G,K Vallis, 2006: Eddy-Zonal Flow Interactions and the Persistence of the Zonal Index, submitted to the Journal of Atmospheric Sciences

E. P. Gerber, 2005. A Dynamical and Statistical Understanding of the North Atlantic Oscillation and Annular Modes, PhD Thesis, Princeton University

Two more papers are in preparation:

E. P. Gerber and G,K Vallis, 2006: The Impact of Zonal Asymmetries on the Persistence of the Zonal Index

E. P. Gerber and G,K Vallis, 2006: On the Zonal Structure of the NAO and Annular Modes

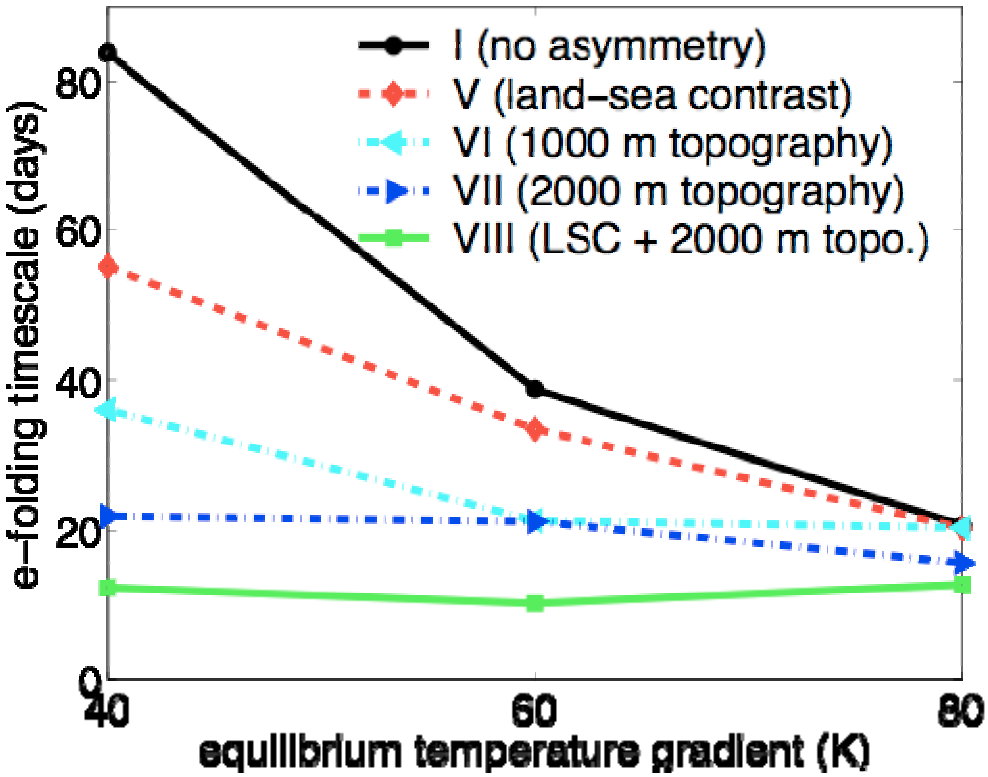


Figure 1: The impact of zonally asymmetric forcing and the equilibrium temperature gradient on the persistence of the annular mode, as quantified by the e-folding timescale of the annular mode index's autocorrelation function. Experiment I refers to three simulations with the standard Held-Suarez forcing. In experiment V, thermal anomalies were added to approximate land sea contrast. In experiments VI and VII, idealized topography with the spatial scale of the Rocky Mountains was added, with maximum height 1000 and 2000 m, respectively. Lastly, in experiment VII, both the thermal and topographic perturbations we added, to best approximate the North Atlantic storm track. Note the dramatic drop in both the absolute timescale and the sensitivity to the equilibrium temperature gradient with increasing zonally asymmetric forcing.

Progress Report: **Hybrid Ocean Model Development**

Principal Investigator: Thomas Haine (Johns Hopkins University Professor)

Other Participating Researchers: Steve Griffies and Bob Hallberg(GFDL), Alistair Adcroft (Princeton)

Theme #1: Earth System Studies/Climate Research

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

Objectives:
Develop the foundations of the next generation ocean model at GFDL/NOAA

Methods and Results/Accomplishments:

Code Development: The model development has continued through regular collaborative visits of the PI to GFDL. In Summer and Fall 2005 a major upgrade to the working code was performed with the help of Alistair Adcroft. This involved migrating to the latest release of the MITgcm code and benchmarking new features in this release. The new features include: the z* vertical coordinate following Adcroft and Campin (2004), the Leith (1968) viscosity parametrization, a 3rd order flux-limited advection scheme, and improved IBCAO bathymetry (Jacobbson et al., 2001; a significant improvement over the Smith and Sandwell (1997) product on the Greenland shelf). We explored open boundary conditions in some detail too but found they caused numerical instabilities with the new more inertial solutions. Some tests with the MITgcm nonhydrostatic code were made but at 1.8km horizontal resolution they did not make much difference. A new initial condition based on ICES hydrographic profiles was implemented which significantly improved the solution realism.

New Runs: Two major new solutions have been integrated, both lasting 15 months of model time in 2003/4. The fidelity of these solutions has been assessed by comparing to published accounts of the circulation in the Denmark Strait and Irminger Sea. The model solutions look quite realistic and adequately reproduce the major jets and water mass structures. The overflow through Denmark Strait is reasonably well reproduced at this resolution (up to 1.8km horizontal, and typically 20m vertical resolution). Diagnosis of the entrainment into the overflow plume is pending and will provide a useful test case for the Gravity Current Entrainment CPT led by Sonya Legg. Another integration for the year of 2004/2005 is planned to begin shortly. The summer of 2004 was a time of high East Greenland sea ice, in contrast to that of 2003 which was relatively ice free.

Denmark Strait Overflow Volume Transport Results: A major focus of recent work has been to assess and understand Denmark Strait overflow variations. In the simulations, a quasi-periodic 2-4 day transport oscillation is apparent at a section immediately downstream of the sill [at the "Denmark Strait South" (DSS) section; see figure]. This variability is seen in other less-resolved models, in satellite radiometric data (Bruce, 1995), and in in-situ observations. The model solutions show a very strong correlation between these overflow pulses and sea-surface height anomalies in the region. This relationship suggests that altimetry can be used directly to estimate outflow variations in the real Denmark Strait for the last 15 years or so. Current work is to investigate this very important prospect using the archived altimetry data from the TOPEX, Jason-1, ERS-2, GFO, and Envisat missions.

Assimilation Results: Work with a coarser resolution version of the Denmark Strait/Irminger Sea model and 4DVAR data assimilation system continues. In identical twin experiments to test the data assimilation system, the DSS overflow transport variability is tightly constrained in phase and amplitude by altimetry and radiometry data (see figure; Lea et al., 2006). This finding applies despite the absence of in-situ measurements of the overflow in the area. A post doc has joined the PI's group to collaborate on this part of the project and is performing more identical twin experiments to explore the issue in more detail. A major upgrade of the assimilation code is also underway and the code is being ported to the GFDL HPCS.

References:

A. Adcroft and J.-M. Campin, Rescaled height coordinates for accurate representation of free-surface flows in ocean circulation models, Ocean Modelling, 7, 269-284, 2004.

J. G. Bruce, Eddies southwest of the Denmark Strait, Deep-Sea Research I, 42, 13-29, 1995.

M. Jakobsson and IBCAO Editorial Board Members, Improvement to the International Bathymetric Chart of the Arctic Ocean (IBCAO): Updating the data base and the grid model, Eos Trans. AGU, 82(47), Fall Meet. Suppl., Abstract OS11B-0371, 2001

C. E. Leith, Diffusion approximation for two-dimensional turbulence, Physics of Fluids, 10, 1409-1416, 1968.

W. H. F. Smith and D. T. Sandwell, Global sea floor topography from satellite altimetry and ship depth soundings, Science, 277, 1956-1962, 1997.

Publications:

D. J. Lea and T. W. N. Haine and R. F. Gasparovic, Observability of the Irminger Sea circulation using variational data assimilation, Quarterly Journal of the Royal Meteorological Society, 2006.

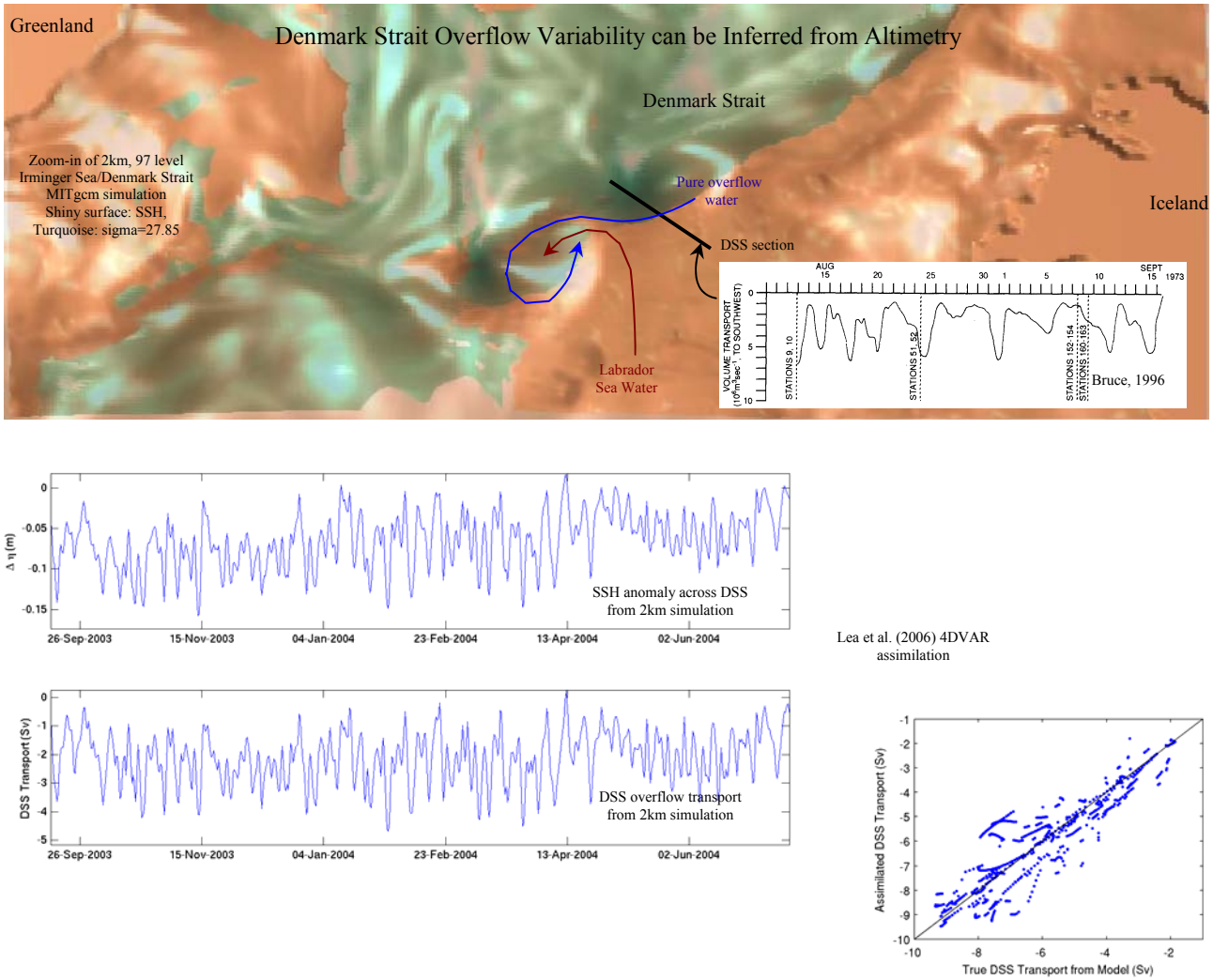


Figure: Results from highly-resolved Irminger Sea/Denmark Strait simulations suggest overflow variability can be inferred directly from altimetry. The **main panel** shows a zoom-in of the Denmark Strait from the PI's 2km, 97 level MITgcm simulation. The sigma=27.85 isopycnal is colored in turquoise

and viewed through the model sea-surface height field (shiny). A cyclonic eddy is seen downstream of the DSS section and is the primary mechanism of lateral entrainment of the overflow (relatively warm Labrador Sea Water is wrapped up with colder pure overflow waters). An animation of this process is available at: http://www.jhu.edu/~eps/faculty/haine/index.html. The **main panel inset** shows the DSS transport time series (for temperature<2°C) from the 1973 mooring array at section DSS [reproduced from Deep-Sea Research I, 42, J. G. Bruce, Eddies southwest of the Denmark Strait, 13-29, copyright (1995) with permission from Elsevier] and confirms the presence of quasi-periodic overflow pulses in the real ocean. The two **time series at bottom left** show the simulated SSH anomaly across section DSS and the simulated DSS overflow transport. The model outflow variability is realistic and highly correlated with SSH. The **scatter plot at right** shows results from the PI's 4DVAR data assimilation system: Using satellite data the assimilation system can also accurately reproduce the DSS transport variations (Lea et al., 2006).

Progress Report: **The Role of Eddies in the Dynamics of the Antarctic Circumpolar Current**

Principal Investigator: Arno Hammann (Princeton AOS graduate student)

Other Participating Researchers: Anand Gnanadesikan (advisor, GFDL)

Theme: Earth System Studies/Climate Research

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

Objectives:
To understand the role of ocean eddies in the dynamics of the Antarctic Circumpolar Current (ACC), and the implications for global climate modeling.

Methods and Results/Accomplishments:

The investigation aims to use the Hallberg Isopycnal Model (HIM) in strongly idealized settings to explore the role of eddies in the dynamics of the ACC. Eddies are thought to play an important role in the momentum balance of the current and hence in determining its total zonal transport. They also appear to have an effect on the meridional (overturning) part of the circulation, which interlinks the ACC with the global ocean circulation. It is possible that this link between the dynamics of the ACC and the global overturning circulation affects our ability to simulate long-term climate change negatively, since up to now, global climate model are not capable of resolving ocean eddies.

Therefore, experiments will be conducted comparing eddy-resolving and coarse resolution simulations (with different eddy parameterizations) in simplified ACC-like ocean domains. One additional aim is to judge the success of various existing eddy parameterizations, and possibly search for better ways to parameterize eddies.

The experiments follow loosely the experimental setup of Hallberg and Gnanadesikan (2001), and most of the work so far has gone into reproducing and checking their results with a newer version of HIM (which has been converted entirely from C to Fortran code to be embedded into the GFDL Flexible Modeling System).

References

Hallberg, Robert and Gnanadesikan, Anand (2001), "An exploration of the role of transient eddies in determining the transport of a zonally reentrant current", *J. Phy. Oceanogr.*, 31, 3312-3330

Progress Report: **Synergistic Use Of Observations And Climate Modeling In Climate Diagnostics**

Principal Investigator: Xianglei Huang (Princeton research associate - AOS Program)

Other Participating Researchers: Host: V. Ramaswamy (GFDL). Collaborators: M. Daniel Schwarzkopf, N.-C. Lau (GFDL), Brian J. Soden (Univ. of Miami), LinHo (National Taiwan University, Republic of China).

Theme #1: Earth System Studies/Climate Research

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

Objectives:
To use observational data sets and climate modeling together to address various questions relevant to climate variability

Methods and Results/Accomplishments:

(1) The Influence of Ozone Change on the Cooling of the Tropical Lower Stratosphere: a Modeling Study: We use AM2 to investigate the relative contribution of tropical and extratropical ozone changes to the cooling in the TLS. The results indicate that the tropical ozone change is more responsible for the cooling in the TLS than the extratropical ozone change. We also examine the trends month by month. The results are consistent with this conclusion. The cooling induced by tropical ozone change is strong and significant in June and July as well as November and December. This is different from observation in which the strongest cooling happens in December and January. This suggests that additional physical processes have to bee taken into account to fully explain the cooling in the TLS and the contrast between tropics and extratropics.

(2) An Observational and Modeling Study of the Winter-to-Spring Transition in East Asia: Analysis of observations from 1979 to 2002 shows that the seasonal transition from winter to spring in East Asia is marked with a distinctive abrupt change—the onset of the South China spring rain (SCSR). We reveal the detailed physical mechanism responsbile for this abrupt change as well as a chain of events in response to this abrupt change. A parallel analysis using output from an experiment with a GFDL coupled GCM shows that the above sequence of circulation changes are well simulated in that model.

Publications:

Huang, X.L**.,** V. Ramaswamy, and M. Daniel Schwarzkopf, Quantification of the source of errors in AM2 simulated tropical clear-sky outgoing longwave radiation, *Journal of Geophysical Research – Atmospheres*, 111, D14107, doi:10.1029/2005JD006576, 2006.

Li, L., A.P. Ingersoll, X.L. Huang, Interaction of Moist Convection with Zonal Jets on Jupiter and Saturn, *Icarus*, 180(1), 113-123, doi:10.1016/j.icarus.2005.08.016, 2006.

Soden, B.J., D.L. Jackson, V. Ramaswamy, M.D. Schwarzkopf and X.L. Huang, The radiative signature of upper tropospheric moistening, *Science*, 310(5749), 841-844, 10.1126/science.1115602, 2005.

Natraj, V., X. Jiang, R.-L. Shia, X.L. Huang, J.S. Margolis, and Y.L. Yung, The Application of Principal Component Analysis in Fast, Highly Accurate and High Spectral Resolution Radiative Transfer Modeling: A Case Study of the O_2 A-band, *Journal of Quantitative Spectroscopy and Radiative Transfer*, 95(4), 539-556, 2005.

Huang, X.L., B.J. Soden, and D.L. Jackson, Interannual co-variability of tropical temperature and humidity: a comparison of model, reanalysis data and satellite observation, *Geophysical Research Letters*, *32*, L17808, doi:10.1029/2005GL023375, 2005.

Manuscripts to be submitted

Huang, X.L., M. Daniel Schwarzkopf, and V. Ramaswamy, The influence of ozone change on the cooling of the tropical lower stratosphere: a modeling study.

LinHo, X.L. Huang, N.-C. Lau, An Observational and Modeling Study of the Winter-to-Spring Transition in East Asia

Conference Abstract

Huang, X., M. Daniel Schwarzkopf, and V. Ramaswamy, The influence of ozone change on the cooling of the tropical lower stratosphere: a modeling study, Eos Trans. AGU, 86 (52), Fall Meet. Suppl., Abstract A23B-0944, 2005.

Progress Report: **Temperature Dependence Of Gas Absorptivity And Its Implication For Climate Change Problem**

Principal Investigator: Yi Huang (Princeton Graduate student of the AOS program)

Other Participating Researchers: Advisor: V.Ramaswamy (GFDL)

Theme #1: Earth System Studies/Climate Research

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

Objectives:
To analyze the influence of the gas absorptivity's temperature dependence upon the clear-sky outgoing longwave radiation (OLR) at the top of the atmosphere and downward longwave radiation (DLR) at the surface.

Methods and Results/Accomplishments:
Method: Radiative Jacobians, which quantify the sensitivity of radiative flux to atmospheric temperature perturbations.

The results show that the temperature dependence of gas absorptivity strongly influences the radiation energy transfer in the atmosphere. In terms of OLR, the temperature-dependent gas absorptivity effect induces only a minor change compared to the Planck effect on the overall sensitivity of the outgoing irradiance flux to a small (+1 K) temperature perturbation. However, this occurs because the change in the emission from the perturbed layer and the change in the interception of the radiation from the layers below and the surface comprise an offset. A prominent feature is that more of the radiation emitted by the surface, mainly in the atmospheric window region, escapes to outer space, than if the absorptivity were not temperature-dependent. In terms of DLR, the temperature dependent gas absorptivity effect reduces the downward radiation from the atmosphere to the surface. Generally speaking, the temperature dependence of gas absorptivity reduces the climate sensitivity in terms of the surface temperature than if it were ignored, with the effect becoming more prominent in a warmer climate.

References:
Huang, Y., V. Ramaswamy, and B. Soden, An Investigation of the Sensitivity of the Clear-sky Outgoing Longwave Radiation to Atmospheric Temperature and Water Vapor, submitted to Journal of Geophysical Research, 2006.

Publications:
Huang, Y. and V. Ramaswamy, Temperature dependence of gas absorptivit and its implication for climate change problem, submitted to Journal of Geophysical Research, 2006.

Progress Report: **Gravity Current Entrainment Climate Process Team and Eddy Mixed Layer Interactions Climate Process Team**

Principal Investigator: Laura Jackson (Princeton Research Associate)

Other Participating Researchers: Robert Hallberg (GFDL), Sonya Legg (Princeton)

Theme #1: Earth System Studies/Climate Research

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

Objectives:
To work with both the Gravity Current Entrainment and the Eddy Mixed Layer Interactions Climate Process Teams in developing parameterizations of these processes and testing these in regional and climate models.

Methods and Results/Accomplishments:
This year I have been continuing to develop a shear-driven diapycnal mixing parameterization that can be used in both isopycnal- and z-coordinate models. This new parameterization describes vertically non-local quasi-equilibrium shear-driven mixing, which we hope will be able to capture shear-driven mixing in both gravity currents and the Equatorial Undercurrent.

I have conducted direct numerical simulations of shear-driven stratified turbulence to compare to, and calibrate this theory. Time and spatially averaged eddy diffusivities and fluxes are shown in Fig. 1. and are compared to our new parameterization and the Hallberg (2000) parameterization. Our new theory captures the diffusivities and buoyancy fluxes much better than local parameterizations such as Hallberg (2000) and the interior part of KPP (not shown), particularly for the jet case. However, it is much simpler (and more appropriate for climate studies) than two-equation models such as k-epsilon and Mellor-Yamada. If successful, it will replace both the interior shear-mixing part of KPP (Large et al., 1994) and the Hallberg (2000) shear mixing parameterization.

I have also been working on implementing this new parameterization for use in our climate models and am working with collaborators in U. Miami to compare this parameterization with Large Eddy simulations of gravity current entrainment. I have given several presentations of my results this past year, including at the Ocean Sciences meeting in February, and am completing a paper for publication. A separate paper describing the numerical implementation and results for global simulations is also in progress, and a paper with our collaborators in Miami is planned.

References:
Hallberg, R., 2000: Time integration of diapycnal diffusion and Richardson number-dependentmixing in isopycnal coordinate ocean models, Mon. Wea. Rev., 128, 1402-1419

Large, W. G., J. C. McWilliams, and S. C. Doney, 1994: Oceanic vertical mixing: A review and a model with a nonlocal boundary layer parameterization, Rev. Geophys., 32, 363-403.

Publications:
Jackson, L., R. Hallberg and S. Legg, 2006: A shear-driven mixing parameterization for gravity current entrainment. In preparation

Jackson, L. and R. Hallberg, 2006: Shear-driven mixing in overflows and the Equatorial Undercurrent. In preparation.

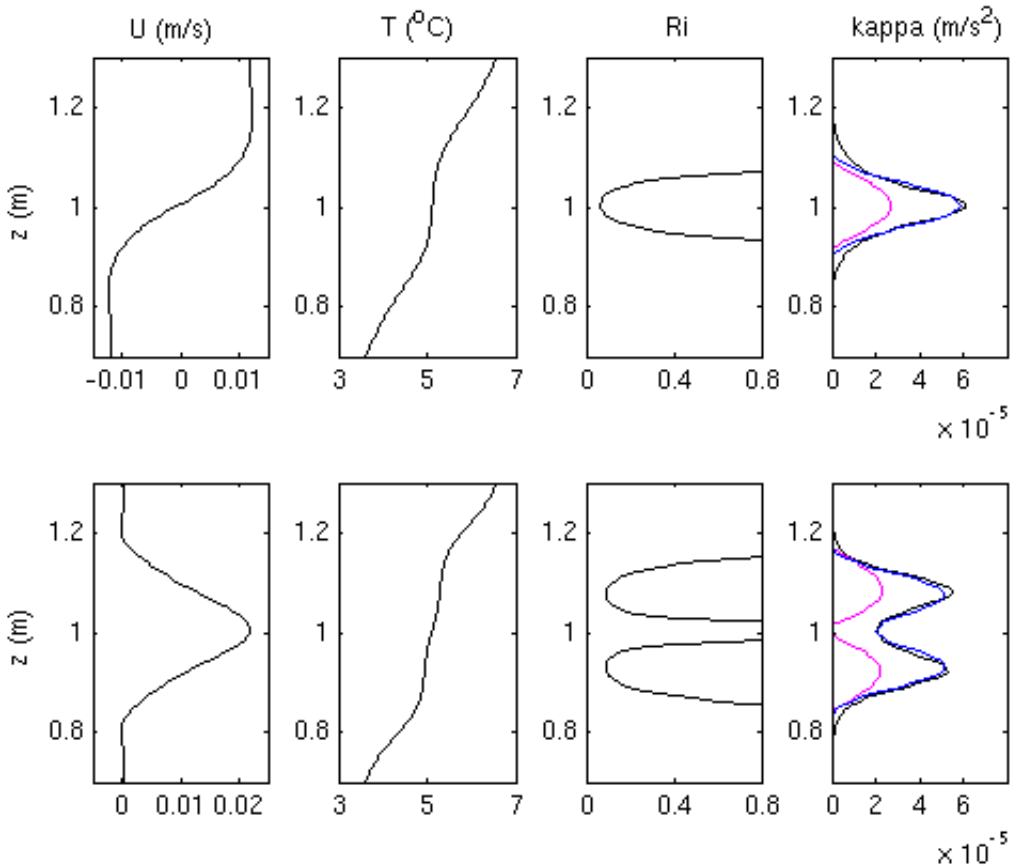


Fig 1. Profiles of horizontal velocity, temperature, Richardson number and turbulent eddy diffusivity for the shear case (upper panels) and jet case (lower panels). The DNS results are plotted in black, the previous Hallberg (2000) parameterization for the eddy diffusivity is plotted in red and the new parameterization is plotted in blue.

Progress Report: **Warm Season Climate Over Us Continent As Simulated By The GFDL AGCM**

Principal Investigator: Xianan Jiang (Princeton Research Associate)

Other Participating Researchers: Ngar-Cheung Lau, Isaac M. Held, Jeffrey J. Ploshay (GFDL), Stephen A. Klein (Lawrence Livermore National Lab)

Theme #1: Earth System Studies/Climate Research

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

Objectives:
This study aims to explore physical mechanisms responsible for the summertime precipitation regime over the North American Continent, and to assess the fidelity of the GFDL AGCM in simulating of the observed features.

Methods and Results/Accomplishments:
In this past year, Jiang has mainly focused on the following research topics, which are aimed at gaining a better understanding of the warm season climate over US continent and capability of the GFDL GCM in simulating this climate system.
(1) Mechanisms of the Great-Plains low-level jet (LLJ): As reported in last year, this activity is based on a realistic simulation by the GFDL AGCM of the Great Plains LLJ, which is one of the key elements of warm season regional climate over North America. This study has been conducted to re-evaluate the physical mechanisms for the formation of the nocturnal LLJ. A manuscript containing the results of this study has been accepted for publication in Journal of the Atmospheric Sciences.
(2) Identifying AGCM deficiencies in simulating the diurnal cycle of rainfall over the central US: The warm season climate over the central US simulated by the GFDL AGCM exhibits large dry and warm biases compared to the observations. These biases in the seasonal mean patterns largely result from GCM deficiencies in depicting the diurnal cycle of precipitation over this region. The precipitation is characterized by a strong nocturnal peak in the observations, whereas the simulated precipitation shows a maximum in the afternoon. In order to identify key factors responsible for these AGCM deficiencies, we have conducted detailed comparison between the AGCM simulation and observations of the thermo-dynamical/dynamical conditions necessary for producing the observed nocturnal rainfall over this region. It turns out that the inadequate model simulation of eastward migrating convection systems from the Rockies into the Great Plains could be the key reason for the aforementioned AGCM deficiencies. Our further investigation based on the observations confirms the essential role of this eastward propagating mode for the warm season climate over the central US. This propagating mode could be the deciding factor for the observed nocturnal rainfall peak over the Great Plains. It is also found that nearly half of the total summer rainfall over this region is associated with these propagating convective systems. However, the reasons for the lack of eastward propagating precipitation systems in the GCM atmospheres remain to be determined.
(3) Low-frequency variability of summertime rainfall over the South-western US: Currently, Jiang is conducting a study on the low-frequency variability (period >8 days) of the rainfall over the South-western US. Such variability results from interactions among multi-scale systems, including Madden-Julian Oscillation, easterly waves, and Gulf of California wind surge events. Preliminary results also demonstrate a strong linkage between the rainfall variability over this region and convective activities over the western North Pacific Ocean near the Philippine Sea through a cross-Pacific tele-connection wave train.

Publications:

Xianan Jiang, Ngar-Cheung Lau, Isaac M. Held, and Jeffrey J. Ploshay, 2006: Mechanisms of the Great-Plains low-level jet as simulated in an AGCM. J. Atmos. Sci, accepted.

Xianan Jiang, Ngar-Cheung Lau, and Stephen A. Klein, 2006: Role of eastward propagating convection systems in the diurnal cycle and seasonal mean of summertime rainfall over the U.S. Great Plains. Submitted to Geophys. Res. Lett, revised.

Stephen A. Klein, Xianan Jiang, Jim Boyle, Sergey Malyshev, and Shaocheng Xie, 2006: Diagnosis of the summertime warm and dry bias over the U.S. Southern Great Plains in the GFDL climate model using a weather forecasting approach. Submitted to Geophys. Res. Lett.

Progress Report: **What Determines The Position Of ITCZ?**

Principal Investigator: Sarah M. Kang (Princeton graduate student)

Other Participating Researchers: Advisor: Isaac Held (GFDL)

Theme #1: Earth System Studies/Climate Research

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

Objectives:
To understand what determines the position of ITCZ to eventually investigate on the Sahel drought.

Methods and Results/Accomplishments:

Kang worked with a simplified moist GCM by Frierson et al. and this enabled to analyze the energy budget easily.

Kang mainly looked at how the ITCZ responses to interhemispheric differential forcing. When the external forcing is confined in the tropics, the ITCZ moves substantially toward the warmer hemisphere and it is close to the boundary between two Hadley cells (thermal equator). On the other hand, when the external forcing is outside of the Hadley cells, the ITCZ moves little but the thermal equator moves significantly. Thus, for the tropical case the thermal equator can be used to predict the ITCZ, but for the extratropical case we need another theory.

In tropical case, almost all of the imposed ocean flux is balanced by the atmospheric energy flux change at the equator. In extratropical case, there is very low compensation (~25%) by the atmospheric energy flux. The reason that there is non-zero compensation in extratropical case is that the eddy energy fluxes reach the Hadley cell. Therefore the Hadley circulation responds to that by redistributing heat throughout the whole cell to flatten the temperature. This is why the thermal equator in extratropical case moves significantly. Thus the degree of compensation by the atmospheric energy flux determines the position of thermal equator.

In case of extratropical case, Kang is going to use the energy balance model of Frierson et al. to predict changes in extratropical energy fluxes and also predict the compensation percentage in the tropics. This might give us a simple theory to predict the thermal equator. Kang will also do the same experiment with AM2 over aquaplanet boundary condition to see how consistent the results are. This simulation will help us understand how cloud forcing and water vapor feedback modify the results since the radiation is no longer just a function of temperature.

References:

Chiang, J.C.H., C. M. Bitz, 2005: Influence of high latitude ice cover on the marine Intertropical Convergence Zone. Clim. Dyn., Vol 25, 477-496.

Held, I. M., and A. Y. Hou, 1980: Nonlinear axially symmetric circulations in a nearly inviscid atmosphere. J. Atmos. Sci., Vol 37, 515-533.

Lindzen, R. S., and A. Y. Hou, 1988: Hadley circulations for zonally averaged heating centered off the equator. J. Atmos. Sci., Vol 45, 2416-2427.

Zhang, R., T. L. Delworth, 2005: Simulated tropical response to a substantial weakening of the Atlantic thermohaline circulation. J. Climate., Vol 18, 1853-1860.

Progress Report: **Impact Of Aerosols On Precipitation In Deep Convection Simulated By Double-Moment Bulk Microphysics With Explicit Cloud Droplet Nucleation**

Principal Investigator: Seoung Soo Lee (Princeton AOS Graduate Student)

Other Participating Researchers: Leo Donner (GFDL), Vaughan Phillips (GFDL), AND Yi Ming (GFDL).

Theme #1: Earth System Studies/Climate Research

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 first aim of the present paper is to investigate the impact of aerosol number concentration on precipitation (the aerosol second indirect effect) by using a double-moment microphysics in MCS. The second aim is to investigate the impact of aerosol chemical composition on precipitation in the MCS.

Methods and Results/Accomplishments:

For the investigation into the effect of aerosol number concentration, clean continental and moderately polluted continental aerosols are applied to the model respectively. The effect of the chemical composition is examined by varying the mass fraction of soluble and insoluble substances.

The increase in organics by replacing sulfate lowers critical supersaturation (Sc) and leads to larger Cloud Droplet Number Concentration (CDNC). The larger CDNC results in the stronger interactions between microphysics and dynamics, leading to larger precipitation, as compared to the case of 100 % sulfate aerosols. The conventional assumption of sulfate aerosol as a surrogate for whole aerosol mass can be inapplicable for the case with strong source of organics.

The range of variation of precipitation caused by the change in mass fraction between the soluble and insoluble substances is larger than that caused by the change in mass fraction between the soluble substances. This indicates the need to consider the insoluble substance in the simulation of droplet nucleation.

References:

Khain, A., D. Rosenfeld, and A. Pokrovsky, Aerosol impact on the dynamics and microphysics of deep convective clouds, Quart. J. Roy. Meteor. Soc., 131, 2639-2663,2005.

Publications:

Lee, S., L. J. Donner, and V. Phillips, Impact of aerosols on precipitation in deep convection, submitted to J. Geophys. Res.

Progress Report: **Ocean Tidal Mixing**

Principal Investigator: Sonya Legg (Princeton Research Oceanographer)

Other Participating Researchers: Jody Klymak (Scripps) and other members of Hawaiian Ocean Mixing Experiment, Karin Huijts (summer student fellow at WHOI, now graduate student at the University of Twente, Netherlands), GFDL researchers.

Theme #1: Earth System Studies/Climate Research

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

Objectives:
To understand and quantify the conversion of tidal energy into internal waves and mixing over topography and incorporate this understanding into mixing parameterizations in GFDL climate models.

Methods and Results/Accomplishments:

In the past year Legg has completed a study begun with Huijts, examining the rate of energy conversion from barotropic to baroclinic tide over isolated idealized topography. This research has been described in a publication (Legg and Huijts, 2006) which was accepted in November 2005, and appeared in press early in 2006. Principal results of this study were an agreement between theoretical predictions and model results for energy conversion rates for tall steep topographies, and identification of a greatly enhanced local dissipation for very narrow topography.

In recent months Legg has been focusing on tidal mixing occuring near the top of the flanks of tall topography such as the Hawaiian Ridge. In collaboration with members of the Hawaiian Ocean Mixing Experiment, especially Jody Klymak, Legg has carried out simulations of the baroclinic response to tidal forcing across the Hawaiian ridge, and compared them with observations. An interesting feature of these simulations is a region of enhanced overturning and dissipation near the top of the slope. Sensitivity studies carried out with an idealized version of the ridge topography and stratificaiton show that the overturning is associated with an internal hydraulic jump generated during maximum ebb tide, which subsequent to relaxation of the flow propagates toward the slope and breaks at a region of near critical slope. This mixing is highly sensitive to details of the slope, but should be generic to any steeply sloping tall topography topped by a finite region of critical slope. Legg is currently completing 2 manuscripts describing this work, one jointly with the observationalists using the model results to interpret the observations, and one describing the internal hydraulic jumps in the sensitivity study.

All of these simulations have been carried out with the nonhydrostatic MIT model. Legg is involved in ongoing discussions with GFDL researchers to apply these results to parameterizations of mixing in the GFDL climate models, and is also an active participant in discussions concerning the next generation GFDL ocean model, which is planned to have a nonhydrostatic capability.

Publications:

S. Legg and K.M.H.Huijts, 2006: Preliminary simulations of internal waves and mixing generated by finite amplitude tidal flow over isolated topography.Deep Sea Research part II, v53, 140-156.

S. Legg, 2006: Internal hydraulic jumps and overturning generated by tidal flow over a tall, steep ridge. In preparation for submission to Journal of Physical Oceanography.

J.M. Klymak, R. Pinkel, L. Rainville, and S. Legg, 2006: Direct breaking of the internal tide near topography: Kaena Ridge, Hawaii. In preparation for submission to Journal of Physical Oceanography.

Progress Report: **Dense Overflows**

Principal Investigator: Sonya Legg (Princeton Research Oceanographer)

Other Participating Researchers: Robert Hallberg, Laura Jackson, Ulrike Riemenschneider (WHOI postdoc), Steve Griffies, other members of the NSF/NOAA funded Gravity Current Entrainment Climate Process Team.

Theme #1: Earth System Studies/Climate Research

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

Objectives:
To develop improved parameterizations for dense overflows in ocean climate models

Methods and Results/Accomplishments:

Coordinated with the efforts of the gravity current entrainment climate process team, Legg has been examining the ability of z-coordinate models to represent dense overflows at both coarse and high resolutions using the MITgcm in an idealized domain. A principal effort this year has been an examination of the cause of mixing at coarse resolutions. While some researchers have proposed that convective adjustment is responsible for the excessive mixing, in the MITgcm Legg has shown that switching off convective adjustment does not reduce spurious mixing, which must therefore be caused by the advection scheme (explicit diffusivity is also set to zero). A current focus is on the role of vertical viscosity, which in addition to influencing the steepness of descent down the slope, as known from previous studies, also appears to inversely affect the diapycnal mixing - stronger viscosity leads to LESS diapycnal mixing in overflows, at least at intermediate resolutions. This result may be sensitive to the advection scheme used, a possibility to be explored in coming months. Legg is working with Steve Griffies to examine whether similar behavior is seen in MOM4, and to examine the ability of the parameterization schemes such as sigma diffusion to improve the results at low resolution. Ultimately it is intended to draw these results together in a comparison article as a follow-on to Legg et al, 2006.

Legg is also supervising the work of Ulrike Riemenschneider at Woods Hole, examining the ability of z-coordinate models such as the MITgcm to simulate the Faroe Bank Channel overflow, as a complement to the more idealized studies mentioned above. This work is nearing completion and Riemenschneider and Legg are preparing a manuscript for publication. A principal result is that the MITgcm can reproduce the observaitons from the Faroe Bank Channel well at higher resolutions (2km), while at coarse resolutions (50km) both the inability to resolve the narrow features of the topography and the difficulties moving dense fluid downslope lead to problems in simulating the overflow.

Legg has assisted Laura Jackson in using the MITgcm for direct numerical simulations of shear-driven turbulence intended to calibrate and test a new parameterization of shear driven mixing such as in overflows under development by Jackson and Hallberg.

Legg has expended considerable effort in the past year in coordinating the renewal proposal for the Gravity Current Entrainment Climate Process Team, which was ultimately successful, and in organising the CPT workshop held at GFDL in May 2006. Legg also coordinated the writing of a short article reviewing the whole CPT for the US CLIVAR Variations newsletter, and is currently coordinating a synthesis article planned to be submitted to the Bulletin of the American Meteorological Society in the next few months.

Publications:

S. Legg, R.W. Hallberg and J.B. Girton, 2005: Comparison of entrainment in overflows simulated by z-coordinate, isopycnal and nonhydrostatic models. Ocean Modelling, v11, 69-97.

Legg, S. and the members of the gravity current entrainment climate process team, 2006: Gravity Current Entrainment Climate Process Team. US Clivar Variations, v4, p5-7.

Riemenschneider U. and Legg S., 2006: Regional simulations of the Faroe Bank Channel overflow in a level model. In preparation for submission to Journal of Physical Oceanography.

Legg S., S. Griffies, R. Hallberg, G. Danabasoglu, W. Large, J. Yang, J. Price, A. Gordon, E. Chassignet, T. Ozgokmen, H. Peters, T. Ezer, U. Riemenschneider, Y. Chang, L. Jackson and W. Wu, 2006: Improving oceanic overflow representation in climate models: the gravity current entrainment climate process team. In preparation for submission to Bulletin of the American Meteorological Society.

Progress Report: **Brewer-Dobson Circulation in a Changing Climate**

Principal Investigator: Feng Li (Princeton Research Associate)

Other Participating Researchers: John Austin (UCAR), John Wilson (GFDL)

Theme #1: Earth System Studies/Climate Research

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

Objectives:

Investigate the strength of the Brewer-Dobson circulation and its seasonal cycle in a changing climate using the GFDL coupled chemistry-climate model. Evaluate the dynamical performance of the GFDL coupled-chemistry climate model.

Methods and Results/Accomplishments:

Li has been working on two projects during the past year: 1, diagnostics of the stratosphere dynamics in the GFDL coupled chemistry-climate model with a focus on the Brewer-Dobson Circulation (BDC), and 2, investigation of the effects of a gravity wave parameterization scheme on model results.

Multi-decadal simulations of the past (1960-2005) and future (1990-2100) climate were performed using the Atmospheric Model with Transport and Chemistry (AMTRAC). An interesting result is that the model simulated a ~ 30% increase of the tropical upward mass flux in the lower stratosphere during the period 1960 to 2100, consistent with other numerical studies. A changing BDC is important because the strength of the BDC determines troposphere-stratosphere mass exchange and tracer transport in the stratosphere. We found that the tropical mass upwelling and the reciprocal of the age of air is linearly related [Austin and Li, 2006]. It is found that oxidation of increased methane from enhanced tropical upwelling can explain the higher stratosphere water vapor amounts [Austin et al., 2006].

The intensification of the BDC is caused by the enhancement of both the planetary wave activities and the parameterized orographic gravity wave drag. The relative importance of the two processes depends on the location and the season. More interestingly, model results show that the seasonal cycle of the BDC is different in the past and future climate simulations. Analyses show that this discrepancy is primarily due to the behavior of the planetary wave activities in the Southern Hemisphere DJF season, which is closely related to the Antarctic ozone depletion in the past decades and the subsequent recovery in the future.

The main stratospheric dynamical features, such as the strength of the zonal flow and temperature distribution, are reasonably well reproduced in AMTRAC, but a Quasi-Biennial Oscillation (QBO) is absent. In addition, there is a particular warm bias over Antarctic during spring and the axis of the mesospheric jet does not tilt toward the equator with height. The model simulates a Semi-Annual Oscillation (SAO), but it penetrates too deep into the stratosphere and the first westerly phase is too strong. These model biases appear to be related to the implementation of the non-orographic gravity wave parameterization, the Alexander and Dunkerton scheme. One problem of the current implementation is that the gravity wave drag is only applied in the zonal direction, implying an anisotropic gravity wave source. The implementation has been modified to include gravity wave drag in the meridional direction. The major impacts occur in the high-latitude region, where the magnitude of the meridional wind is comparable to that of the zonal wind. Significant change of temperature is found in the polar stratosphere, but the vertical tilting of the jet does not change. Experiments and tuning are being carried on and will be continued in the next year to improve model results.

Publications:

Austin, J., J. Wilson, F. Li, and H. Voemel, Evolution of water vapor and age of air in coupled chemistry-climate model simulations of the stratosphere, accepted by *Journal of the Atmospheric Sciences*, 2006.

Austin, J., and F. Li, On the relationship between the strength of the Brewer-Dobson circulation and the age of stratospheric air, submitted to *Geophysical Research Letter.*

Li, F., J. Austin, and J. Wilson, The strength of the Brewer-Dobson circulation in a changing climate, in preparation, to be submitted to *Journal of Climate*.

Progress Report: **The Distribution Of Mineral Dust In Sh Oceans And High Latitudes**

Principal Investigator: Fuyu Li (Princeton Graduate student)

Other Participating Researchers: V. Ramaswamy (GFDL), Paul Ginoux (GFDL)

Theme #1: Earth System Studies/Climate Research

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

Objectives:
To understand the distribution of dust in the SH oceans and high latitudes, in particular evaluating the contributions from different sources.

Methods and Results/Accomplishments:

Fuyu Li is working with V. Ramaswamy and Paul Ginoux to study the distribution of mineral dust in SH oceans and high latitudes by using a version of GFDL AM2. Basically, in the simulations, Li used a topography related dust emission scheme (Ginoux et al., 2001) with the help of information on desert surfaces (DeFries et al., 1994), topographic depressions and TOMS observations of dust storm frequency.

Li has simulated the distribution of dust in the low latitudes of SH, the Southern Oceans and the high latitudes. He has isolated the contributions from the different sources in SH, as well as differentiated the contribution of NH from SH. Thus, he has identified the major causes of the burdens in the high southern latitudes, as well as those sources that are responsible for deposition in the Antarctic.

The results show that the simulation using a topography related dust emission scheme can yield reasonable estimate of dust in SH. We identify three major sources in SH. In Southern Ocean, very little South Africa dust can be seen. In the surface and lower troposphere, concentrations are due to South America and Australia. In Antarctica, the upper troposphere dust is mainly from NH and Australia, while that in lower troposphere is from South America.For total dust burden, NH dust can account for ~40% dust burden in Antarctica, while south America and Australia have comparable contributions. As for the dust deposition, the contribution in SH oceans and high latitudes is essentially from Australia and South America. Over Antarctica, NH's contribution to total deposition is less than that to dust burden.

References:

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Prospero, J. M., P. Ginoux, O. Torres, S. E. Nicholson, and T. E. Gill, 2002: Environmental characterization of global sources of atmospheric soil dust identified with the NIMBUS 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product. Reviews of Geophysics, 40(1), 1002, doi:10.1029/2000RG000095.

Progress Report: **Constraining Oceanic Circulation And Basal Melting Rates Beneath Ice Shelves**

Principal Investigator: Christopher Little (Princeton graduate student)

Other Participating Researchers: Anand Gnanadesikan (GFDL/Princeton), Michael Oppenheimer (Princeton), Robert Hallberg (GFDL)

Theme #1: Earth System Studies/Climate Research

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

Objectives:
The melting of ice shelves from beneath due to oceanic heat transport constitutes a loss of ice from the cryosphere and a source of freshwater to the ocean; it also influences ice sheet (Antarctic and Greenland) dynamics. My overarching goals are to understand the factors controlling the location and rate of basal melting, as well as its sensitivity to changed oceanic conditions, and its influence on ice shelf/sheet stability, oceanic freshwater balance, and global climate.

Methods and Results/Accomplishments:
I rely primarily on numerical ocean models (primarily the Hallberg Isopycnal Model) to describe the transport and mixing of water masses and heat. I have divided my research into four phases (see table), in which the complexity of the model and the physical processes it represents are incrementally increased.

PHASE	KEY PROCESS INVESTIGATED	KEY VARIABLES	MODEL CONFIGURATION
I	• **Topographic control** • **Role of eddies**	• **Ice shelf draft** • **Bathymetry**	• **Surface pressure field** • **Two layers**
II	• **Top and bottom boundary layers**	• **Boundary layer thickness** • **Vertical viscosity**	• **Ice-ocean frictional interface** • **Additional isopycnal layers**
III	• **Melt rate sensitivity to imposed heat fluxes**	• **Melt/freeze parameterization**	• **Thermodynamically active ice-ocean interface**
IV	• **Communication with the open ocean**	• **Temporally and spatially variable forcing**	• **Ice shelf front**

By the end of the summer, I anticipate publishing the results of phase I and completing the development of a more realistic ice interface. This model will allow an investigation of the mechanisms by which advected heat drives basal melting, including tides, winds, and open ocean dynamics. It is also the first step towards integrating the sub-ice shelf circulation with that of the open ocean circulation.

Progress Report: **Aerosols, Clouds And Climate**

Principal Investigator: Vaughan Phillips (Princeton Research Staff)

Other Participating Researchers: L. Donner, V. Ramaswamy, Y. Ming, C. Seman (GFDL)

Theme #1: Earth System Studies/Climate Research

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:
To assess the aerosol interaction with deep convection

Methods and Results/Accomplishments:
A representation of the aerosol interaction with deep cumulus clouds has been incorporated into the GFDL General Circulation Model (GCM). Number concentrations of droplets and crystals are now predicted from fields of multiple aerosol species in the parametrisation of deep convective towers in the GCM. This enables the microphysical and dynamical evolution of the clouds to be predicted accurately. Preliminary GCM runs for a period of 4 years have been compared with global observations. Predicted rates of precipitation over Amazonia have improved. Further off-line development of this new version of the convection scheme (Donner 1993) is being performed, in comparison with observations from cases over the tropical oceans.

References:
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Publications:
Phillips, V. T. J., A. Pokrovsky, and A. Khain, "The influence of time-dependent melting on the dynamics and precipitation production in maritime and continental storm-clouds", J. Atmos. Sci. In press (2006)

Sherwood, S., V. T. J. Phillips, and J. S. Wettlaufer, "Small ice crystals and the climatology of lightning", Geophys. Res. Lett., 33, L05804, doi:10.1029/2005GL025242 (2006)

Andronache, C., T. Gronholm, L. Laakso, V. T. J. Phillips, and A. Venalainen, "Ultra-fine particle scavenging by rainfall at a boreal site: observations and model estimates", Atmos. Chem. Phys. Discuss., 6, 3801-3844 (2006)

Phillips, V. T. J. S. C. Sherwood, C. Andronache, and co-authors, "Anvil glaciation in a deep cumulus updraft over Florida simulated with an Explicit Microphysics Model. I: The impact of various nucleation processes", Q. J. R. Meteorol. Soc., 131, 2019-2046 (2005)

Ming, Y., V. Ramaswamy, L. J. Donner, and V. T. J. Phillips, "A new parameterization of cloud droplet activation applicable to general circulation models", J. Atmos. Sci., 63, 1348-1356 (2006)

Phillips, V. T. J., L. J. Donner, and S. Garner, "Nucleation processes in deep convection simulated by a cloud-system resolving model with double-moment bulk microphysics and interactive radiation", in revision for J. Atmos. Sci. (2006)

Phillips, V. T. J. and L. J. Donner, "Cloud microphysics, radiation and vertical velocities in two- and three-dimensional simulations of deep convection", in revision for Q. J. R. Meteorol. Soc. (2006)

Progress Report: **Climate Effects Of Carbonaceous Aerosol**

Principal Investigator: Cynthia A. Randles (Princeton graduate student)

Other Participating Researchers: V. Ramaswamy (Graduate Advisor, GFDL), Paul Ginoux (GFDL, Committee Member), Hiram Levy III (GFDL, Committee Member), Lynn M. Russell (Scripps Institution of Oceanography, Committee Member), Omar Torres (NASA Goddard Space Flight Center, collaborator)

Theme #1: Earth System Studies/Climate Research

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

Objectives:
To understand the climatic effects of black and organic carbon (BC and OC) from anthropogenic and biomass burning sources.

Methods and Results/Accomplishments:

Using a thermodynamic equilibrium hygroscopic growth model coupled to a Mie scattering model, Randles has investigated the climatic effects of internal mixtures of organic carbon (OC) and sea salt. This work showed that the reduction in hygroscopic growth accompanying increases in OC could significantly reduce the scattering, and thus cooling, associated with pure sea salt aerosol. The work highlighted that the uncertainty in the absorption of OC can cause an even greater reduction in cooling over the oceans and that similar effects can be seen for mixtures of OC and sulfate. Thus, this study showed that if water-soluble organic carbon is associated with sulfates and sea salt, the global radiative cooling associated with organic compounds is overestimated because of inadequate accounting of OC hygroscopic growth and absorption effects, making it imperative that evaluations of aerosol climate effects consider these physical processes explicitly.

With the previous work culminating in a publication (see below), Randles is now examining the climatic effects of black carbon (BC) over Asia. In this study, she is employing the Geophysical Fluid Dynamic Laboratory's atmospheric Global Climate Model (GCM) AM2 to examine the impact of increased BC (and thus increased absorption) over China and India. In this study, AM2 is being run with fixed sea-surface temperatures (SSTs) and greenhouse gasses (GHGs) so that only the impact of aerosol changes is considered. This work aims to augment the studies of Menon et. al [2002], Chung and Ramanathan [2002], and Ramanathan et. al. [2005] by focusing attention on changes in the surface energy balance as well as changes in the vertical temperature profile, the surface termperature, and the hydrologic cycle resulting from (1) increased absorption due to increased BC, (2) increased optical depth and increased absorption (3) increased optical depth due to hygroscopic growth, and (3) changes in the vertical distribution of BC absorption.

Randles is also looking at the effects of biomass burning OC and BC over Southern Africa. The GFDL GCM is bein used to investigate climate forcing and response to realistic biomass burning aerosol fields from remotely sensed and in situ aerosol spatial distributions and optical properties. Biomass burning over southern Africa in 2000 is being considered due to the plethora of data associated with the SAFARI 2000 field campaign . Measurements of aerosol extinction optical thickness (τext) and single-scattering albedo (ω) from both ground-based and satellite-based remote sensing platforms and in situ data will be incorporated into the GCM [Haywood et. al., 2003a; Haywood et. al., 2003b; Kiel and Haywood, 2003; Torres et. al., 2005] . Uncertainty associated with biomass aerosol direct and semi-direct forcing is constrained by detailed sensitivity studies of forcing to the parameters τext and ω. Model response to the imposed spatial and optical aerosol properties is being studied, with particular attention to

the response of the hydrologic cycle and the surface energy balance. The results will help to constrain the uncertainty associated with biomass burning aerosol forcing and climate response.

References:

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Haywood, J.M., S.R. Osborne, P.N. Francis, A. Keil, P. Formenti, M.O. Andreae, and P.H. Kaye, (2003b) The mean physical and optical properties of regional haze dominated by biomass burning aerosol measured from the C-130 aircraft during SAFARI 2000, J. Geophys. Res., 108 (D13), 8473, doi:10.1029/2002JD002226.

Keil, A., and J.M. Haywood (2003), Solar radiative forcing by biomass burning aerosol particles during SAFARI 2000: A case study based on measured aerosol and cloud properties, J. Geophys. Res., 108 (D13), 8467, doi:10.1029/2002JD002315.

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Progress Report: **Characteristics Of The Atlantic Storm-Track Eddy Activity And Its Relation With The North Atlantic Oscillation**

Principal Investigator: Gwendal Rivière (Princeton Research Associate)

Other Participating Researchers: Isidoro Orlanski (GFDL)

Theme #1: Earth System Studies/Climate Research

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

Objectives:
To understand the mechanism of the North Atlantic Oscillation

Methods and Results/Accomplishments:

The aim of Riviere's research is to provide a better understanding of the Atlantic storm track variability and trends. Our study focuses on feedbacks of the high frequency eddy activity onto the quasi-stationary circulation, particularly with regard to the North Atlantic Oscillation (NAO). The work consists of the analysis of observations using NCEP reanalysis data, and of numerical simulations from the high resolution non hydrostatic regional model (ZETAC) developed at GFDL.

The first objective, using NCEP reanalysis dataset was to confirm (following the recent results of Orlanski, 2003 and Benedict et al. 2004) that the jet displacement characteristic of the NAO phenomenon depends strongly on the dynamics of the high frequency synoptic-scale waves and the way they break. Positive and negative phases of the NAO are closely related to anticyclonic and cyclonic wave breaking respectively. Indeed, the monthly average of the high-frequency momentum fluxes whose sign is directly related to the type of wave breaking is shown to be correlated with the monthly NAO index over the Atlantic. Furthermore, a daily analysis indicates that the signal associated with the high-frequency fluxes precedes that of the NAO by a few days suggesting that wave breaking is triggering NAO events.

The previous statistical results have been illustrated by analyzing particular events. It has been shown that single storms, in particular those occurring in the East coast of the US, can have a significant impact on the NAO index. The wave breaking at the end of the life cycle of these particular storms can suddenly change the NAO index in few days and as the return to equilibrium takes generally a longer time, it can even affect the sign of the NAO during few weeks.

The second objective, using numerical simulations of the ZETAC model, was to reproduce a similar behavior to that previously shown in reanalysis data and to explain it by performing a number of sensitivity runs by modifying different parameters. We focused on two consecutive months (December 1987 and January 1988) which are particularly interesting to study since they correspond to negative and positive phases of the NAO.We successfully reproduce the behavior of these two months with the regional ZETAC model by forcing it with real SST and a western boundary condition corresponding to the reanalysis data over the Eastern Pacific. Sensitivity runs prove that the difference between the two months is not due to SST but rather to the western boundary condition showing that the properties of the waves coming from the Pacific are crucial to determine the North Atlantic Oscillation.

All the above results have already been presented in a paper which is accepted for publication in Journal of Atmospheric Sciences. They are not only useful for explaining the intraseasonal variations of the NAO but would serve also as a basis for understanding its interannual and interdecadal variations.

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Publications:

G. Rivière, and I. Orlanski, 2006: Characteristics of the Atlantic Storm-track eddy activity and its relation with the North Atlantic Oscillation. Journal of Atmospheric Sciences, accepted.

Progress Report: **Space-Time Variability of Soil Moisture**

Principal Investigator: Ignacio Rodriguez-Iturbe (Princeton Faculty)

Other Participating Researchers: Salvatore Manfreda (Princeton), Sir David R.Cox (Oxford), Valerie Isham (University College, London), and Amilcare Porporato (Duke)

Theme #1: Earth System Studies/Climate Research

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

Objectives:
Characterizing the spatial dynamics of soil moisture fields is a key issue in hydrology, offering an avenue to improve our understanding of complex land surface-atmosphere interactions. The main objective of the present research was to investigate on the spatial structure of soil moisture fields and to develop a theoretical framework for the modeling of the space-time variability of soil moisture. Of particular interest is the space-time correlation structure of soil moisture that may be used to obtain the sampling requirements to estimate the averaged soil moisture content - in space and/or in space and time -with a prescribed statistical variance of estimation.

Methods and Results/Accomplishments:
Recent work by Isham et al. (2005) and Rodrìguez-Iturbe et al. (2006) has characterized the space-time variability of soil moisture through its covariance function which depends on soil properties, vegetation structure and rainfall patterns typical of a region. The present research used such characterization to address the strategies and methodologies for the sampling of soil-moisture fields. The focus was on the estimation of the long-term mean soil moisture and the daily soil moisture averaged over a given area as a function of the network geometry, number of stations, number of sampling days and landscape heterogeneity using the mathematical framework developed by Rodrìguez-Iturbe and Mejìa (1974). It was found that the spatial geometry of the network has a significant impact on the sampling of the average soil moisture over an area in any particular day, while it is much less relevant for the sampling of the long-term mean daily soil moisture over the region. In the latter case, the length of the record is a commanding factor in what concerns the variance of estimation, specially for soils with shallow rooted vegetation. Spatial vegetation heterogeneity plays an important role on the variance of estimation of the soil moisture, being particularly critical for the sampling of the average soil moisture over an area for a given day.

Further investigation on the soil moisture structure were carried out using the spatial patterns of soil moisture obtained via numerical simulation. In particular, the statistical structure of soil moisture patterns was examined using modelled soil moisture obtained from the North American Land Data Assimilation System (NLDAS) at 0.125 degrees resolution. The study focused on the vertically averaged soil moisture in the top 10 cm and 100 cm layers. The two variables display a weak dependence for lower values of surface soil moisture, with the strength of the relationship increasing with the water content of the top layer. In both cases, the variance of the soil moisture follows a power law decay as a function of the averaging area. The superficial layer shows a lower degree of spatial organization and higher temporal variability, which is reflected in rapid changes in time of the slope of the scaling functions of the soil moisture variance. Conversely, the soil moisture in the top 100 cm has lower variability in time and larger spatial correlation. The scaling of these patterns was found to be controlled by the changes in the soil water content. Results have implications for the downscaling of soil moisture to prevent model bias.

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Publications:

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Rodrìguez-Iturbe, I., V. Isham, D.R. Cox, S. Manfreda, A. Porporato, Space-time modeling of soil moisture: Stochastic rainfall forcing with heterogeneous vegetation, Water Resources Research, 42, W06D05, 2006.

Progress Report: **Scalable Performance And Parallel Programming Models**

Principal Investigator: Jaswinder Pal Singh (Professor, Computer Science Department)

Other Participating Researchers: Adrian Soviani (Computer Science Department)

Theme #1: Earth System Studies/Climate Research

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

Objectives:
To understand how to greatly improve scalability of the NOAA MOM application and others in the FMS framework, building any necessary tools in the process. To design and develop programming models that make parallel programming easier for this class of applications.

Methods and Results/Accomplishments:

Briefly, we analyzed the performance of another major GFDL application that is part of the FMS framework, building and extending new timing tools to be able to measure time spent in different portions of the code and different operations in an extremely flexible, granular and powerful way. For example, by discovering exactly what kinds of communication patterns were taking a lot of time, and being able to relate that back to what the application was actually trying to achieve, we were able to redesign a major repeatedly used communication pattern in a way that dramatically reduced the number of small messages and greatly improved performance, at the cost of a small amount of memory (which was not a critical resource). Other improvements were also made which improved performance and scalability substantially. The input-output behavior of the programs and its impact on performance and scalability was understood and methods to improve it designed. The methods and results were presented to GFDL scientists and modelers.

We have developed a new programming model with general applicability but especially well suited to a class of applications that closely reflects NOAA/GFDL's needs. The idea of this model is to allow scientists to specify sequential routines rather than worry about parallelism, and to simply at a high level specify the data needs of their routines. The runtime system then handles and optimizes the communication, and also restructures the computational and data movement flow to optimize performance and scalability. The programming model also makes it much easier to reason about parallel performance, which is a key area of difficulty in programming for performance. Having designed and refined the model, presented it to GFDL researchers and received feedback, and tried it on two types of NOAA/GFDL applications in principle, we are now working on further refinements to it as well as on building a runtime library.

Publications:

None specifically. Presentations made to GFDL scientists and researchers, and in PICASso program seminar series.

Progress Report: **Tropical Cyclone Radius of Maximum Wind: Investigation with an Axisymmetric Model**

Principal Investigator: Agnieszka Smith-Mrowiec (Princeton Graduate Student)

Other Participating Researchers: Princeton Advisor: Stephen Garner, Olivier Pauluis (NYU)

Theme #1: Earth System Studies/Climate Research

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

Objectives:
To understand mechanisms responsible for setting hurricane's Radius of Maximum Wind.

Methods and Results/Accomplishments:

Hurricanes wreak devastation on costal communities each year, causing loss of life and billions of dollars of damage. Nevertheless, many basic aspects of the dynamics that control the formation and steady state parameters of a hurricane are not understood and hence not predictable. One example is the horizontal size of a hurricane. A typical hurricane is nearly axisymmetric, and has an axial wind profile that achieves a maximum at some distance from its center. This distance is called the Radius of Maximum Wind (RMW), and is one of the most important dynamical parameters necessary to describe any given hurricane. Understanding it's dynamics would be invaluable when assessing possible disaster range at landfall. Not much is known about what sets the RMW. Based on previous studies (Mallen & Montgomery 2005) it is clear, though, that there is no simple correlation between RMW and other parameters, such as maximum wind speed, minimum central pressure or sea surface temperature.

Smith-Mrowiec has been working with Garner and Pauluis to investigate what sets the RMW. This is an ongoing project. The investigation involves the use of an axisymmetric, nonhydrostatic hurricane model (ZETAC). The model uses the GFDL radiation package and Lin microphysics and convection is fully resolved. The resolution of the model is 1 km at this point and the domain size is 500 km. Simulations are usually made for 15 days of hurricane life, with the objective of generating a steady state and investigating how the RMW depends on model parameters. We have set up the model to run in both 2D and 3D. 3D is interesting because convective dynamics is altered and also the azimuthal wave instability can be observed.

Right now we are studying the correlation of the RMW with a quantity called Maximum Potential Intensity (MPI - see Emanuel, 1988,1995,2003, Holland 1996). Hurricanes derive their energy from the thermodynamic disequilibrium between the tropical oceans and the atmosphere, and the MPI quantitatively summarizes this. Emanuel's maximum potential intensity theory predicts an upper limit for the maximum wind, depending mostly on the sea surface temperature, atmosphere temperature and the efficiency of the heat conversion into wind energy. We will use the Emmanuel theory as a basis from which to approach the underlying dynamics controlling the RMW (see figure below).

References:

Emanuel, K. A., 1988: The maximum intensity of hurricanes. J. Atmos. Sci., 45, 1143–1155.

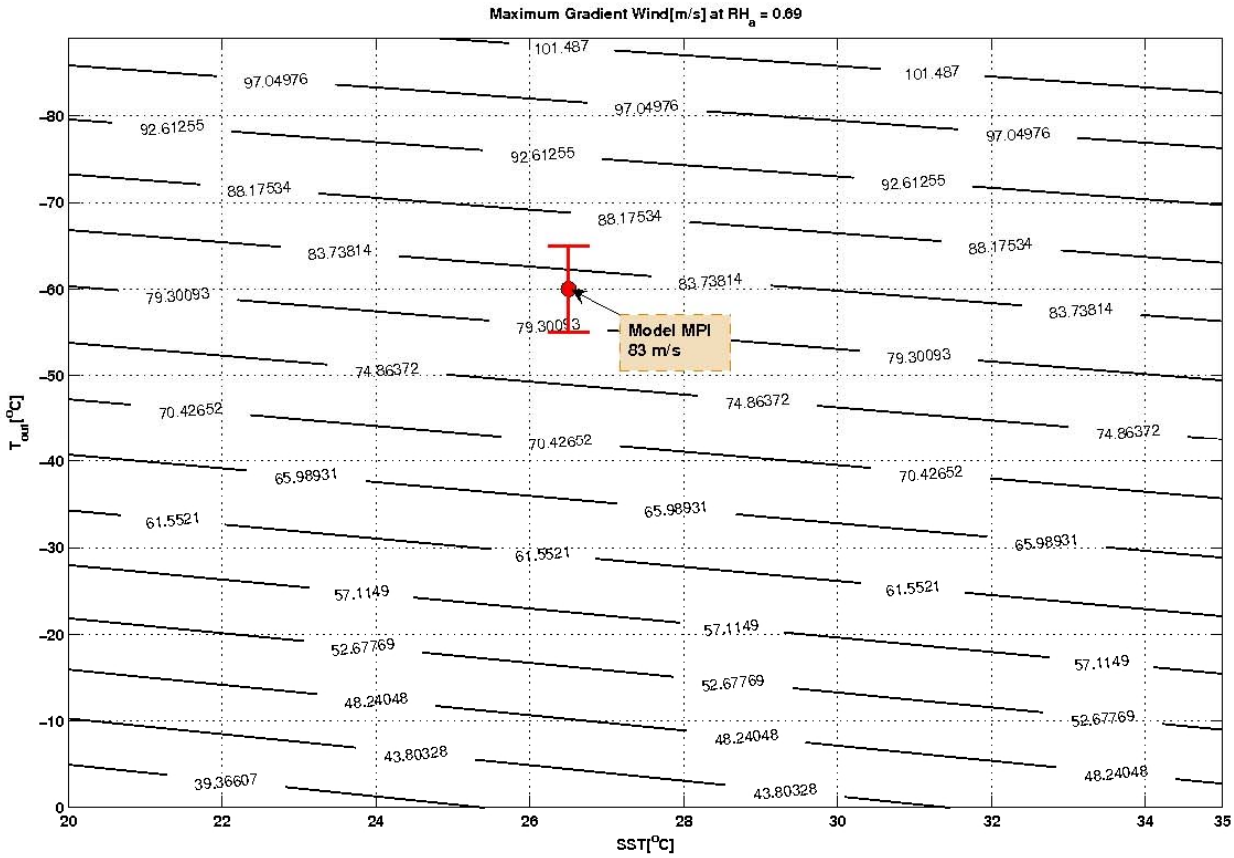
Emanuel, K. A., 1995: Sensitivity of tropical cyclones to surface exchange coefficients and a revised steady-state model incorporating eye dynamics. J. Atmos. Sci., 52, 3969-3976.

Holland, G., 1996: The maximum potential intensity of tropical cyclones. J. Atmos. Sci.

Emanuel, K., 2003: Tropical Cyclones. Ann Rev. Earth Planet. Sci., 31, 75-104

Mallen and Montgomery 2005: "Reexamining the Near - Core Radial Structure of the Tropical Cyclone Primary Circulation: Implications for Vortex Resiliency", J. Atmos. Sci., 62

figure: Maximum gradient wind derived from Emanuel's MPI theory (black contour) and example model maximum gradient wind plotted in the same figure.



Progress Report: **Dynamics of the Indian Ocean Variability**

Principal Investigator: Qian Song (Princeton Research Associate)

Other Participating Researchers: Tony Rosati (GFDL), Gabriel Vecchi (UCAR)

Theme #1: Earth System Studies/Climate Research

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

Objectives:
To understand the dynamics of the interannual variability of the Indian Ocean and its relation with ENSO.

Methods and Results/Accomplishments:
In 2006, I have been working on two projects using the GFDL CM2.1 coupled climate model. Detailed description of the projects is as follows.

(1) Effects of the Indonesian Throughflow (ITF) on the global climate. (a presentation was made at the 2005 AGU fall meeting and as a GFDL lunchtime seminar, and a manuscript is in preparation for *J. Clim.*)

We, for the first time, investigated the effects of the ITF on the interannual variability of the tropical Indo-Pacific domain using the GFDL CM2.1 coupled climate model. Our approach was to compare two experiments, one with the ITF passages open and the other with them closed. The differences between the two experiments show that the interannual variability in the equatorial Pacific and the eastern tropical Indian Ocean is substantially intensified by the closure of the ITF. In addition to becoming more energetic, ENSO exhibits a shorter timescale of variability and becomes more skewed toward its warm phase. In the eastern tropical Indian Ocean, the interannual SST variability off the coast of Java/Sumatra is noticeably amplified by the occurrence of much stronger cooling events. These results suggest that coupled general circulation models need to reasonably simulate the ITF in order to successfully represent not just the mean climate, but its variations as well.

(2) Dynamics and predictability of the Indian Ocean Dipole (IOD) (a seminar was given at the Center for Ocean-Land-Atmosphere Studies, and a paper is in press in *J. Clim*, and another paper is in preparation for *Geophys. Res. Lett.*)

We first explored the air-sea coupled dynamics of the IOD and its relationship with ENSO in the 300-yr 1990-control simulation in the GFDL CM2.1 coupled model, through a composite analysis. One of the major findings of this study is that IOD events are often preceded by distinctive Indo-Pacific warm pool anomaly patterns in boreal spring: in the central Indian Ocean easterly surface winds, and in the western equatorial Pacific an eastward shift of deep convection, westerly surface winds and warm sea surface temperature.

Our next step was to test the precursor hypothesis through perturbation experiments with the CM2.1 coupled model. We first selected a few IOD events from the control simulation and conducted perturbation simulations for each event, by modifying oceanic initial conditions or disabling air-sea coupling in various regions. This research is in progress.

We also studied the predictability of the occurrence of IOD events (in collaboration with Drs. Gabriel A. Vecchi and Tony Rosati). Our approach is to perform ensemble simulations (same oceanic initial conditions but difference atmospheric initial conditions) of the IOD events randomly selected from the control simulation. We find that the occurrence of some IODZM events is preconditioned by oceanic

conditions and potentially predictable two to three seasons in advance, while other IODZM events appear to be triggered by weather noise and has low predictability. The same result is also observed in the IOD forecast during 1990s in the GFDL seasonal forecast system. For instance, the 1997 IOD event appears to be more predictable than the 1994 event.

Publications:

Song, Q., G.A. Vecchi, and A. Rosati, 2006: The role of the Indonesian Throughflow in the Indo-Pacific climate. Journal of Climate (in press).

Song, Q., G.A. Vecchi, and A. Rosati, 2006: On the predictability of the Indian Ocean sea surface temperature anomalies. Geophysical Research Letters. (in preparation).

Progress Report: **Development of an Experimental 4d Assimilation and ENSO Prediction System Based on the Latest MOM4 GFDL Model**
(Part of a collaborative effort of GFDL, JPL and Harvard)

Principal Investigator: Eli Tziperman (Harvard Professor)

Other Participating Researchers: Jake Gebbie (Harvard), Tony Rosati, Matt Harrison, Andrew Wittenberg, and Shaoqing Zhang (GFDL), Tony Lee, Benny Cheng, and Ichiro Fukumori (JPL)

Theme #1: Earth System Studies/Climate Research

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

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. Geoffrey (Jake) Gebbie has coordinated the effort of all three institutions, as well as carried out the bulk of the work at Harvard on this project. Jake also coordinated with Ralf Giering the significant work that was required to improve the adjoint compiler to make it compatible with the adjoint 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 with the JPL scientists. Together we 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 are being carried out by GFDL, Harvard, and JPL, correspondingly. Some of the work on these stages was carried out in parallel. Stage (1) at GFDL is close to being completed (still need to do this for the momentum equations). Good progress was achieved on (2) at Harvard. At this stage the adjoint for the tracer equations, a partial adjoint for the momentum equations and some work on the physics packages (KPP, neutral physics) is completed. Jake sent the adjoint code to JPL and they were able to complete the parallelization work of stage (3). The adjoint to the external forcing routines was recently completed as well, as well as the implementation of many different types of cost functions, including global sums, Gaussian (in space) cost structure, and more. Fig. 1 shows the adjoint model results for a preliminary test case calculation using the global model configuration and a parallel version of the adjoint code.

The adjoint is derived using the TAF adjoint compiler; "recomputation" and "storage" directives have been added to the forward code, and a preliminary checkpointing scheme has been implemented. This involved adding comments to the MOM4 code that will be interpreted by the adjoint compiler to store a forward model variable in order to use it in the adjoint run.

We plan to have all work done so far merged from the CVS built for the adjoint project into the general MOM4 CVS code within the next few weeks for easy access and use by the wider community. In the past year, the adjoint of the parallelization routines has been added to the GFDL CVS repository. After quite a bit of work, we now use the 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 been meeting Tony, Matt, Andrew and Shaoqing regularly, including meetings at GFDL in October, 2005, and February, 2006, and attendance at the larger ECCO meeting in Cambridge, Massachusetts, in January, 2006.

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 1-2 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).

While working on the adjoint model, we have also completed a manuscript using the hybrid coupled forward model to be adjointed to study the role of westerly wind bursts.

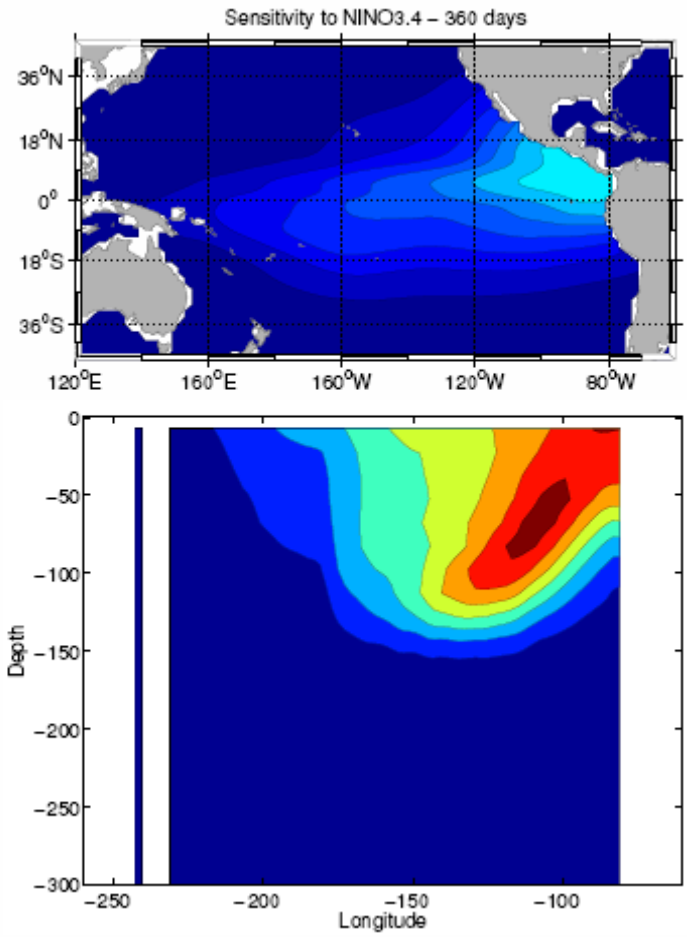


Figure 1: Adjoint-calculated sensitivity results from the MOM4 parallelized (16-pe), adjoint advection-diffusion model over a one-year integration. The sensitivity is defined as the gradient of the NINO 3.4 index with respect to the temperature field one year earlier. The sensitivity field has the units of [degrees C/degree C]. The left panel shows the sensitivity of the NINO 3.4 index to SST one year earlier, and the right panel shows the sensitivity with respect to a section of the temperature field along the equator. The adjoint code has been developed for use with the tripolar grid, telescoping horizontal resolution in the tropics, and a 16-processor decomposed domain for parallel computations (the adjoint code now allows for any number of processors).

(Gebbie et al., 2006), and we anticipate being able to use the adjoint code itself for a scientific sensitivity study within the next year of the project. 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:

Gebbie, G., Eisenman, I., Wittenberg, A., and Tziperman, E. (2006). Modulation of westerly wind burst occurrence by warm pool sst as an intrinsic part of enso's dynamics. *Submitted*.

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.

Progress Report: **Resolving and Parameterizing Convection in Weather and Climate Models.**

Principal Investigator: Geoffrey K.Vallis (Princeton Professor)

Other Participating Researchers: Steve Garner (GFDL), Isaac Held (GFDL), Olivier Pauluis (NYU), Dargan Frierson (U. Chicago)

Theme #1: Earth System Studies/Climate Research

NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond (60%)
NOAA's Goal #3: Serve Society's Needs for Weather and Water Information (40%)

Objectives:
To investigate the interaction of convection with large-scale flow, and to develop an improved parameterization scheme for convection.

Methods and Results/Accomplishments:
We have investigated a new method for incorporating small-scale convection in large-scale atmospheric models. In the atmosphere, convection occurs at a much smaller scale than the grid scale, not only in climate models, but even in fine resolution models that are designed for weather forecasting. Typically, complicated convective parameterization schemes have been designed to parameterize convection. We have explored a method that does not parameterize convection per se, but rather, by a simple modification of the equations of motion, allows the convection to occur at a larger scale. We have implemented the method in two classes of models. In one class, we use the method in a low-resolution model covering the entire Earth. In the second, we use the method in higher resolution studies, and compare with a model that explicitly resolves the convection. Preliminary results are encouraging.

Publications:
Garner, S., Frierson, D., Held, I, Pauluis, O and Vallis, G. K. 2006. Resolving convection in a global hypohydrostatic Model. Submitted to J. Atmos. Sci.

Pauluis, O., Frierson, D., Garner, S., Held, I. M. and Vallis, G. K. 2006:The hypohydrostatic rescaling and its impacts on atmosphericconvection.Theoretical and Comp.Fluid Dyn.(in press).

Progress Report: **Ocean Circulation Studies**

Principal Investigator: Geoffrey Vallis (Princeton Faculty)

Other Participating Researchers: Jolene Loving (UCSC), Rong Zhang (Princeton)

Theme #1: Earth System Studies/Climate Research

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

Objectives:
To better understand the large-scale circulation of the ocean, and its interaction with the climate system as a whole.

Methods and Results/Accomplishments:
The P.I. has been involved in a variety of projects on the ocean circulation. Some of these are described elsewhere in this report (see, for example, the reports by Farneti, Fuckar and Zhao). In addition to the work described therein, we have:

1. Developed a model of climate variability on long timescales, and in particular of so-called Dansgaard-Oeschger oscillations (Loving and Vallis, 2006). These is the largest mde of climate variability on century to millenial timescales, and may be relevant to abrupt climate change in todays climate.

2. Developed a theory of the formation and maintenance of mode water, or 18 degree water, in the subtropical gyres.

3. Shown how Great Salinity anomalies can affect the climate of the Atlantic on interannaul to decadal timescales.

Publications:
Zhang, R. and Vallis, G. K.2006. Impact of Great Salinity Anomalies on the Low Frequency Variability of the North Atlantic Climate. J. Climate., (in press).

Dewar, W. D., R. S. Samelson and G. K. Vallis. 2005. The ventilated pool: A model of subtropical mode water. J. Phys. Oceanogr., 35, 137-150.

Henning, C and Vallis, G. K. 2005. The Effects of Mesoscale Eddies on the Stratification and Transport of an Ocean with a Circumpolar Channel. J. Phys. Oceanogr., 35, 880–896.

Loving, Jolene L., and Geoffrey K. Vallis, 2005. Mechanisms for climate variability during glacial and interglacial periods. Paleoceanography, 20, PA4024, doi:10.1029/2004PA00111

Progress Report: **Management Of Tropospheric Ozone By Reducing Methane Emissions**

Principal Investigator: J. Jason West (Princeton Associate Research Scholar)

Other Participating Researchers: Arlene M. Fiore (GFDL), Larry W. Horowitz (GFDL), Vaishali Naik (Princeton), Denise L. Mauzerall (Princeton)

Theme #1: Earth System Studies/Climate Research

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

Objectives:
To model the effects of emissions of ozone precursors (methane, nitrogen oxides, carbon monoxide, and volatile organic compounds) on radiative forcing of climate, and on global surface air quality due to ozone and particulate matter. Also, to quantify the impacts on human health of changes in ozone due to mitigation of methane emissions

Methods and Results/Accomplishments:

Using the MOZART-2 model of atmospheric chemistry-transport, we studied the effects of changes in methane emissions on global concentrations of ozone. We find that a 20% reduction in current global anthropogenic methane emissions would decrease 8-hr. surface ozone in populated regions by ~1 ppbv, with fairly uniform decreases in surface ozone globally. Using epidemiological relationships between methane and ozone, we then estimated the global health benefits resulting from this global decrease in ozone. We estimate that roughly 30,000 premature mortalities can be avoided in the year 2030, due to this 20% methane reduction. In addition, we find that when these health benefits are monetized, they can exceed the costs of the methane reduction (West et al., 2006).

This work has recently been extended by considering the comparative effects of reductions in emissions of ozone precursors (methane, nitrogen oxides, carbon monoxide, and non-methane volatile organic compounds) on metrics of both surface ozone air quality and the radiative forcing of climate. We use the MOZART-2 model to consider 20% reductions in global anthropogenic emissions of each precursor individually, and the GFDL radiative transfer model (from AM2) to estimate the radiative forcing due to changes in ozone. Results show that the methane reduction causes the greatest negative radiative forcing, while the reduction in NOx emissions causes the greatest change in population-weighted metrics of surface ozone concentration. We also show that reducing methane causes the greatest reduction in net radiative forcing per unit improvement in ozone air quality. Of the means to improve ozone air quality, therefore, mitigation of methane emissions best reduces climate forcing (West et al., submitted).

Altogether, this research highlights the mitigation of methane emissions as a cost-effective means for international ozone air quality management, which has concurrent benefits in reducing greenhouse warming.

Related to this work, Dr. West contributed to a study of the global budget of atmospheric methane over the period 1990-2004 (Fiore et al., 2006). Dr. West has further begun writing a paper on the inter-continental transport of ozone, due to emissions of NOx from different world regions (West et al., in preparation).

Publications:

West, J. J., A. M. Fiore, L. W. Horowitz, and D. L. Mauzerall (2006) Global health benefits of mitigating ozone pollution with methane emission controls, Proceedings of the National Academy of Sciences, 103(11): 3988-3993, doi: 10.1073/pnas.0600201103.

West, J. J., A. M. Fiore, V. Naik, L. W. Horowitz, M. D. Schwarzkopf, and D. L. Mauzerall (submitted) Ozone air quality and radiative forcing consequences of changes in ozone precursor emissions, Geophysical Research Letters.

Fiore, A. M., L. W. Horowitz, E. J. Dlugokencky, and J. J. West (2006) Impact of meteorology and emissions on methane trends, 1990-2004, Geophysical Research Letters, 33: L12809, doi: 10.1029/2006GL026199.

West, J. J., V. Naik, L. W. Horowitz, and D. L. Mauzerall (in preparation) Ozone long-range transport: effect of regional NOx emission controls, Atmospheric Environment.

Progress Report: A Hydrologic Ensemble Seasonal Forecast System over the Eastern US

Principal Investigator: Eric F. Wood (Princeton Professor)

Other Participating Researchers*:* Lifeng Luo (Princeton Research Associate)

***Theme #*1:** Earth System Study/Climate Research

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:

"Progress in diagnosing, modeling and predicting seasonal climate variability represents a major scientific advancement of the 20th century, however, progress in the effective utilization of forecasts has lagged behind" (Goddard et al., 2001). This research builds on an experimental seasonal hydrologic forecast system in the Ohio River basin to address a central scientific question of whether seasonal climate predictions have sufficient skill to provide useful hydrologic forecasts and water management information across the eastern U.S., as well as consider how seasonal hydrologic predictions can be made most skillful given the climate predictions, and how this skill can be quantified.

The project focuses over the eastern U.S., and carries out the following two major activities:

1) The development of an expanded Eastern U.S. hydrologic ensemble forecast system that will include all basins east of the Mississippi main stem up to the mouth of the Ohio River.

2) An evaluation and analysis of the resulting seasonal hydrological predictions, with a focus on understanding the reliability of the ensemble forecasts and the overall uncertainty in the hydrologic ensembles due to model (seasonal climate and hydrologic) uncertainty, calibration uncertainty, data uncertainty, and so forth.

The project will enhance NOAA operational activities by extending current links to the NCEP-lead LDAS activities, by providing results useful for the NWS/HDL proposed water initiative and by demonstrating the usefulness of the seasonal hydrologic forecasts through application studies.

Methods and Results/Accomplishments:

The major research activities during last year can be summarized as the following:

- Implementation of the methodology for producing multiple climate model based seasonal hydrologic forecasting
- Validation and evaluation of the seasonal hydrologic ensemble prediction system over the selected regions.
- Develop realtime US drought monitoring capability

As shown previously by Wood et al. (2002), it is possible to force the hydrological model with seasonal meteorological forecast from GCMs such as the NCEP global spectral model (GSM). In that study, they illustrated their methodology, and focused on how to correct the bias in the model forecast and how to downscale GCM forecast to the scale that is appropriate for hydrologic applications. However, that method has a few critical limitations. Their forecast method implicitly assumes that GCM forecasts are skillful as the GCM forecasts are directly transferred into the observed distribution without any consideration of their skill and usefulness. Because the skill of seasonal streamflow forecast is significantly affected by the skill of the meteorological forcing, in particular, precipitation and temperature, such an assumption will significantly limits the skill of seasonal hydrologic forecast own to the fact that GCMs are not very skillful in predicting seasonal precipitation and temperature over the mid-latitudes. The second limitation is that their method can only produces the same number of ensembles as provided by the GCM.

Although the climate model seasonal forecast are not very skillful, they still provide certain amount of useful information, what is needed is a better method to extract such useful information from the climate model forecast. Upon such needs, we developed a Bayesian approach for merging multiple climate model seasonal forecast to produce a more reliable and skillful seasonal forecast. In a Bayesian framework, the climatological distribution is selected as the prior distribution, which reflects our best estimate of the possible outcome both in its mean and uncertainty. Then climate model forecasts are used to update the prior distribution through a likelihood function. Each climate model is evaluated by comparing its hindcast against observations; hence a proper weight can be assigned to this model based on its past performance. A likelihood function is built based the current forecast and past forecast performance. Then a probability distribution (the posterior distribution) is calculated based on the prior and the likelihood function, and is used to describe the estimate of monthly precipitation or temperature. By principle, climate models that are lack of skill in precipitation forecast will have less contribution to the posterior distribution. Therefore, such an approach is expected to extract useful information from each source and form our best estimate. This approach was initially tested with sea surface temperature (SST) seasonal forecast from European Union DEMETER project, in which each of the seven climate models produce a 9-member ensemble forecast with lead time up to 6 months. Figure 1 illustrates how the posterior (multimodel posterior) is better than the climatology and the original model forecast. The merged forecast shows the smallest root mean square (RMS) error in comparison to the climatological forecast and the original model forecasts (see Figure 2).

A VIC-based seasonal hydrological ensemble forecast system has been developed. The Bayesian merging approach is one of the central elements in processing the atmospheric ensemble forcing. In our system, the ensemble forecast from NCEP Climate Forecast System (CFS) are merged with observed climatology to produce a posterior distribution of monthly precipitation and air temperature at 1/8 degree spatial scale during the forecast period. The merging effectively takes care of bias correction and spatial downscaling at the same time when we build the likelihood function using two variables at different spatial scale. The downscaled atmospheric forcing is then used to drive the VIC model to produce ensemble forecast of soil moisture and streamflow. During such processes, the historical observations of precipitation and temperature were used as templates. Because a distribution is provided, we can generate as many ensembles as needed.

The forecast has been implemented over the Eastern US, and we now routinely produce seasonal forecasts with lead time up to 6 months with the forecast system. In retrospective mode, the forecast system takes seasonal forecast from CFS and seven EU DEMETER climate models and produces a multi-model posterior forecast before driving the VIC hydrological model. The retrospective period covers the last 20 years and will be used to evaluate the performance of the forecast system. Figure 3 shows an example of soil moisture forecast over the Ohio River basin for the period for May 1997 to October 1997. The CFS-based forecast and multi-model forecast reassembly the anomaly patterns of the "observed" soil moisture very well. Figure 4 shows the probabilistic streamflow forecast over selected USGS streamflow stations with the Ohio River basin. The forecast probability from the multimodel-based forecast closely resembles the observed probability (expressed as either 0 or 1 for a given event).

In conjunction with the hydrologic forecasting, we also developed the capability to monitor the drought condition over the US in realtime. This capability is built up VIC model and the North American Land Data Assimilation (NLDAS) products. Compared to the current approach being used by the Climate Prediction Center's (CPC) Drought Monitor, which is empirical and does not allow for drought forecasting or skill assessment, our products provide a more quantitative assessment of drought (Figure 5).

We have set up a web site (http://hydrology.princeton.edu/forecast) for this project, and it has been visited over 26000 times since it was up online. More information and recently progress can be found there.

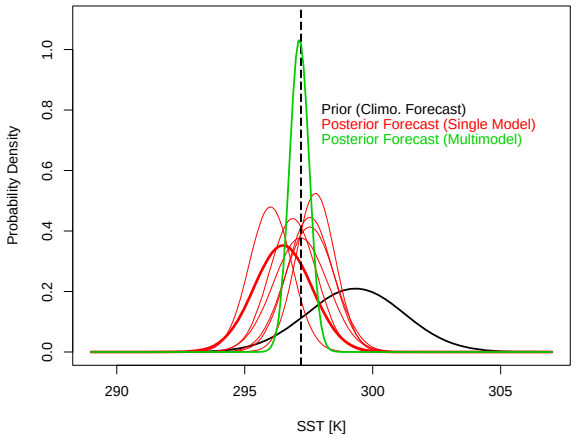


Figure 1: The prior distribution (black), the posterior distribution updated with one of the seven DEMETER climate models forecast (red), and the posterior distribution updated with all seven models forecast (green), for the forecast of December 1998 monthly mean SST over selected grid (2.5×2.5 centered at 0 and 130W).

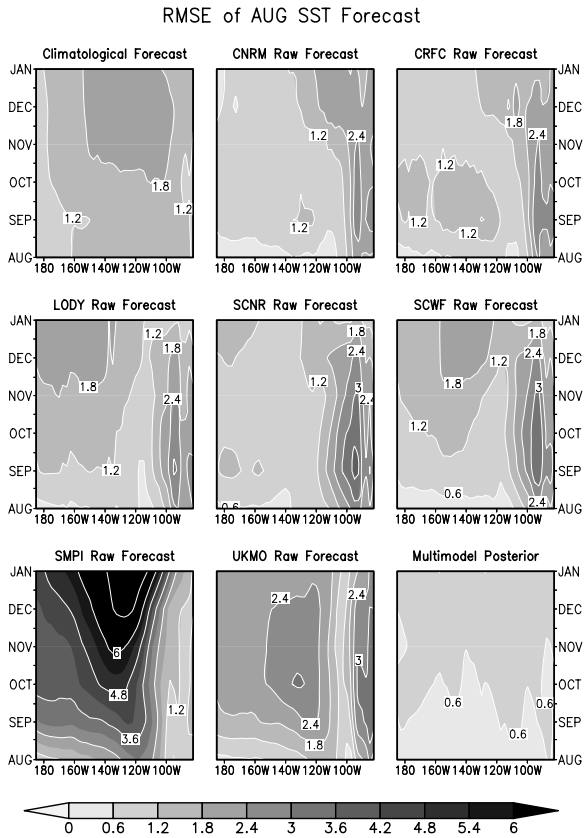


Figure 2: The variation of RMSE with lead time and location from difference forecasts: climatological forecast, raw forecast from seven DEMETER climate models, and the posterior forecast using the seven model forecast and the climatological forecast. This is for all the forecasts starting in August.

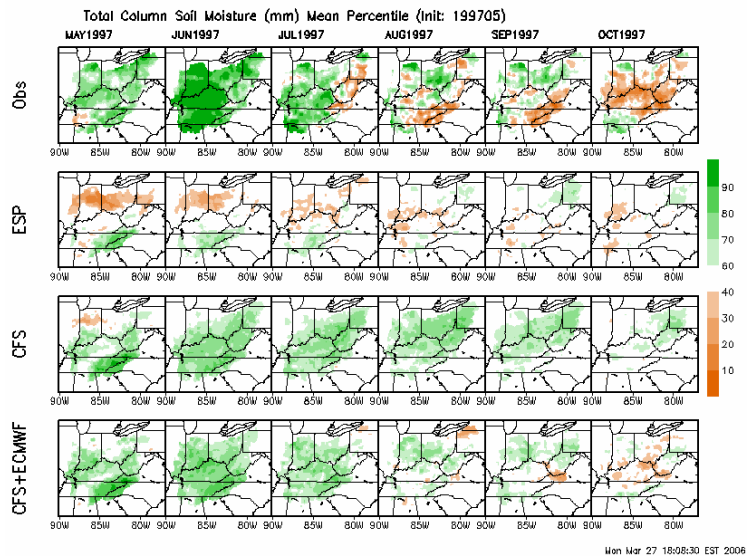


Figure 3: The seasonal forecast of soil moisture over Ohio River basin for the period of May 1997 to Oct 1997. The CFS-based forecast (third row) and multimodel-based forecast show promising skill in predicting soil moisture anomalies months ahead. The multimodel-based forecast uses the merging technique developed in this research.

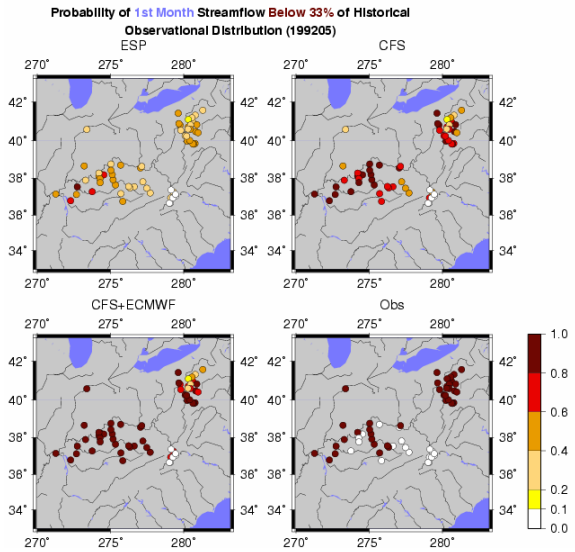


Figure 4: The probabilistic streamflow forecast for streamflow stations within the Ohio River basin for the month of May 1992. The forecast probability from multimodel-based forecast (lower left panel) closely resembles the observed probability (0 or 1).

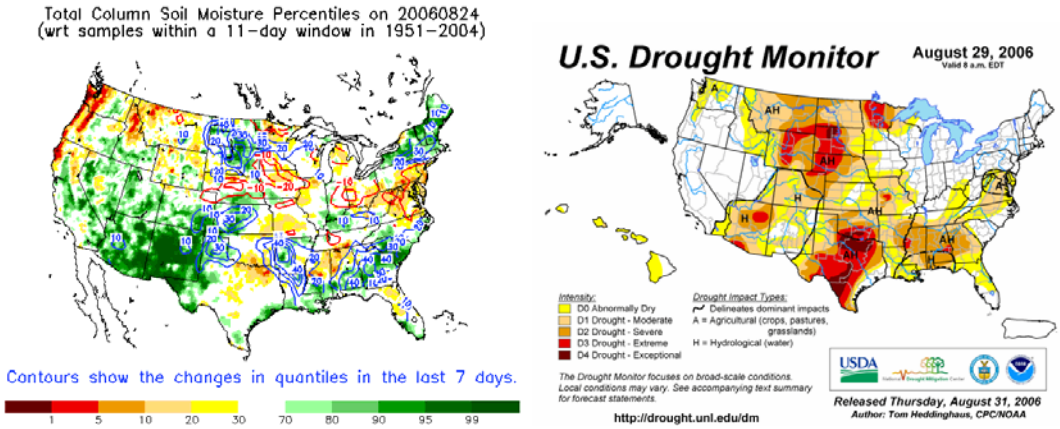


Figure 5: The realtime drought monitor developed by Princeton University (left) compared with the official US drought monitor developed by NOAA.

References:

Godard et al. (2001) Current Approaches to Seasonal to Interannual Climate Predictions. *International Journal of Climatology*

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:

Luo, L. and E. F. Wood (2006): Assessing the idealized predictability of precipitation and temperature in the NCEP Climate Forecast System. *Geophys. Res. Lett*., **33**, L04708, doi 10.1029/2005GL02592.

Lifeng Luo, Eric F. Wood and Ming Pan: Bayesian merging of multiple climate models forecast for seasonal hydrologic prediction. Submitted *to JGR-Atmosphere*.

Lifeng Luo and Eric F. Wood: Seasonal hydrologic forecasting with VIC model over the Ohio River basin. In preparation for *J. Hydrometeorology*.

Eric F. Wood and Lifeng Luo (2005), Seasonal Hydrologic Prediction System over the Eastern U.S., *Eos Trans. AGU, 86*(52), Fall Meet. Suppl., Abstract H14A-06 INVITED

Lifeng Luo and Eric F. Wood (2006), Seasonal Hydrologic Prediction for the Ohio River Basin, *Eos Trans. AGU, 87*(36), Jt. Assem. Suppl., Abstract H31B-05

Progress Report: **Building a Real-time National Streamflow Information System (NSIS)**

Principal Investigator: Youlong Xia (Princeton research staff)

Other Participating Researchers: P.C.D. Milly (GFDL Supervisor), and K. A. Dunne (USGS)

Theme #1: Earth System Studies/Climate Research

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

Objectives:
To provide a streamflow information system to meet society's needs for water resource management and use

Methods and Results/Accomplishments:

Calibration of GFDL land models (LM) is important for establishing **a Real-time National Streamflow Information System** and for development of the GFDL coupled climate model. Both old (LM2) and new (LM3) versions of the GFDL LM have many uncertain and unmeasureable model parameters. The purpose of calibrating GFDL LMs is to reduce the uncertainties of these model parameters and to obtain best performance for our research purposes.

To overcome disadvantages and limits of the manual calibration method used by Milly and Shmakin (2002), we applied an automatic calibration method (very fast simulated annealing, or VFSA) to tune GFDL LMs. To ensure the reliability and efficiency of the algorithm for our application, we have performed many sensitivity tests with respect to VFSA parameters. Additionally, Xia has used this algorithm to develop new methods to correct precipitation bias arising from gauge undercatch and orographic effect, respectively. These methods integrate VFSA, LM2, and observed streamflow, and have been applied on national and global scales. This method has been tested in the east of the United States by use of the NLDAS (North Land Data Assimilation System) data set for the period from 1997 to 2002. The results show that this method is able to correct gauge bias caused from wind-blowing, wet loss and evaporation loss. This work has been accepted by Journal of Hydrometeorology as shown below. For global topographic effect on precipitation data, a topographic bias adjustment method combining VFSA, LM2, observed streamflow, and topographic variance is used. The primary results show that this method can adjust topographic bias for global precipitation data because comparison of corrected precipitation and PRISM (see http://www.ocs.orst.edu/prism/) data is very consistent. The draft about this work is progressing.

The optimization algorithm is used to optimize WMO (World Meteorological Organization) regression models to adjust NLDAS (North-America Land Data Assimilation System) precipitation using NLDAS daily wind speed and 2m air temperature. The paper was published in JGR this year as shown below. Impacts of systematic precipitation bias on simulations of water and energy balances in northwestern United States are discussed using LM2 model. A manuscript is being submitted for review.

Publications:

Xia, Y., 2006a: Optimization and uncertainty estimates of WMO regression models for the systematic bias adjustment of NLDAS precipitation in the United States. Journal of Geophysical Research, ***111***, D08102, doi:10.1029/2005JD006188.

Xia, Y., 2006b: Calibration of the LaD model in northeastern US using observed streamflow, Journal of Hydrometeorology (accepted with minor revision).

Xia, Y., and G.Q. Xu, 2006c: Impacts of systematic precipitation bias on simulations of water and energy balances in northwestern United States, Advances in Atmospheric Sciences (submitted).

Progress Report: **Research On The Atlantic Thermohaline Circulation**

Principal Investigator: Jianjun Yin (Princeton Research Associate)

Other Participating Researchers: Ronald Stouffer, Keith Dixon, Stephen Griffies, Mike Spelman (GFDL), Axel Timmermann (University of Hawaii)

Theme #1: Earth System Studies/Climate Research

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

Objectives:
To study the stability property of the Atlantic Thermohaline Circulation (THC) and reduce the large uncertainty in the response of the THC to changes in the GHG concentrations; To investigate the Atlantic-Pacific teleconnection and THC-ENSO interaction

Methods and Results/Accomplishments:

By performing the CMIP/PMIP "water-hosing" experiments, Yin has found that the THC is bi-stable in the GFDL R30 model but mono-stable in the GFDL CM2.1 model under the present-day climate forcing. The differences in the stability of the THC is due to the differences in the simulation of a reversed thermohaline circulation (RTHC), which forms in the upper South Atlantic Ocean after the shutdown of the THC. The RTHC is strong and stable in R30 but weak and unstable in CM2.1. The differences in the southward propagation of the salinity and temperature anomalies from the perturbation region in R30 and CM2.1, and associated different development of a reversed meridional density gradient in the upper South Atlantic are the cause of the differences in the RTHC. The stable RTHC in R30 transports freshwater into the Atlantic basin, decreasing the basin-averaged salinity, therefore stabilizing the "off" mode of the THC. In contrast, the RTHC disappears in CM2.1 after the termination of the hosing and the rapid recovery of the salinity in the subtropical North Atlantic induced by the excess evaporation there leads to a strong meridional salinity gradient at the mid-latitude Atlantic. Large-scale baroclinic eddies are continuously generated along the frontal zone and then propagate northward to restart the deep convection in the high latitudes. The results shed light on the mechanism responsible for the difference between other models and provide useful information for future model development.

Yin has also collaborated with 9 climate research institutes to investigate the Atlantic-Pacific teleconnection and THC-ENSO interaction. The study compared the ENSO simulations in the water-hosing experiments by 5 coupled atmosphere-ocean general circulation models (AOGCMs). It has been found that a moderate weakening of the THC has little impact on ENSO. However, a significant slowdown or a shutdown of the THC can lead to a substantial weakening of the annual cycle in the eastern equatorial Pacific and an intensification of ENSO variability. The atmospheric transmission of the climate anomalies across the Isthmus of Panama plays an important role in the THC-ENSO interaction.

Publications:

Timmermann, A., An, S. I., Clement, A., Guilyardi, E., Jungclaus, J., Hu, A., Renold, M., Stocker, T. F., Stouffer, R. J., Xie, S. P., and Yin, J., The Influence of a Shutdown of the Atlantic Meridional Overturning Circulation on ENSO. Journal of Climate, 2006. (submitted)

Yin, J., Stouffer, R. J., Spelman, M. J. and Griffies, S. M., Evaluating the Uncertainty Induced by the Virtual Salt Flux Assumption in Climate Simulation and Prediction with a Coupled Atmosphere-Ocean General Circulation Model. Journal of Physical Oceanography, 2006. (to be submitted)

Yin, J. and Stouffer, R. J., Comparison of the Stability of the Atlantic Thermohaline Circulation in Two Coupled Atmosphere-Ocean General Circulation Models. Journal of Climate, 2006. (submitted)

Stouffer, R. J., Yin, J., Gregory, J. M., Dixon, K. W., Spelman, M. J., Hurlin, W., Weaver, A. J., Eby, M., Flato, G. M., Hasumi, H., Hu, A., Jungclaus, J. H., Kamenkovich, I. V., Levermann, A., Montoya, M., Murakami, S., Nawrath, S., Oka, A., Peltier, W. R., Robitaille, D. Y., Sokolov, A., Vettoretti, G., Weber, S. L., Investigating the Causes of the Response of the Thermohaline Circulation to Past and Future Climate Changes. Journal of Climate, 19, 1365-1387, 2006.

Progress Report: **Impact Of Atlantic Multidecadal Oscillations On India/Sahel Rainfall And Atlantic Hurricanes**

Principal Investigator: Rong Zhang (Princeton Research Staff)

Other Participating Researchers: Tom Delworth (GFDL)

Theme #1: Earth System Studies/Climate Research

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

Objectives:
Studying the impact of the Atlantic Multidecadal Oscillations on the observed multidecadal fluctuations of India summer rainfall, Sahel summer rainfall, and Atlantic Hurricane activity during the 20th century.

Methods and Results/Accomplishments:
We first use statistical analyses to show that the observed multidecadal fluctuations of India summer rainfall, Sahel summer rainfall, and Atlantic Hurricane activity are coherently linked. Next, we use the GFDL CM2.1 climate model to show that the multidecadal variability in the Atlantic ocean can cause the observed multidecadal variations of India summer rainfall, Sahel summer rainfall and Atlantic Hurricane activity (as inferred from vertical wind shear changes) (Figure 1). The in-phase relationship between Indian rainfall and the AMO is consistent with our previous work [Zhang and Delworth, 2005] showing that Indian monsoon is significantly reduced when the Atlantic THC is substantially weakened. Paleo records indicate that weakened Indian monsoons were associated with Greenland cold periods during the glacial period and the Holocene [Altabet et al., 2002; Gupta et al. 2003]. These results suggest that to interpret recent climate change we can not ignore the important role of the Atlantic multidecadal variability.

References:
Altabet M. A., M. J. Higginson, and D. W. Murray, 2002. The effect of millennial-scale changes in Arabian Sea denitrification on atmospheric CO_2. Nature, 415, 159-162.

Gupta A. K., D. M. Anderson, and J. T. Overpeck, 2003. Abrupt changes in the Asian southwest monsoon during the Holocene and their links to the North Atlantic Ocean. Nature, 421, 354-357.

Zhang, R., and T. L. Delworth, 2005: Simulated tropical response to a substantial weakening of the Atlantic thermohaline circulation. J. Climate, 18, 1853-1860.

Publications:
Zhang, R. and T. L. Delworth, 2006. Impact Of Atlantic Multidecadal Oscillations On India/Sahel Rainfall And Atlantic Hurricanes. Geophysical Research Letters, Accepted.

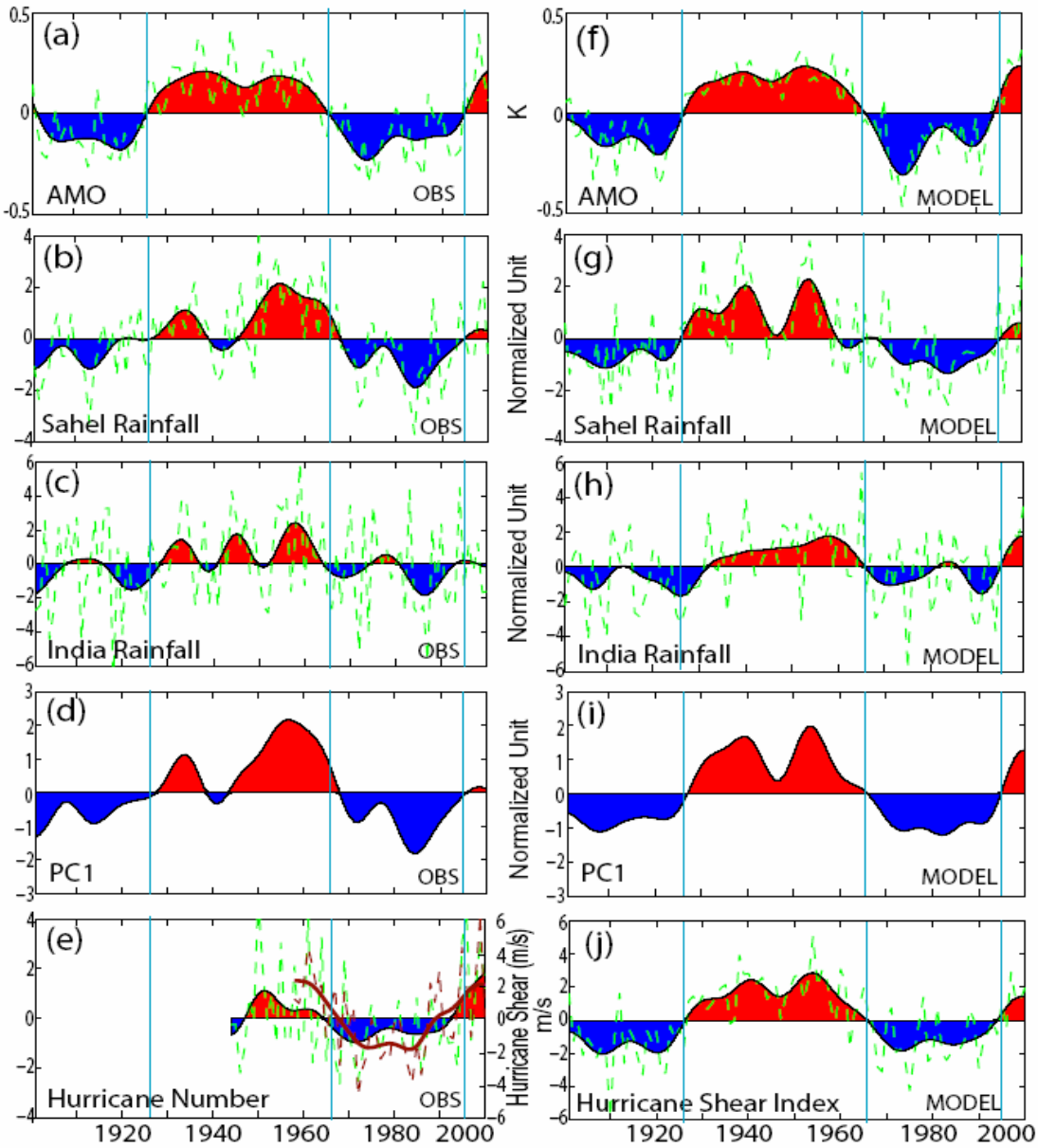


Figure 1 Observed and modeled variability. The color shading is the low-pass filtered (LF) data and the green dash line is the unfiltered data. (a) Observed AMO Index (K) (b) Observed JJAS Sahel rainfall anomalies. (c) Observed JJAS west central India rainfall anomalies (d) Observed time series of the dominant pattern (PC 1) of LF JJAS rainfall anomalies (e) Observed anomalous Atlantic major Hurricane number (axis on the left), and observed Hurricane Shear Index (1958-2000) (m/s, brown solid line for LF data, brown dash line for unfiltered data, axis on the right) (f) Modeled AMO Index (K) (g) Modeled JJAS Sahel rainfall anomalies (h) Modeled JJAS west central India rainfall anomalies (i) Modeled PC 1 of LF JJAS rainfall anomalies (j) Modeled Hurricane Shear Index(m/s). Light blue lines mark the phase-switch of AMO.

Progress Report: **Can the Atlantic Ocean Drive the Observed Multidecadal Fluctuations in Northern Hemisphere Mean Temperature?**

Principal Investigator: Rong Zhang (Princeton Research Staff)

Other Participating Researchers: Tom Delworth, Isaac Held (GFDL)

Theme #1: Earth System Studies/Climate Research

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

Objectives:
Studying the impact of the low frequency variability of the Atlantic ocean on the observed multidecadal fluctuations in northern hemisphere mean temperature.

Methods and Results/Accomplishments:

While the Northern Hemisphere mean surface temperature has clearly warmed over the 20th century due to increasing greenhouse gases, this warming has not been monotonic. The departures from steady warming on multidecadal timescales might be associated in part with radiative forcing, especially solar irradiance, volcanoes, and anthropogenic aerosols [Stott, et al., 2000]. It is also possible that internal oceanic variability explains a part of this variation. We report here on simulations with a climate model in which the Atlantic Ocean is constrained to produce multidecadal fluctuations similar to observations by redistributing heat within the Atlantic, with other oceans left free to adjust to these Atlantic perturbations. The model is capable of generating multidecadal variability in the northern hemisphere mean similar in phase and magnitude to detrended observations (Figure 2). The results confirm that variability in the Atlantic is a viable explanation for a substantial part of the multidecadal variability in the Northern Hemisphere mean temperature record.

References:

Stott, P. A., S. F. B. Tett, G. S. Jones, M. R. Allen, J. F. B. Mitchell, and G. J. Jenkins, 2000. External control of 20th century temperature by natural and anthropogenic forcings. Science, 290, 2133-2137.

Publications:

Zhang, R., T. L. Delworth and Isaac M. Held, 2006. Can the Atlantic Ocean Drive the Observed Multidecadal Fluctuations in Northern Hemisphere Mean Temperature? Geophysical Research Letters. To be submitted.

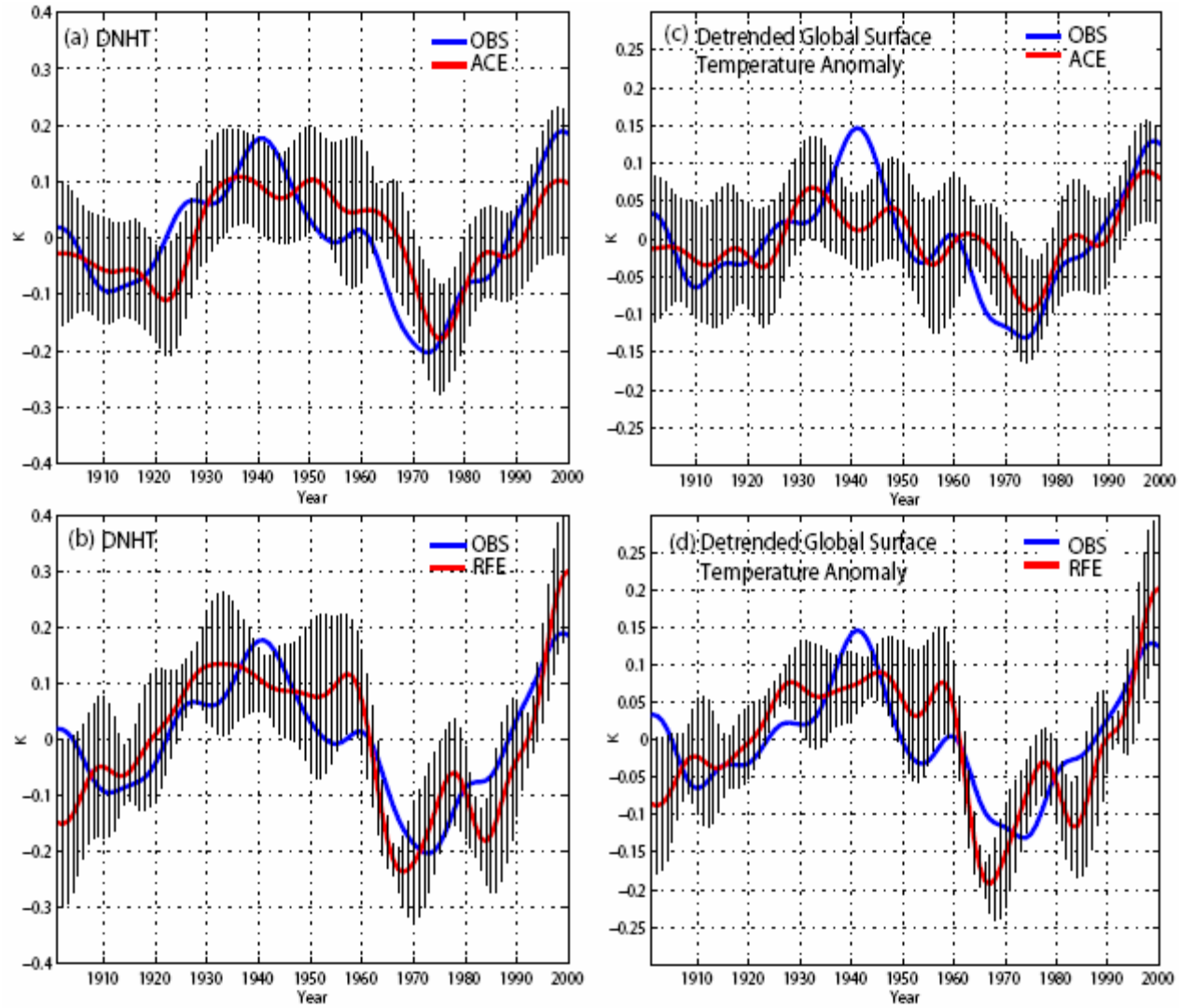


Figure 2 Observed and modeled low-pass filtered annual mean time series. (a),(b) Detrended northern hemisphere mean surface temperature (DNHT); (c),(d) Detrended global mean surface temperature time series. (a),(c) Observed and modeled from Atlantic-Constrained Experiment (ACE, n=10); (b),(d) Observed and modeled from Radiatively Forced Experiment (RFE, n=5). The areas covered with black lines show one standard deviation about the ensemble mean calculated from 10 members of ACE in (a,c) and 5 members of RFE in (b,d) respectively.

Progress Report: **Impact of Great Salinity Anomalies on the Low Frequency Variability of the North Atlantic Climate**

Principal Investigator: Rong Zhang (Princeton Research Staff)

Other Participating Researchers: Geoff Vallis (Princeton Research Scholar)

Theme #1: Earth System Studies/Climate Research

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

Objectives:
Understanding the mechanism of North Atlantic low frequency variability

Methods and Results/Accomplishments:

We 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° 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). We show that such dipolar anomaly 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 3). The multidecadal variations of the Iceland sea ice extent and Labrador Sea SST (Figure 3) may have contributed to the cool phases in the North Atlantic during 1905-1925 and 1970-1990, and the warm phase in the North Atlantic in the middle of the 20th century, i.e. the observed Atlantic Multidecadal Oscillation (AMO).

Publications:

Zhang, R. and G. K. Vallis, 2006. Impact of Great Salinity Anomalies on the Low Frequency Variability of the North Atlantic Climate. *Journal of Climate*, 19, 470-482.

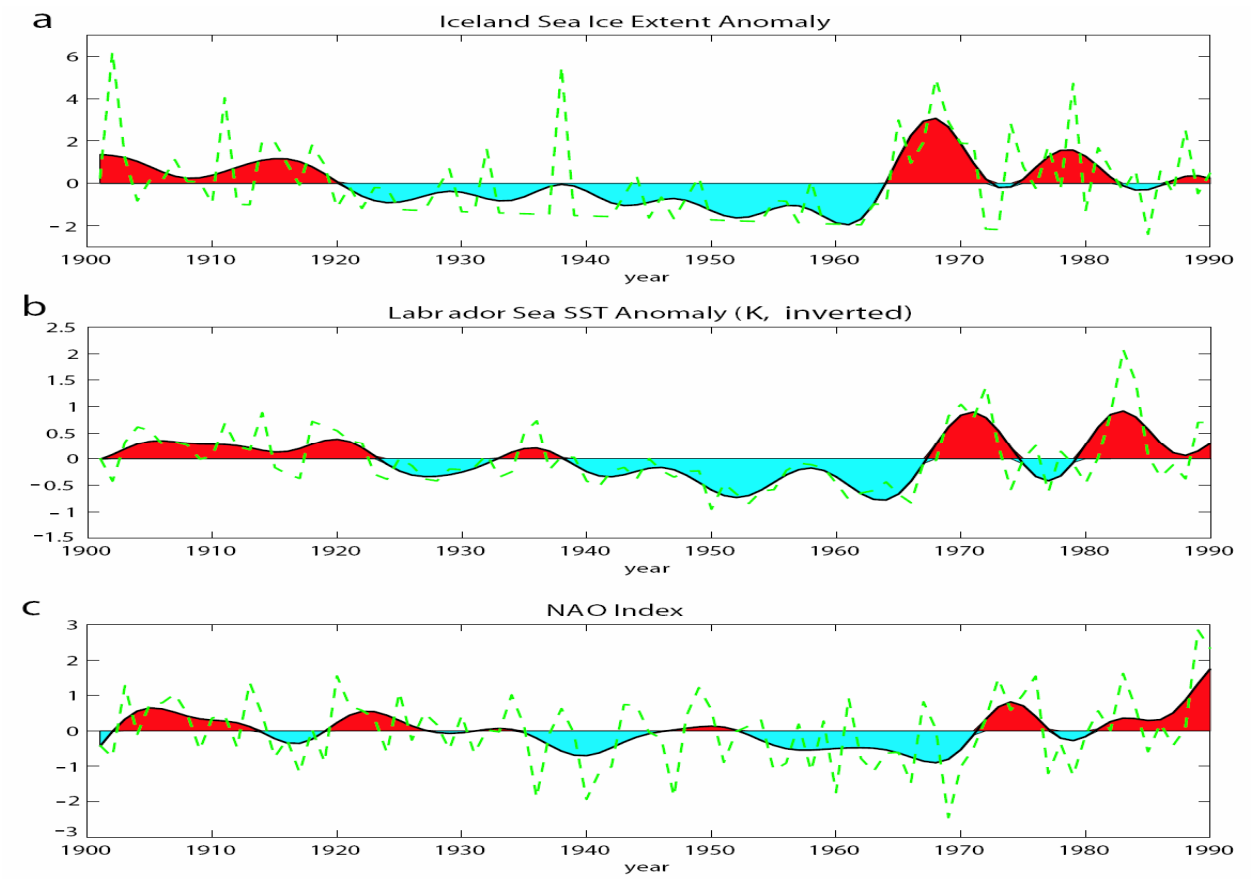


Figure 3 Observed time series during the 20th century. **a**, Annual Iceland sea ice extent anomaly **b**, Central Labrador Sea annual mean SST anomaly from HadISST dataset (K, inverted) **c**, Winter (Dec-Mar) principal component based NAO Index. The green dash line is the unfiltered data and the color shade is the 8-yr low-pass filtered data. The linear trends for the whole period (1901-1990) of the time series are removed.

Project Report: **GFDL Participation in Atmospheric CPT on Low-Latitude Cloud Feedbacks on Climate Sensitivity**

Principal Investigator: Ming Zhao (Princeton Research Associate), Isaac Held, Leo Donner, and V. Ramaswamy (GFDL)

Other Participating Researchers: Bruce Wyman (GFDL), Chris Bretherton (UW), Matt Wyant (UW), Steve Klein (LLNL), Brian Soden (UM), Brian Mapes (UM), Robert Pincus (CDC/NOAA), Joel Norric (Scripps), M. Zhang (SUNY Stony Bk), Bjorn Stevens (UCLA), Marat Khairoutdinov (CSU), Cara-lyn Lappen (CSU), K-M Xue (NASA Langley), Julio Bacmeister (GMAO), Jeff Kiehl (NCAR), Cecile Hannay (NCAR liaison scientist) et.al.

Theme #1: Earth System Studies/Climate Research

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

Objectives:
1) To understand the difference in the low-latitude cloud trends in the GFDL, NCAR and GMAO models when CO_2 is doubled.
2) To use observations and recent advances in understanding the component physical processes to improve both models.
3) To reduce, or better estimate, our uncertainty about the sensitivity of climate to low-latitude marine boundary layer clouds.

Methods and Results/Accomplishments:

Ming serves as the GFDL liaison in support of the GFDL participation in the atmospheric CPT project. Ming's work includes both supporting and original research components. The following briefly describes the work that Ming has been doing with Isaac Held, Leo Donner, Bruce Wyman, and others.

Understanding the complex Earth climate system demands model hierarchies. As a component model targeting studies of column physics, we have made available an idealized setting of the GFDL atmospheric model AM2, which can be run over a limited area using Cartesian coordinate. This model has doubly periodic lateral boundary with lower-boundary being either fixed or mixed-layer ocean. Unlike a single-column model (SCM), this model allows physical processes of convection, clouds, radiation and surface fluxes to interact explicitly with model dynamics and therefore provides a possible venue for testing ideas about these interaction that might be simple enough to be understandable, but rich enough to be useful in interpreting some of the full model behavior. We explore the model sensitivities to physics parameters as well as SST under simple boundary forcings. The results from a set of dynamical radiative-convective equilibrium (DRCE) simulations have been described in the previous report and in a paper listed below. Continuing along this line of research, we have carried out some new experiments with the rotation effect turned on. The simulations show several (typically 2-4) tropical-cyclone-like entities developed in a domain of 128 x 128 degree with 2 degree resolution. These "tropical cyclone (TC)" intensity increases with SST while the number of "tropical cyclone" stays relatively the same for different SSTs. High resolution (1 degree) simulations show similar TC intensity trend with SST. Given a fixed SST, high resolution simulations produce more (typically 5-7) "TC" with better developed rain-bands and TC eyes. We are currently exploring the sensitivity of simulated "tropical cyclones" with respect to different configurations, for instance, different ambient wind shear. Since the model uses the identical physics package as in AM2, we expect to make connections to AM2's simulation of tropical cyclones and their trend on global warming.

Over the past year, Ming has implemented the University of Washington shallow convection scheme (UW-ShCu) in AM2 and has carried out extensive tests in both single column and full AM2 experiments.

The experiments using UW-ShCu show significant improvement for vertical structure of low cloud condensate and cloud fraction compared with using RAS as shallow convection scheme. However, further improvement of the mean climate requires a more careful consideration of the interaction among shallow, deep convection, boundary layer and stratiform cloud scheme. For example, we showed that UW-ShCu with excessively smaller entrainment rate (RAS-like) produces simulations somewhat similar as the AM2 default. But using a more realistic entrainment rate (constrained by observations and large-eddy-simulations) leads to excessive shortwave cloud radiative forcing, particularly over mid-latitude ocean. Therefore, compensating errors may occur in the default AM2 and need to be further identified. It is also interesting to point out that AM2 tropical cloud feedback to climate sensitivity shows an opposite sign when changing the shallow convection scheme from RAS to UW-ShCu, indicating the importance of shallow cumulus parameterization. Further diagnostics are required to understand what cause the different response. Recently, Ming has devoted much of his model development effort on a unification of UW-ShCu and the Donner deep convection, which have been proposed as candidate convection schemes for AM3 physics.

During the past year, Ming continued to serve as the GFDL liaison participating on several different CPT sub-projects. They are: 1) GCM single-column output, analysis and inter-comparison (leader: Mapes). 2) Single-column-modeling effort on understanding the GCM low-cloud feedback to climate sensitivities (leader: Zhang). 3) Aqua-planet inter-comparison (leader: Stevens). 4) Mock Walker circulation simulations (leader: Bretherton). 5) GCSS Pacific Cross-section Inter-comparison (leader: Goao). 5) Single-column modeling of the stratocumulus off the California coast during DYCOMS RF02 (leader: Bretherton). Results will be reported from the individual project leader.

Publications:

M. C. Wyant, C. S. Bretherton, J. T. Bacmeister, J. T. Kiehl, I. M. Held, M. Zhao, S. A. Klein and B. J. Soden, 2005: A Comparison of Low-Latitude Cloud Properties and Their Response to Climate Change in Three US AGCMs Sorted into Regimes Using Mid-Tropospheric Vertical Velocity. Climate Dyn. 27, 261-279.

I. M. Held, M. Zhao and B. Wyman 2005: Dynamic Radiative-Convective Equilibrium Using GCM Column Physics. J. Atmos. Sci. In press.

Progress Report: **Parameterization Of Mesoscale Eddies For Upper Ocean Boundary**

Principal Investigator: Rongrong Zhao (Princeton Research Associate)

Other Participating Researchers: Geoffrey Vallis and Laura Jackson (Princeton), Stephen Griffies and Robert Hallberg (GFDL)

Theme #1: Earth System Studies/Climate Research

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

Objectives:
Develop suitable parameterization of mesoscale eddies for upper ocean boundary.

Methods and Results/Accomplishments:

The effects of eddies on the general circulation are explored by integrating primitive equation ocean model in a number of different idealized ocean domains (more specifically idealized ACC models with or without a gyre region in its northern boundary). Eddy-permitting simulations (horizontal resolution is 1/8 by 1/8 degree) are used to provide a 'ground-truth' for various lower resolution simulations with different parameterization schemes. Distinctions between eddy-permitting runs and non-eddying runs confirm that both stratification and transport of ACC are largely affected by eddy activities. Using TEM representation, it is also shown by the eddy-permitting model that residual overturning circulation is along isopycnals in the ocean interior.

Traditional parameterizations (i.e. Gent and McWilliams scheme) are applied to the low resolution model. With a series of perturbation tests, the GM scheme is found to be fairly sensitive to the choices made as to how
the schemes are implemented in the upper ocean. For example, tapering
off GM in the top boundary can result in an unphysical upper ocean, and model results are sensitive on the selection of GM skew diffusivity and a model parameter called slope max (which is used to determine the onset of tapering). In addition, it is quite difficult to tune the parameters in the traditional GM scheme to get eddy-permitting-like results.

A variety of changes and new schemes are developed in order to improve the current eddy parameterization: 1. a transitional layer between the adiabatic ocean interior and the diabatic upper ocean (based Ferrari & Raffaele 2005) was applied to the GM scheme; 2. Beta effects are included in the neutral physics to implement the pv based parameterization; and 3. residual form of velocity is used for model integration therefore there are no need to give parameterization in tracer equations. This is realized by adding a stratification dependent vertical viscosity to the momentum equations.

It is found that residual form of parameterization is numerically simple and robust, and it shows to be effective in representing eddy effects. Figure 1 shows a comparison of temperature contour from an eddy-permitting run and from newly implemented PV-based parameterization using residual form of velocity in the momentum equation. Furthermore, a comparison between the tests with vertically constant viscosity and the one with residual run (vertically stratification-dependent viscosity) shows a large improvement of the latter scheme (see figure 2).

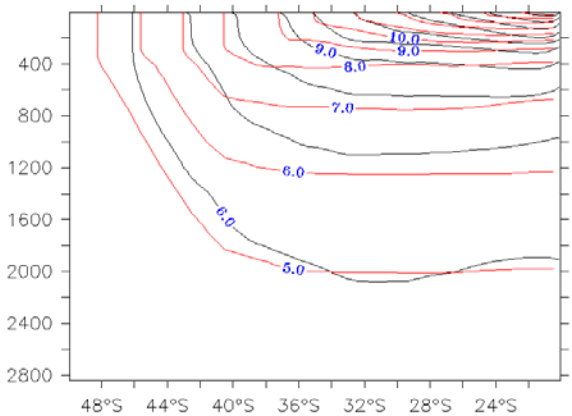


Figure 1. Zonally averaged temperature field: 50S ~ 40S: channel; 40S ~ 20S: gyre.

Black: Eddy-permitting run;
Red: PV-based parameterization by using residual form of momentum equation

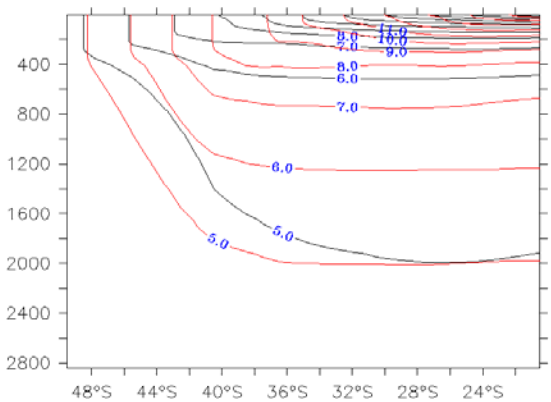


Figure 2. Zonally averaged temperature field: 50S ~ 40S: channel; 40S ~ 20S: gyre.

Black: Eddy parameterization by using a vertically constant viscosity;
Red: PV-based parameterization by using residual form of momentum equation

References:

Ferrari, R. and McWilliams, J. C., 2005, Parameterization of eddy fluxes near Oceanic Boundaries, Submittied to J. Phys. Oceanogr.

Ferreira, D. and Marshall, J., 2006, Formulation and implementation of a “residual-mean” ocean circulation model, Ocean Modelling, 13, 86-107.

Trequier, A. M., Held, I. M., and Larichev, V. D., 1997, On the parameterization of the quasigeostrophic eddies in primitive equation ocean models, J. Phys. Oceanogr. 27, 567-580

Progress Reports:

Biogeochemistry

Progress Report: **A Direct Carbon Budgeting Approach To Infer Carbon Sources And Sinks**

Principal Investigator: Cyril Crevoisier (Princeton Research Associate)

Other Participating Researchers: Manuel Gloor (University of Leeds), Arlyn Andrews (NOAA/GMD), Colm Sweeney (NOAA/GMD), Pieter Tans (NOAA/GMD)

Theme #2: Biogeochemistry

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

Objectives:
Estimating North American Carbon Balance

Methods and Results/Accomplishments:

Determining the location, the intensity and the evolution in time of the sink of carbon in the northern hemisphere remains one of the main unresolved issues of the contemporary carbon cycle. For North America, the current estimate of this sink is of the order of 0.9 $GtC.yr^{-1}$, with an uncertainty ranging from 0.4 to 0.8 $GtC.yr^{-1}$ (Jacobson et al., accepted). To constrain this problem, measurements of CO_2 vertical profiles by aircraft and continuous CO_2 data along tall towers are performed at twenty locations across the United States, within the framework of the North American Carbon Program (NACP). In order to exploit these data to infer CO_2 sources and sinks in North America, we have designed a direct carbon budgeting approach.

Direct budgeting puts a control volume on top of North America, balances air mass in- and outflows into the volume and solves for the surface fluxes. The flows are derived from the observations through a geostatistical interpolation technique called Kriging combined with transport fields from weather analysis.

The use of CO_2 vertical profiles simulated by the atmospheric transport model MOZART-2 at the planned 19 stations of the NACP network has given an estimation of the error of 0.39 $GtC.yr^{-1}$ within the model world. Reducing this error may be achieved through a better estimation of mass fluxes associated with convective processes affecting North America. Complementary stations in the North-West and the North-East are also needed to resolve the variability of CO_2 in these regions (see figure). For instance, the addition of a single station near 52°N; 110°W is shown to decrease the estimation error to 0.34 $GtC.yr^{-1}$.

Publications:

Crevoisier C., Gloor M., Gloaguen E., Sarmiento J. L., Horowitz L. W., Sweeney C. and Tans P. P., A direct carbon budgeting approach to infer carbon sources and sinks. Design and synthetic application to complement the NACP observation network, in press, TellusB, 2006.

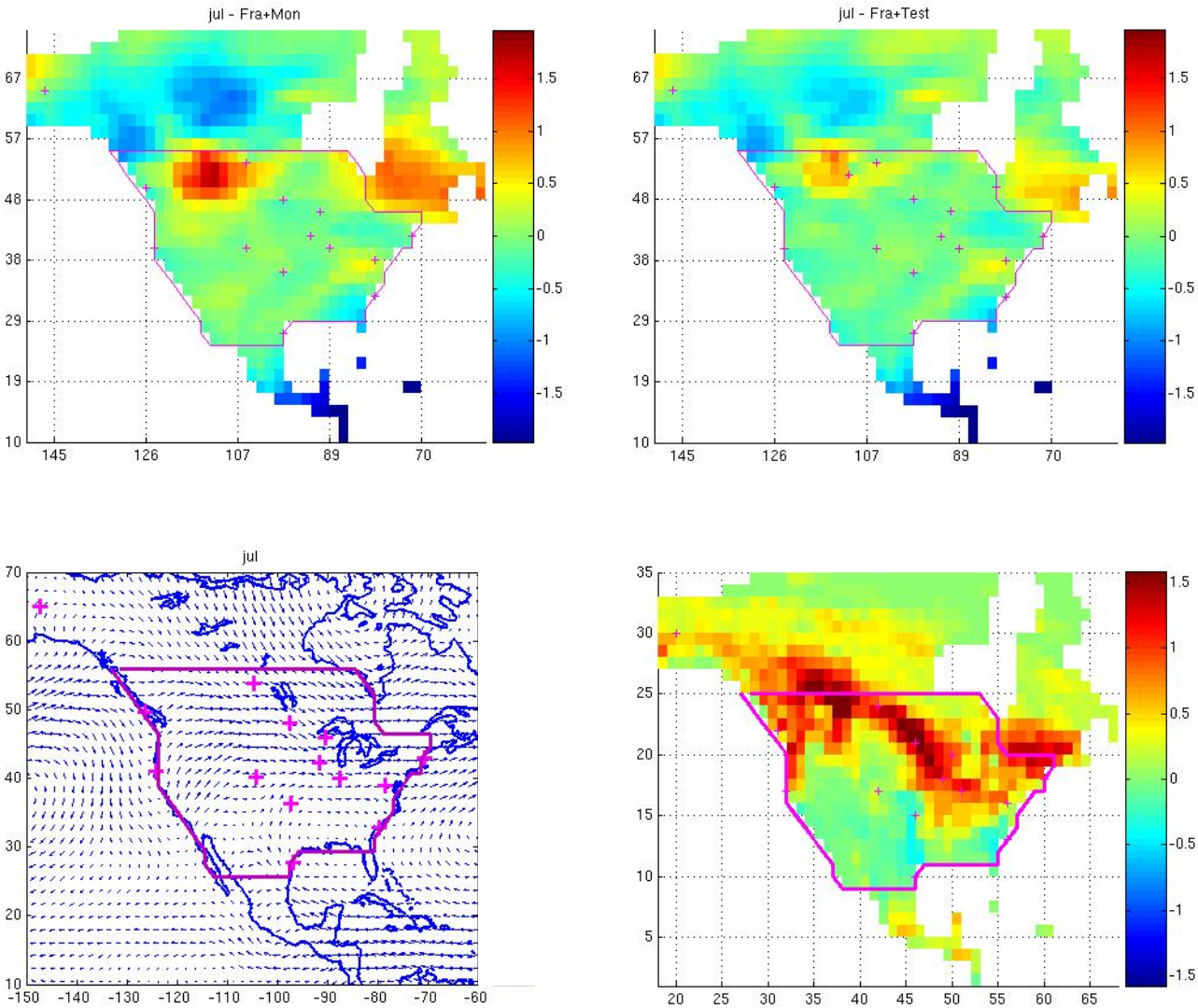


Figure - (a) shows the error (ppmv) on the CO_2 integrated content (0-8km) obtained after interpolating the measurements made at the 19 NACP stations (shown as crosses). The large errors obtained above Montana and in Quebec region are due to two factors: the wind (c) and the surface fluxes (d – CASA NEP in GtC.month^{-1}). In these regions, high surface fluxes (d) induce high variability in atmospheric CO_2. To be measured, this variability must be transported by the wind towards some stations, which is not the case with the current network (c). Adding two stations, one at 52N-110W and the other at Fraserdale, reduce the error by a factor of 4 in the North-West and in eastern Canada (b).

Progress Report: **Disturbance of Vegetation by Fire in the Boreal Forest.**

Principal Investigator: Cyril Crevoisier (Princeton Research Associate)

Other Participating Researchers: Elena Shevliakova (Princeton), Stephen Pacala (Princeton), Manuel Gloor (Leeds), Christian Wirth (MPI-Jena)

Theme #2: Biogeochemistry

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

Objectives:
Predicting the evolution of vegetation disturbance and related carbon emissions from fire.

Methods and Results/Accomplishments:

Boreal regions are important for the global carbon cycle because it is the largest forested area on earth and there are large belowground carbon pools, partially in a frozen state or in form of peat (altogether ~1000 PgC). It is also a region where largest warming trends on the globe over the last decades have been observed and changes of the land ecosystems have already started. A major factor that determines the structure and carbon dynamics of the boreal forest is fire. As fire frequency depends strongly on climate, increased fire occurrence and related losses to the atmosphere are likely, and have already been reported (Kajii et al., 2002). In order to predict with more confidence the occurrence and effect on forest ecosystems in the boreal region, we are developing a fire model that takes advantage of the large on-ground, remote sensing and climate data from Canada, Alaska and Siberia.

We have designed a prognostic model to estimate the monthly burned area in a grid cell of 2 by 2.5 degrees, from four climate (air temperature, air relative humidity, precipitation and soil water content) and one human-related variables (road density), assuming logit functional forms. Parameters are estimated using a Markov Chain Monte Carlo method applied to a dataset of observed burned area, the Large Fire Data Base for Canada (Stock et al. 1997).

The model is able to reproduce the seasonality of fire as well as the location of fire events, and to predict the large fire events that have occurred in the last two decades, for both Canada (on which data the model has been designed) and Siberia, as may be seen on the following figure. The results also compare well with remote sensing observation. The fire model will be implemented in LM3, the vegetation model developed by S. Pacala, E. Shevliakova and S. Malyshev, in order to make prediction of future fire behavior in boreal regions, and the related disturbance of the vegetation and carbon emissions.

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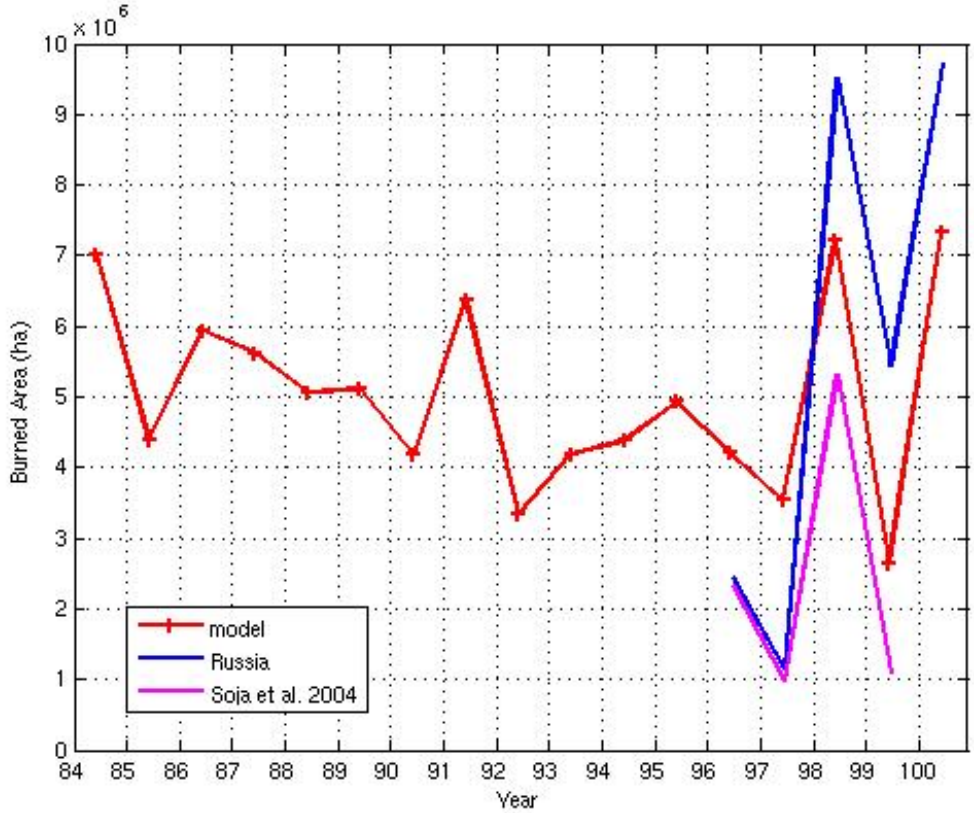

Figure - Annual burned area as estimated by the Russia Forest Fund (purple), using remote sensing (AVHRR) observations from Soja et al. 2004 (blue) and estimated by our fire model (red). The model, built on Canadian observations, is able to capture the good interannual variability in Siberia.

Progress Report: **O_2 Air-sea Flux Variability Derived From Atmospheric Data and Atmospheric Transport**

Principal Investigator: Cyril Crevoisier (Princeton Research Associate)

Other Participating Researchers: Michael Bender (Princeton), Nicolas Cassar (Princeton), Manuel Gloor (Leeds)

Theme #2: Biogeochemistry

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

Objectives:
Understanding the Oxygen Cycle

Methods and Results/Accomplishments:

Seasonal air-sea oxygen exchange is, among other things, dependent on the variability and magnitude of ocean productivity. To estimate marine productivity for a given set of oceanic regions, we exploit the information on flux-magnitude contained in the seasonal cycle of Atmospheric Potential Oxygen (defined as APO=O_2 + 1.1 CO_2). APO is a composite tracer of air-sea gas exchange only (Stephens et al., 1998), where 1.1 is the O_2:C stoichiometric ratio for land biotic photosynthesis and respiration (Severinghaus, 1995). Because APO is conservative with respect to terrestrial biotic exchanges, its seasonal variation and global distribution are predominantly determined by, and therefore reflect mainly, ocean processes. These processes include ocean productivity, large-scale ocean, transport like equatorial upwelling and inter-hemispheric transport, and high-latitude convection.

Measurements of atmospheric O_2 and CO_2 are available at various locations around the globe. In this study, use is made of Princeton and Scripps air sampling programs, as well as new observations collected from ships in the low-latitude Pacific (Battle et al., 2006). The relationship between atmospheric observations at various stations around the globe and regional air-sea fluxes is provided by the atmospheric transport model MOZART-2. Inversions of the atmospheric data in terms of air-sea fluxes have been performed for a set of broad oceanic regions (see Figure). The global annual APO air-sea flux has been estimated to be of the order of 960 $TmolO_2.yr^{-1}$, ie 2.7 $Tmol.m^{-2}.yr^{-1}$. Values for both North Atlantic and North Pacific are close to in-situ observed values. Adding a few stations in the South Atlantic (which is not covered by the current networks) would help improve the inversion. The analyze of these results is still in progress and should provide insight on the productivity in the different basins.

Independently from the direct flux estimates, O_2 air-sea fluxes and productivity are studied with simulations from a new ocean ecosystem model developed at GFDL by John Dunne. The model is forced by the 43-year atmospheric reanalysis from the Common Ocean Reference Experiments (CORE) program. The differences between the observation derived fluxes and the model predictions is expected to give insight into the drivers of flux variability.

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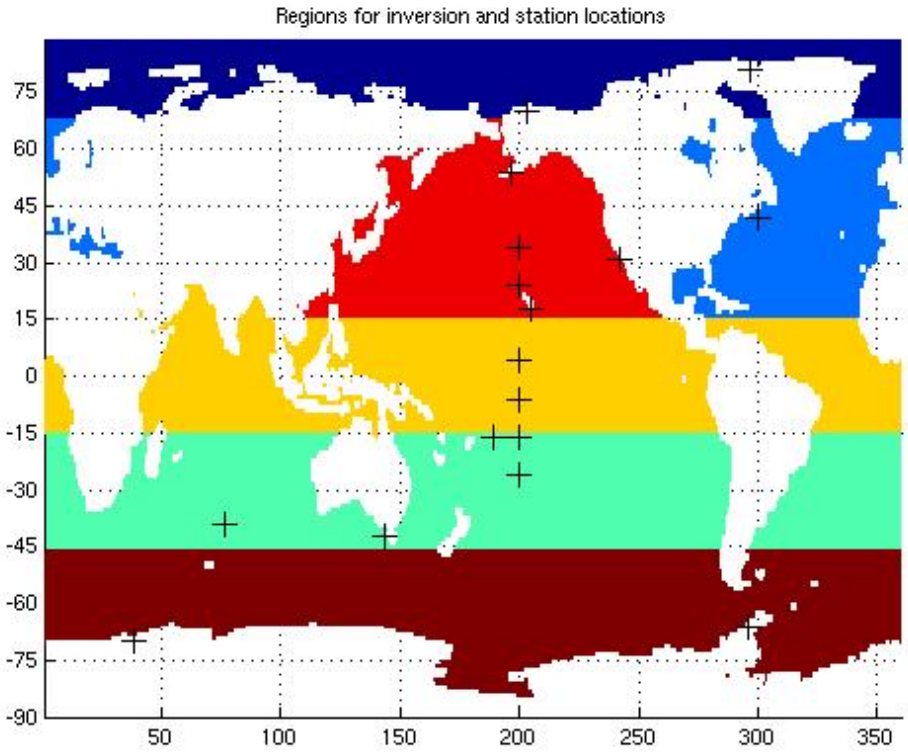

Figure - Six regions are used to perform the inversion: Artic (3 stations), North Atlantic (1), North Pacific (5), Tropical Band, Southern Band (South Atlantic + South Pacific + South Indian - 5) and Southern Ocean (3).

Progress Report: **Estimating Regional Air-sea and Air-land Fluxes from Atmospheric and Oceanic Data and Models**

Principal Investigator: Sara E. Mikaloff Fletcher (Princeton Research Staff)

Other Participating Researchers: N. Gruber (UCLA), A. R. Jacobson (NOAA/GMD), M. Gloor (The University of Leeds), S. C. Doney (Woods Hole Oceanographic Institute), S. Dutkiewicz (Massachusetts Institute of Technology), M. Gerber (The University of Bern), M. Follows (Massachusetts Institute of Technology), F. Joos (The University of Bern), K. Lindsay (NCAR), D. Menemenlis (NASA/JPL), A. Mouchet (The University of Liege)

Theme #2: Biogeochemistry

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

Objectives:
Constraining oceanic and terrestrial sources and sinks of CO_2 by inverse modeling

Methods and Results/Accomplishments:

High-quality estimates of the spatial pattern of air-sea and air-land fluxes of CO_2 are crucial to understanding the mechanisms driving these fluxes and managing earth's carbon reservoirs. Yet, estimates of these fluxes are highly uncertain.

The aim of this project was to address gaps in our understanding of CO_2 exchange using a Green's function-based inverse modeling approach (Gloor et al., 2001, Gruber et al., 2001). This technique determines optimal estimates of the time averaged pre-industrial and anthropogenic air-sea CO_2 fluxes using ocean interior observations and Green's functions representing the response of ocean interior concentrations to CO_2 fluxes at the surface. These Green's functions were calculated for a discrete set of ocean regions using an ocean general circulation model (OGCM) by injecting a unit flux of a dye tracer into each region, distributed spatially within the region according to the climatology of Takahashi et al. (2002), and observing the response to this flux throughout the oceans.

We used the ocean inversion to estimate separately the natural air-sea CO_2 fluxes that existed in preindustrial times and the anthropogenic uptake of CO_2, which is driven by the perturbation of atmospheric CO_2 by fossil fuel burning, cement production, and land use change. These inverse air-sea fluxes were in good general agreement with previous estimates in most regions, but they differed substantially from previous work in the Southern Ocean (south of 44S). We found vigorous natural outgassing of natural CO_2, which is counter-balanced by a slightly larger uptake of anthropogenic CO_2, for a nearly neutral net flux. Furthermore, we found a substantially greater natural CO_2 uptake at southern mid latitudes (18S to 44S) than previous studies. Since the mechanisms responsible for the natural and anthropogenic carbon air-sea fluxes are expected to respond differently to climate change, these results have considerable implications for the future of the carbon cycle.

A suite of 10 OGCMs and a series of scenarios were used to quantify the sensitivity of the inverse estimates to the modeled transport and the tracer-based methods used to partition natural and anthropogenic air-sea fluxes. After extensive error analysis, we found that the inverse estimates are remarkably robust with respect to the choice of OGCM and most potential biases in the tracer-based methods. We also showed that the inverse estimates are driven by strong gradients in the gas exchange tracers used to constrain the inversion. Therefore, we have a high degree of confidence in these results.

The natural and anthropogenic carbon estimates were combined with an analogous atmospheric inversion for both air-sea and air-land fluxes. Due to the overwhelming amount of ocean interior data, the ocean inversion provided strong constraints for the air-land fluxes. In particular, the well-constrained ocean fluxes combined with the atmospheric data imply that the must be a large (~1 Pg C yr-1) land

source in the terrestrial southern hemisphere. This estimate is in line with process-based estimates of emissions from the terrestrial biosphere due to land use change in the tropics, which implies that either the emissions due to land-use change are under-estimated or that there is not a substantial CO_2 fertilization sink in the tropics.

Furthermore, Mikaloff Fletcher and Crevoisier are developing a framework for a combined inversion of CO_2, CO, and CH4 using both in situ and satellite based estimates. The goal is to take advantage of observed relationships between the shared sources or sinks of these trace gases in order to improve the flux estimates and elucidate the source processes responsible for these emissions.

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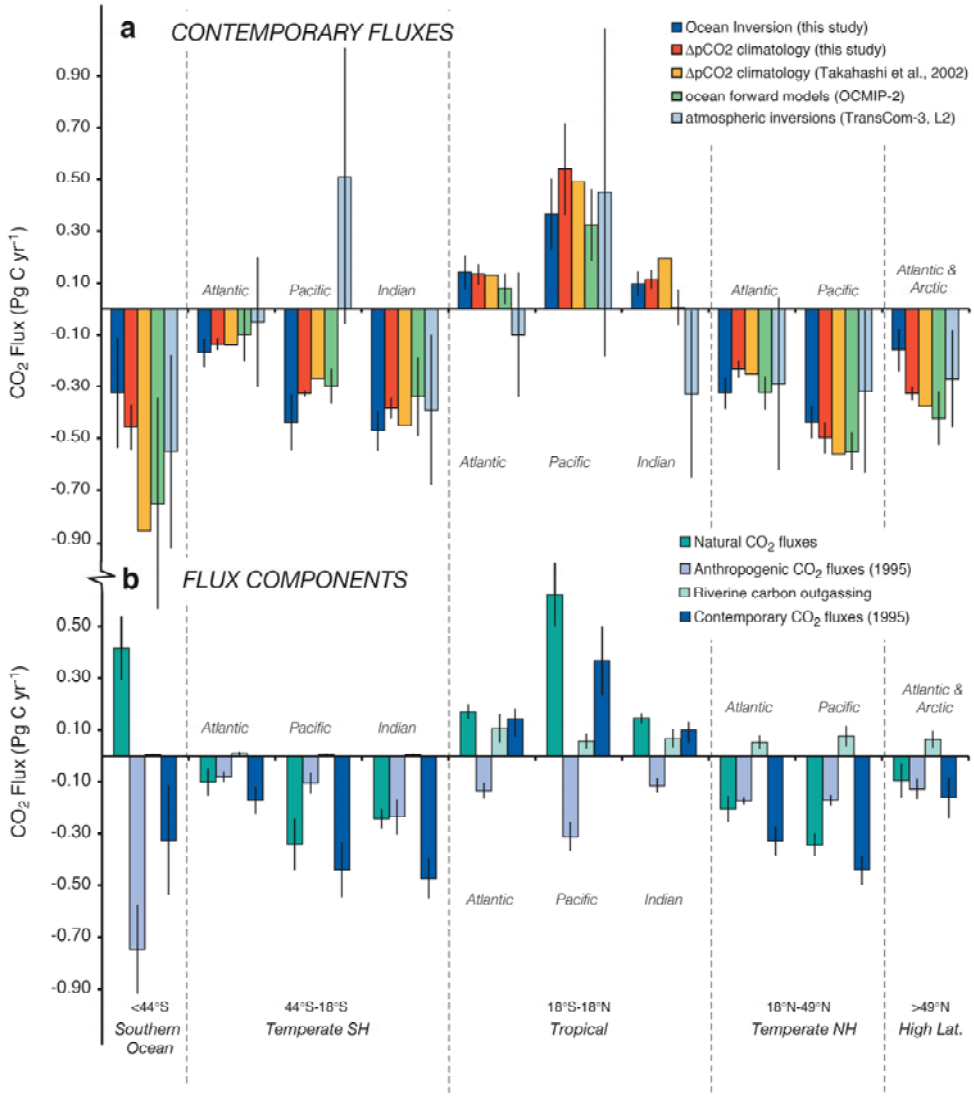


Figure 1. Estimates of net air-sea CO_2 exchange from the ocean inversion (top) compared with a variety of independent estimates (top), and the components that comprise he contemporary air sea flux from the ocean inversion (bottom).

Progress Report: **Modeling Dissolved Organic Nitrogen Losses From Terrestrial Systems**

Principal Investigator: Lars O. Hedin (Princeton Faculty)

Other Participating Researchers: Jack Brookshire, Stefan Gerber (Princeton)

Theme #2: Biogeochemistry

NOAA's Goal #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:
Development of formulation of dissolved organic nitrogen losses in GFDL's LM3V model

Methods and Results/Accomplishments:

Jack Brookshire is a new postdoc with Lars Hedin in the areas of nitrogen biogeochemistry and hydrologic nutrient transport. Brookshire is working with Stefan Gerber and Lars Hedin on incorporating dissolved organic nitrogen (DON) losses into the nitrogen (N) module of GFDL's LM3V. Previous work has shown DON to be a major N loss vector from terrestrial ecosystems and that such losses tend to escape biotic control. In turn, DON losses can constrain forest N economies over long time periods. Thus inclusion of DON in the LM3V is critical to understanding climate-ecosystem N limitation feedbacks. Jack Brookshire arrived two months ago and is already working with Gerber and Hedin on formulating a DON loss routine that captures the dynamics of variability in source pools, decomposition, hydrology, and sorption. We are currently evaluating different model scenarios for soil production and loss that incorporate depletable vs. non-depletable pools and how these losses scale with hydrologic patterns. Currently, DON is produced as a result of organic matter decomposition and leaching potential. The balance of production and competing influences of respiration vs. leaching and sorption is proving to be a sensitive determinant of the quantity of DON ultimately reaching streams. In addition, Brookshire and Hedin are are currently developing a new field effort to quantify patterns of N loss across different tropical forests of Panama and Costa Rica (project funded from other sources). Very little field data exists for tropical forests in general, particularly with regard to DON. This effort will provide information key to biome-specific parameterization of the N module of the LM3V and therefore strengthen its application worldwide.

References:

(This project was recently initiated.)

Publications:

(This project was recently initiated.)

Progress Report: **Development Of A New Global Coupled Terrestrial Carbon-Nitrogen Model**

Principal Investigator: Lars O. Hedin and Michael Oppenheimer (Princeton Faculty)

Other Participating Researchers: Stefan Gerber and Steve Pacala (Princeton University)

Theme #2: Biogeochemistry

NOAA's Goal #1: Protect, Restore, and Manage the Use of Coastal and Ocean Resources through Ecosystem-based Management (55 %)
NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond (15 %)
NOAA's Goal #3: Serve Society's Needs for Weather and Water Information (15%)
NOAA's Goal #4: Support the Nation's Commerce with Information for Safe, Efficient, and Environmentally Sound Transportation (15%)

Objectives:
Implement terrestrial nitrogen cycle into GFDL's earth system model

Methods and Results/Accomplishments:

Model structure and development: We have added nitrogen dynamics to the existing Geophysical Fluid Dynamic Laboratory land model, LM3V, a dynamic vegetation model capable to be coupled within the framework of a global earth system model. The model structure considers stoichiometric carbon to nitrogen ratios in living pools, litter and soil organic matter, which, in turn, allow for nitrogen limitation to plant growth and to litter decomposition. A set of litter and soil organic matter pools with characteristic turnover times, allow for enrichment of nitrogen in soil organic matter during decomposition. Net and gross mineralization is explicit, while microbial pools and rates are calculated implicitly based on carbon and nitrogen supply. Nitrogen leaching is a function of water export and soil mineral nitrogen content.

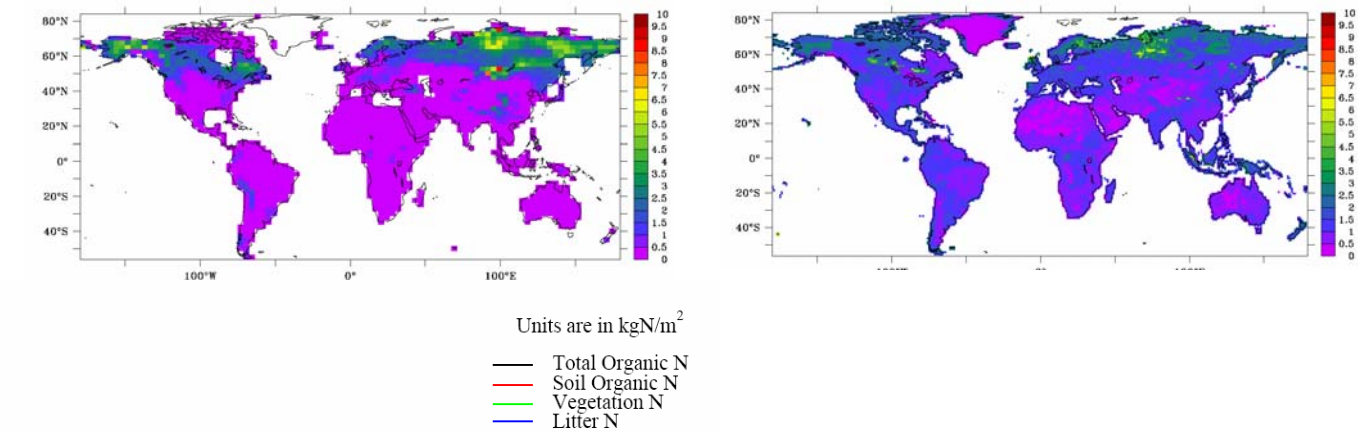
Initial model applications and results: We have performed global integrations in which we, at this point, assume no nitrogen limitation. In Figure 1 we show the global distribution of total soil nitrogen for potential vegetation, when the model is forced with reanalysis data (NCEP Reanalysis 1). Comparisons against reconstructed empirical data (Global Soil Data Task Group, 2000) show reasonable agreement, yet there exists differences that we are currently investigating. Most notably, we currently overestimate soil organic nitrogen (and carbon, see discussion above) content in higher latitudes. We are exploring this mismatch by comparing simulations against actual soil core retrievals, where we hope to rule out biases not directly linked to the model (e.g. interpolation errors, land use etc.).

Dynamical feedbacks: If we allow for nitrogen limitation feedbacks, long-term dynamics differ considerably compared to carbon-only simulations. Build-up of vegetation from bare ground dramatically slows and depends on external nitrogen inputs from deposition and the internal turnover of soil organic nitrogen pools (Figure 2). We have found that incorporation of nitrogen in slow-turnover pools of humic materials is critical for understanding the temporal dynamics of coupled plant-soil nitrogen interactions. This pool effectively prohibits the immediate plant use of nitrogen in young and recently disturbed forests. However, over time and in the absence of disturbances, saturation occurs, as expected based on the system's capacity to retain nitrogen under limiting condition. Tropical and temperate systems display differing responses to external disturbances: We show in Figure 3 that catastrophic reduction of vegetation (90% of the vegetation biomass) by fire or logging (Figure 3) results in a faster recovery of the vegetation in the temperate system, but also that the whole plant-litter-soil system reaches pre-disturbance levels faster in tropical systems.

Summary and prospects: We have constructed a well-founded, intellectually leading, yet conceptually flexible platform for coupling the nitrogen cycle to terrestrial earth system models, and plan to publish the model and its initial results. We also have begun to introduce a formulation of loss

dissolved organic nitrogen, a significant nitrogen leak even in an otherwise tight system with high retentions of mineral forms of nitrogen. With the implementation of biological nitrogen fixation, the core model should be able to address questions of carbon-nitrogen feedbacks, the development of nitrogen limitation due to climate variations, and possibly the response of the terrestrial biosphere to projected increases in atmospheric CO_2 and the accompanied global warming.

Figure 1: Simulation of soil organic nitrogen content (left) compared to data (right). Global Soil Data Task Group



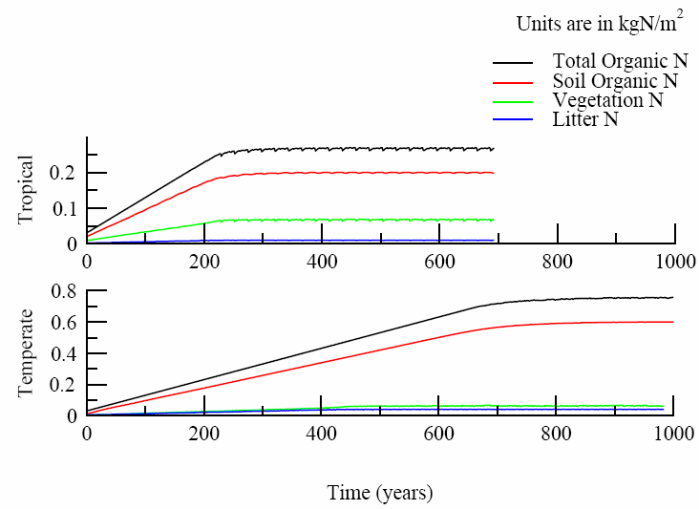


Figure 2: Evolution of above and below ground Nitrogen pools during primary succession. Deposition rate is prescribed with 1gN/m2 for a tropical (top) and a temperate system.

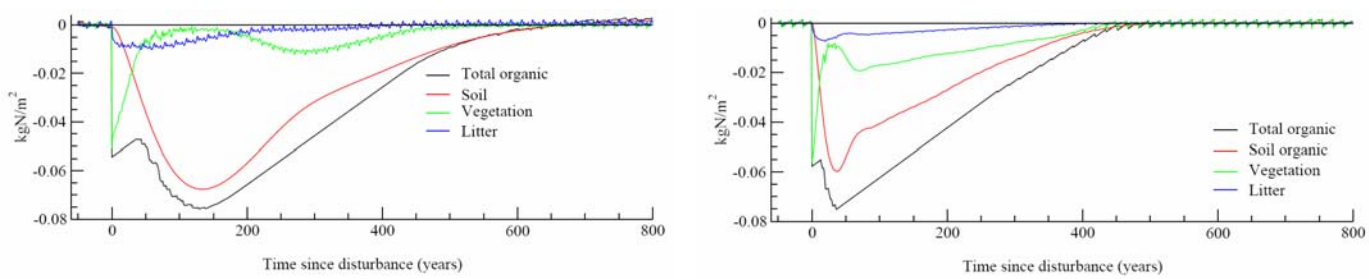


Figure 3: Evolution of above and belowground pools after 90 % of the vegetation has been removed (e.g. due to logging or fire), relative to undisturbed equilibrium.

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

Principal Investigator: George Hurtt, University of New Hampshire Assistant Professor

Other Participating Researchers: Steve Frolking (UNH), Matthew Fearon (UNH), Berrien Moore (UNH), Elena Shevliakova (Princeton), Sergey Malyshev (Princeton), Steve Pacala (Princeton)

Theme #2: Biogeochemistry

NOAA's Goal #1: Protect, Restore, and Manage the Use of Coastal and Ocean Resources through Ecosystem-based Management (25%)
NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond (75%)

Objectives:
To understand the influence of land-use activities on Earth System dynamics

Methods and Results/Accomplishments:

Human activities have altered the land surface and terrestrial ecosystems in significant ways. Important physical properties, biogeochemical cycles, and hydrological stocks/fluxes have all been substantially altered by land-use activities. In order to include these effects in the new GFDL Earth System Model, two essential advances are required: (1) spatio-temporal datasets on land-use activity and management (e.g. location of crop and pasture, land-use transitions, dominant crop types, irrigation, fertilizer use, livestock populations, logging, fire management, fate of products etc.); and (2) the capacity to simulate the dynamics of agricultural systems, including the impacts of changing management practices. In addition, progress in these areas must be fully integrated with the land, water, and atmosphere components of the Earth System model.

For 2005-06, we proposed to concentrate work in three areas: (1) adding important additional information/functionality to global land-use products, (2) improving estimates of fire, fire management, and fire-submodel performance, and (3) integrated model applications assessing the impacts of land-use/land-management activities in the Earth System. We have made substantial progress in all of these areas. Most significantly, we completed the development, and initial implementation of a new spatially resolved 300 year land-use history product for use by global model (Hurtt et al 2005, Hurtt et al 2005a, Hurtt et al 2006). The study provides the first global gridded estimates of the land-use history needed characterize the state of the land surface through time, including patterns of crop, pasture, and the effects of shifting cultivation, logging, and secondary (recovering) lands (Figs. 1, 2). The product is essential for improving the initialization of the land surface in global models, and we continued our work with GFDL/Princeton to integrate these products in the new LM3V. The ability of LM3V to track this land-use information has become a defining feature of that model, and model applications using LM3V have been conducted to document the large impacts of land-use on the carbon-climate system (Shevliakova et al. In prep, Pacala et al 2005, Hurtt et al 2005b). The products are also of general interest and are being used by other global modeling teams and IPCC activities. In 2005-06, we enhanced land-use parameterizatins by creating new agricultural maps with information on multiple crop types (e.g. C3 annual, C3 perennial, C4 annual, N fixers) (Fig. 3), synthesized required model parameters for these crop types (e.g. allometry, physiology, allocation, LAI, …), and developed preliminary algorithms for planting and harvest dates. We also advanced the mapping of rice agriculture over Asia using Remote sensing (Xiao et al. 2006), studied the changes in moisture and energy fluxes due to agriculture in India (Douglas et al. 2006-In press) and logging in tropical forests (D'Almedia et al 2006a-In press, 2006b-In press), and started work with the Netherlands Environmental Assessment Agency (AF Bouwman et al.) on a global simulation of cropland biogeochemistry (C, N, and water cycling, including N and C trace gas emissions and net soil C sequestration). The simulation will be conducted at 5-minute resolution (~10 km), and will be the first

process-based, global assessment of multiple trace gas emissions from croplands. These efforts will contribute to our objectives by enabling by providing high quality inputs and reference datasets for evaluation of future land model and Earth System model simulations. Finally, our work on fire advanced to include the first parameterizations of human fire suppression over the U.S. which is responsible for responsible for 1-2 orders of magnitude reduction in area burned and susbtantial carbon storage in the region (Girod et al 2005,Girod et al 2006, Girod et al In review), improved modeling and interpretation of tropical fire dynamics (Cardoso et al. 2005) and their effects on tropical ecosystems (Zarin et al 2006), and developed a global version has been shown to produce reasonable spatial-temporal dynamics in response to El Nino oscillations (Girod et al 2004).

In 2005, we co-authored a synthesis regulation of natural hazards including floods and fires for the Mellinium Ecosystem Assessement (de Guenni et al 2005). Following the December Science Team Video Conference, we shifted our focus to developing key products/submodels for a global simulation of the integrated effects of land-use activities on coastal ecosystems. Our team is responsible for developing and delivering global gridded estimates of the effects of land use/land management on terrestrial N sources and sinks. This task involves the land-use products developed todate, an acceleration of our efforts at developing needed land-use/land management products/submodels, and the development of products/submodels for the human impacts on N fluxes. To date, we have provided preliminary global gridded estimates of: (i) global land use activites, (ii) major pre-industrial and contemporary N loading terms (Fig. 4), (iii) point source and non-point source N loadings to river systems, and (iv) global gridded estimates of major crop types -- all consistent with the global land-use information developed by this team and already incorporated in LM3V. With these key advances made, we are now working with the GFDL, Princeton, and Vorosmarty et al. (UNH) teams on the key steps of integration needed for the global simulations of the impacts of these activities on coastal systems.

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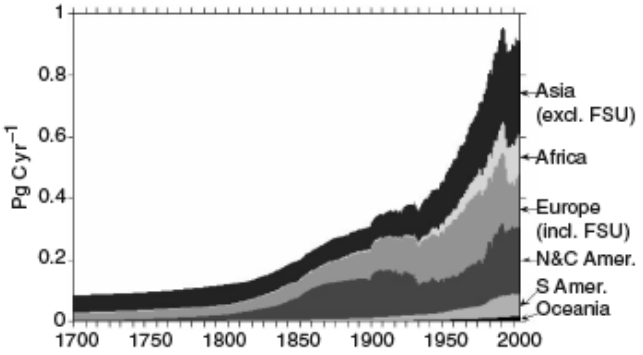

Fig. 1. Annual national wood harvest aggregated by continent 1700-2000. The global integrated wood harvest 1700-2000 is 86 Pg, and is a substantial term in global carbon budgets. (Hurtt et al 2006)

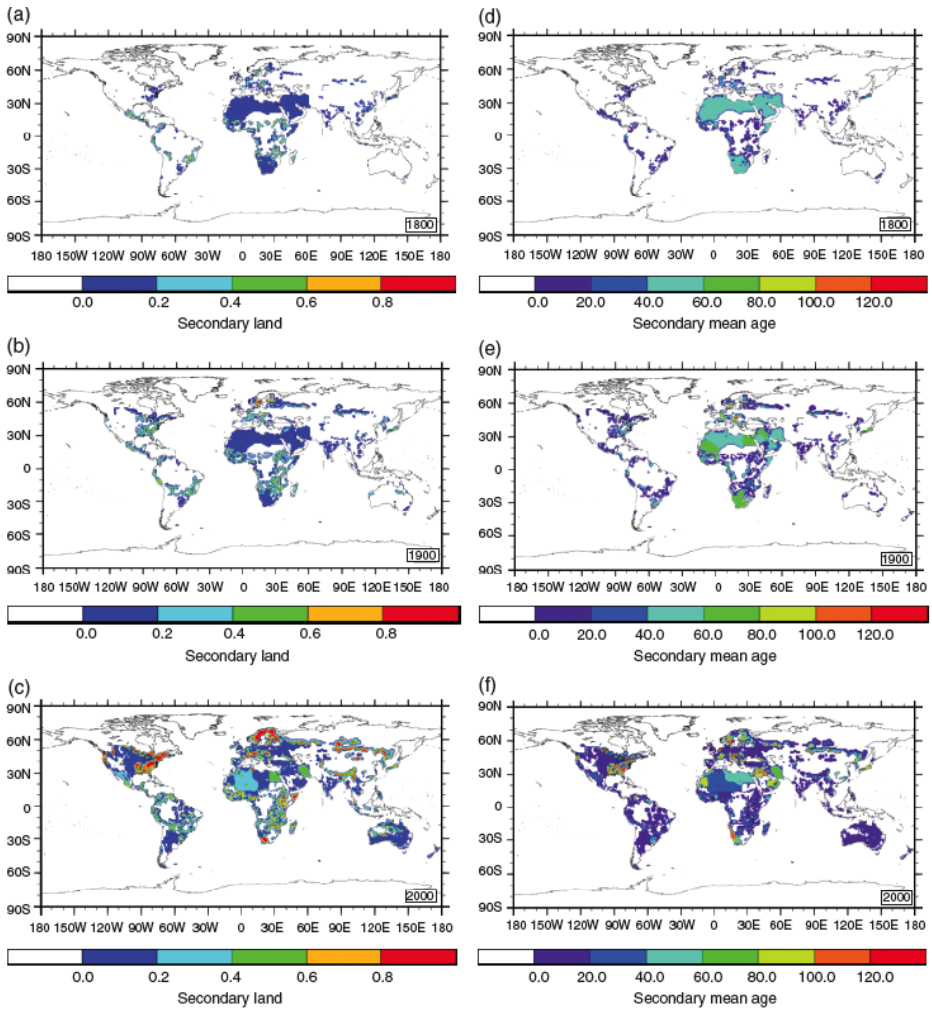

Fig. 2. Secondary land area fraction, and mean age. Secondary land area and age are important factors for ecosystem structure and carbon fluxes, and are generated by abandonment of cropland and pastureland and by wood harvesting. (Hurtt et al 2006)

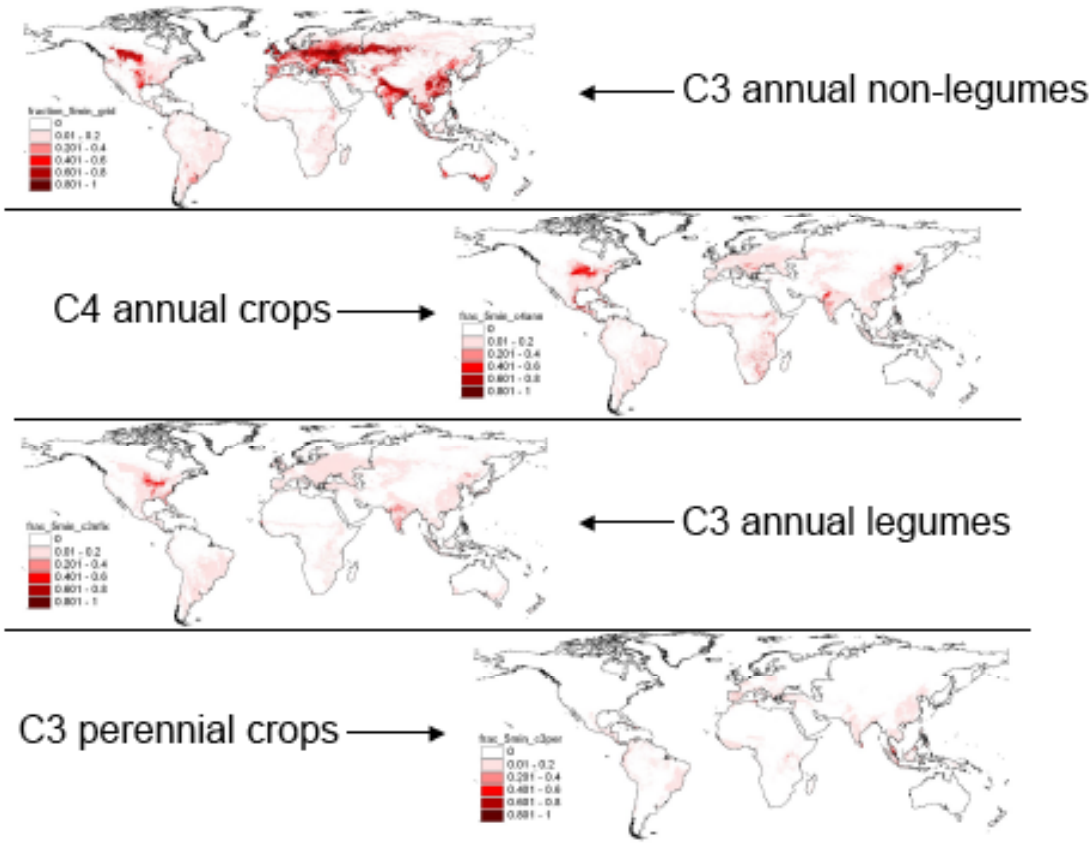

Fig. 3. Global maps of fractional coverage of major functional crop types consistent with the global land-use reconstruction above, and currently used in LM3V. (Hurtt & Frolking, pers comm.)

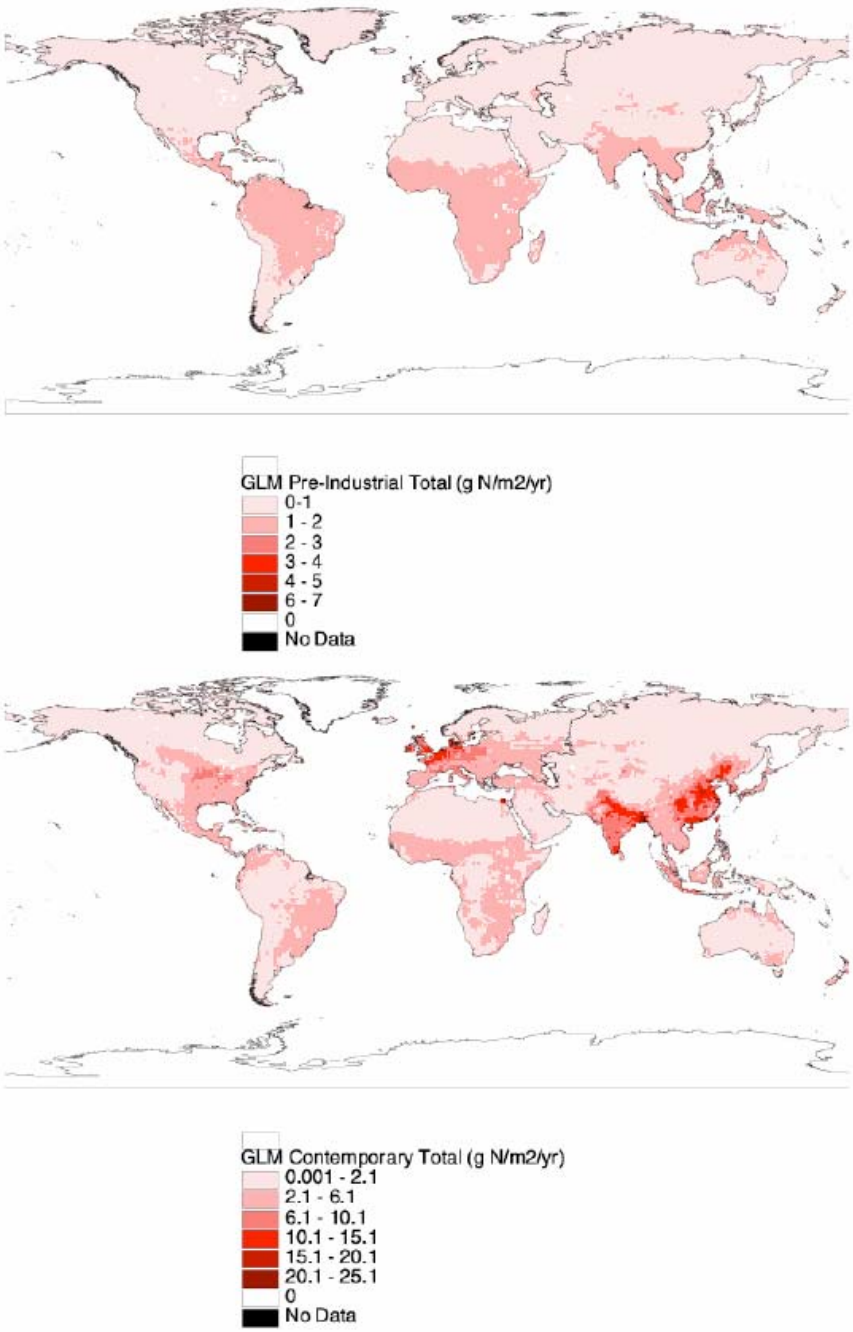

Fig. 4. (a) Pre-industrial, and (b) contemporary, annual total N loadings to the land surface (note scales differ). N loadings to the land surface include processes of fixation, deposition, fertilization, livestock, and other terms. Total contemporary loadings are much greater than pre-industrial loadings. These estimates are consistent with the global land-use information produced by this team and incorporated in the LM3V model. (Hurtt et al In prep.)

Progress Report: **Understanding the Temporal Evolution of the Global Carbon Cycle Using Large-Scale Carbon Observations**

Principal Investigator: Robert M. Key (Princeton Research Oceanographer)

Other Participating Researchers: Chris Sabine, Richard Feely(NOAA/PMEL),Rik Wanninkhof, T.-H. Peng (NOAA/AOML), Alex Kozyr (CDIAC)

Theme #2: Biogeochemistry

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

Objectives:
To quantify the accumulation of anthropogenic carbon dioxide in the global ocean and to use that information to better constrain models used to predict global climate change.

Methods and Results/Accomplishments:
In large part this work represents a continuation and natural extension of the Global Ocean Data Analysis Project (GLODAP). The primary goal of GLODAP was too use the massive oceanographic data set collected during the1990s to quantify the inventory of anthropogenic carbon dioxide in the ocean. The current project has two components: (1) data recovery and (2) analysis and innovation, each discussed briefly below.

(1) The data recovery aspect of this project was described in detail in the 2005 Progress Report. Very significant progress has been made during the past year on this goal, particularly with respect to the large and previously unavailable European data sets collected since approximately 1980. The number of European cruises with carbon and/or tracer data now totals 85 and several more are expected before the end of 2006. Newly acquired cruises include an annually occupied time series at 75N in the Nordic seas and Spanish time series occupied every other year along a line from NW Spain to the southern tip of Greenland. Still expected in an Icelandic time series which was occupied twice annually and covers the local region. Significant is the fact that the European carbon community has accepted Princeton as the initial "trusted" site for their data, both old and new. Arrangements have been developed with CDIAC and the European project office (CARBOOCEAN) in which data processed at Princeton are subsequently archived and distributed those web sites. In early July a meeting was held in Iceland between CARBOOCEAN carbon scientists and members of our team to plan synthesis efforts for the new European collection as well as those data collected by U.S. scientists (primarily from our group). A final submission date of Dec. 31, 2006 was set for those data which are to be included in the synthesis. Additionally, the synthesis effort was geographically segregated into 3 projects: the Nordic Seas, the North Atlantic and the Southern Ocean. Team leaders were selected for each group and lists of potential contributors (who were not at the meeting) compiled. Each group also outlined specific scientific goals in addition to the more routine secondary quality control work which is necessary prior to scientific synthesis. The amount of time and effort required to complete this work far exceeds the original estimate (which was for 30 cruises or less) covered by this proposal and additional funding has been requested. Key will again meet with the European scientists in Dec. 2006 to review progress and continue synthesis planning efforts.

(2) Significant progress has been made on data analysis which is primarily aimed at quantifying the decadal (or shorter time scale) increase in oceanic anthropogenic carbon. At the same time, this determination has turned out to be much more difficult than we originally thought. We had expected that a 10 year cruise separation time would be sufficient to reasonably estimate the carbon change simply by calculating the distribution difference between two occupations of the same line. In many

cases, however, this difference produces distribution patterns which are extremely complex. When the change is integrated for an entire section, the sign and magnitude of the change is reasonable. Some of our group recognized that concurrent changes in oxygen distributions could be responsible for some of the carbon change due to unequal organic carbon remineralization between the two occupations. Various techniques including MLR and graphical have been devised to remove the remineralization signal, however, so far there appears to be a problem with this procedure in shallow water. Independent and active efforts continue at Seattle, Princeton and Maimi to try to de-convolute the details of the carbon change for the data currently being collected.

Publications:

No refereed publications have yet resulted from this work; however several talks and posters have been presented with more planned for the fall AGU meeting. Several publications which were strongly dependent upon earlier efforts of this group are currently in press. Some of these are listed below.

McNeil, B.I., N. Metzl, R.M. Key and R.J. Matear, An empirical estimate of the Southern Ocean air-sea CO_2 flux, Global Biogeochem. Cycles, in press, 2006.

Sarmiento, J.L., J. Simeon and R.M. Key, Untangling deep ocean silicate and nitrate biogeochemistry, Global Biogeochem. Cycles, accepted, 2006.

Sweeney, C., E. Gloor, A.J. Jacobson, R.M. Key, G. McKinley, J.L. Sarmiento, R. Wanninkhof, Constraining global air-sea gas exchange for CO_2 with recent bomb 14C measurements, Global Biogeochem. Cycles, in press, 2006.

Waugh, D.W., T.M. Hall, B.I. McNeil and R.M. Key, Anthropogenic CO_2 in the oceans estimated using transit-time distributions, Tellus, in press, 2006.

Lee, K. L.T. Tong, F.J. Millero, C.L. Sabine, A.G. Dickson, C. Goyet, G.-H. Park, R. Wanninkhof, R.A. Feely and R.M. Key, global relationships of total alkalinity with salinity and temperature in surface waters of the major oceans, Geophys. Res. Lett., in press, 2006.

Progress Report: **CO_2/CLIVAR Repeat Hydrography Program CO_2 Synthesis Science Team**

Principal Investigator: Robert M. Key (Princeton Research Oceanographer)

Other Participating Researchers: Chris Sabine, Richard Feely(NOAA/PMEL),Rik Wanninkhof, T.-H. Peng (NOAA/AOML), Alex Kozyr (CDIAC), Frank J. Millero (RSMAS/Univ. of Miami), Andrew Dickson (Scripps)

Theme #2: Biogeochemistry

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

Objectives:
To quantify the accumulation of anthropogenic carbon dioxide in the global ocean and to use that information to better constrain models used to predict global climate change.

Methods and Results/Accomplishments:
Members of this group (primarily Frank Millero (U. Miami, RSMAS) and Andrew Dickson (UCSD, SIO) are participating in current ocean sampling as part of the U.S. led CLIVAR project. These cruises are covering some of the same lines sampled during the 1990 in order to document the change in anthropogenic carbon dioxide on a decadal time scale. All of the CLIVAR carbon data collected thus far are extremely high quality as are most of the hydrographic data. In keeping with CLIVAR goals, all of the new data that have been submitted have been through the initial quality control and calibration procedures and made public through CDIAC by approximately one year after the end of each cruise. Alkalinity data from 2 U.S. CLIVAR cruises have not been reported in a timely manner. The scientist responsible for the data is not part of our group. Data from the European CarboOcean project, which is focused on carbon in the North Atlantic has started to be accumulated, however the proprietary period for these data is longer than for U.S. data. Key is participating in this effort to help assure that the two projects coordinate as well as possible and to help assure that data sharing between the groups is as easy as possible. We are hopeful that the trust developed between Princeton and the European groups via the CARINA data recovery will eventually result in receipt of the European data quicker than currently envisioned.

Publications:
No refereed publications have yet resulted from this work; however several talks and posters have been presented with more planned for the fall AGU meeting. Several publications which were strongly dependent upon earlier efforts of this group are currently in press. Some of these are listed below.

McNeil, B.I., N. Metzl, R.M. Key and R.J. Matear, An empirical estimate of the Southern Ocean air-sea CO_2 flux, Global Biogeochem. Cycles, in press, 2006.

Sarmiento, J.L., J. Simeon and R.M. Key, Untangling deep ocean silicate and nitrate biogeochemistry, Global Biogeochem. Cycles, accepted, 2006.

Sweeney, C., E. Gloor, A.J. Jacobson, R.M. Key, G. McKinley, J.L. Sarmiento, R. Wanninkhof, Constraining global air-sea gas exchange for CO_2 with recent bomb 14C measurements, Global Biogeochem. Cycles, in press, 2006.

Waugh, D.W., T.M. Hall, B.I. McNeil and R.M. Key, Anthropogenic CO_2 in the oceans estimated using transit-time distributions, Tellus, in press, 2006.

Lee, K. L.T. Tong, F.J. Millero, C.L. Sabine, A.G. Dickson, C. Goyet, G.-H. Park, R. Wanninkhof, R.A. Feely and R.M. Key, global relationships of total alkalinity with salinity and temperature in surface waters of the major oceans, Geophys. Res. Lett., in press, 2006.

Progress Report: **Interannual Oxygen Concentration Variability in the Equatorial Pacific**

Principal Investigator: Keith Rodgers (Princeton Research Staff)

Other Participating Researchers: Jorge Sarmiento (Princeton), John Dunne (GFDL), Anand Gnanadesikan (GFDL), Donxiao Zhang (PMEL), Olivier Aumont (IRD, France)

Theme #2: Biogeochemistry

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

Objectives:
Assess dynamical controls on O_2 variability in the Pacific thermocline

Methods and Results/Accomplishments:

A series of forced ocean model experiments are being conducted to evaluate the dynamical controls on the variability of O_2 in the North Pacific Ocean. The experiments are being performed with two different modeling configurations, the MOM4-OGBC model and the ORCA2-PISCES model. Both have been forced with interannually varying surface fluxes, MOM4-OBGC over 1958-2000 and ORCA2-PISCES over 1948-2003.

Preliminary results indicate that although the models are able to capture some of the O_2 variability measured through Repeat Hydrography surveys, significant differences remain. Additionally, the two modeling configurations have not yet converged in their respective simulations of North Pacific O_2 variability.

The extent to which the difference between the observed and simulated variability in O_2 is due to biases in the model circulation fields, and the extent to which it is due to biases in the ocean biogeochemistry models, is currently being evaluated. In order to deconvolve these signals, it is our intention to include CFCs in future experiments, as this is unambiguously a circulation tracer. Preliminary results suggest that a skillful representation of variability in ocean biogeochemistry requires a skillful representation of the mean state.

Publications:

Rodgers, K.B., J.L. Sarmiento, R.M. Key, A. Gnanadesikan, N. Metzl, and A. Aumont, Natural Variability of Oceanic DIC Larger for North Pacific than Decadal Anthropogenic Perturbation Signal, in preparation for Global Biogeochemical Cycles.

Progress Report: **Detection and Attribution of Anthropogenic Changes in Oceanic DIC**

Principal Investigator: Keith Rodgers (Princeton Research Staff)

Other Participating Researchers: Jorge Sarmiento and Robert Key (Princeton), Anand Gnanadesikan and John Dunne (GFDL), Laurent Bopp (LSCE, France), Yasuhiro Yamanaka (U. Hokkaido, Japan)

Theme #2: Biogeochemistry

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

Objectives:
Use models to identify physical processes controlling natural variability in oceanic DIC, and apply this to the detection of anthropogenic DIC in the ocean.

Methods and Results/Accomplishments:

We are using models which include ocean biogeochemistry to address the question of how ocean chemistry, and in particular the oceanic distribution of DIC, is changing in response to human activity. Initial results through Repeat Hydrography suggest that while changes are occurring, they do not resemble the smoothly varying fields predicted by models which assume that the ocean is in steady state. Importantly, the uncertainties associated with extrapolating the measurements to arrive at a quantitative detection of the evolving ocean inventory of anthropogenic DIC are as large as the target signal. In order to properly interpret and use these data, and to quantify the anthropogenic CO_2 uptake by the ocean, it is vital to put them into a context of a changing ocean using numerical models.

It is our intention to apply the latest generation of the GFDL MOM4 ocean model to this question. The first priority will be to perform explicit interannually varying simulations with both the biogeochemistry model of John Dunne and CFCs, and to evaluate the model results against the existing Repeat Hydrography measurements. Second, in order to reduce uncertainty in the extrapolation of observations, model output will be used to develop a new method for extrapolation to the basin-scale. The third priority will be to use the model to identify the dynamical controls on the natural variability in oceanic DIC, and to use this information to develop new tools to interpret Repeat Hydrography measurements. In particular, we intend to investigate the implications of our preliminary results which suggest that sea surface height variability (a proxy for pycnocline depth variations) is highly correlated with the natural variability of pre-anthropogenic DIC inventories.

As a complement to the forced experiments with MOM4, it is our intention to also make use of the fully coupled GFDL Earth System Model (ESM2.1), as it is only with multiple experiments using an fully coupled model that a clear separation between the background natural variability and the anthropogenic perturbation is possible. This modeling component will provide an estimate of when the anthropogenic DIC perturbation will unambiguously emerge from the background natural variability. It is our intention that these simulations will contribute to decisions regarding the eventual extension of the existing sampling strategy of Repeat Hydrography.

Publications:

Rodgers, K.B., J.L. Sarmiento, R.M. Key, A. Gnanadesikan, N. Metzl, and A. Aumont, Natural Variability of Oceanic DIC Larger for North Pacific than Decadal Anthropogenic Perturbation Signal, in preparation for Global Biogeochemical Cycles.

Rodgers, K.B., J.L. Sarmiento, C. Crevoisier, A. Gnanadesikan, C. de Boyer Montegut, N. Metzel, and O. Aumont, A Wintertime Uptake Window for Anthropogenic CO2 in the North Pacific, in preparation for Global Biogeochemical Cycles.

Progress Report: **Optimal network design to detect spatial patterns and variability of ocean carbon sources and sinks from underway surface CO_2 measurements**

Principal Investigator: Joellen Russell (Princeton Research Staff; now Assistant Professor of Geosciences, University of Arizona)

Other Participating Researchers: Colm Sweeney (NOAA/ESRL), Anand Gnanadesikan (NOAA/GFDL, Princeton University), Richard Feely (NOAA/PMEL), and Rik Wanninkhof (NOAA/AOML).

***Theme #2*:** Biogeochemistry

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

Objectives:
The Second Report on the Adequacy of the Global Observing System for Climate in Support of the United Nations Framework Convention on Climate Change (UNFCCC) concludes, in agreement with the Intergovernmental Panel on Climate Change (IPCC), that there remain serious deficiencies in the ability of the current global observing systems for climate to meet the observational needs of the UNFCCC. One aspect of the effort to redress the identified deficiency has been to expand the surface ocean pCO_2 measurement program in the hopes of quantifying our understanding of the seasonal and interannnual variability of air-sea CO_2 fluxes in the world oceans. While there is a reasonably good understanding of the major sources and sinks of CO_2 based on the sea surface pCO_2 climatology developed by Takahashi et al. (2002), the motivation for this study is to produce the optimal global pCO_2 sampling network design by updating, expanding and extending the preliminary effort of Sweeney et al. (2002) who made a region-by-region estimate of the sampling required to quantify fluxes of CO_2 to the nearest 0.1 Pg C/year (See Fig. 1).

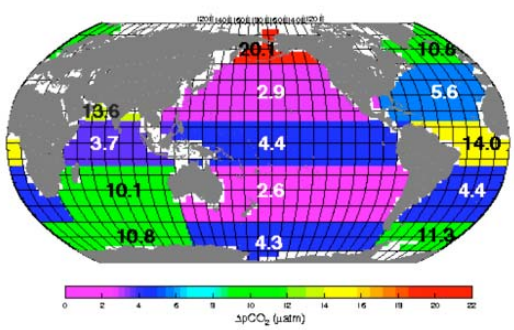

Figure 2: Target ΔpCO_2 to estimate a regional CO_2 flux within ± 0.1Pg-C/yr for the major oceanic regions.

Specific questions to be addressed include:

- What is the effect of seasonality on variability in surface pCO_2?
- Which sampling locations will be most representative of large-scale seasonal, interannual and decadal changes in the surface ocean pCO_2 and air-sea CO_2 flux?
- Which sampling locations will lead to the early detection of changes in surface pCO_2 concentrations and associated fluxes due to climate change?

The Sweeney et al. (2002) study suggests that a desired uncertainty of ±0.1 Pg C/yr in the basin-scale mean annual estimates for net sea-air CO_2 flux may be achieved by evenly time-spaced measurements of pCO_2 **6–15 times a year** throughout the regions of the world ocean with evenly spaced sampling **200–**

1500 km apart (or 2–20 degrees longitude, depending on region and latitude). This study will recalculate these targets using both a global pCO_2 database compiled from measurements made by the international carbon community (See Figs. 2, 3, 4), as well as output from simulations of future climate produced by GFDL's Earth System Model. As an integral part of this study we examine both high-resolution measurements made throughout the World Ocean and the NOAA/GFDL Earth System Model to identify the optimal observation network design to capture variability in surface water pCO_2 and the resulting air-sea flux from the seasonal to decadal time frames. The use of hind-cast and forecasting biogeochemical simulations produced in support of the most recent IPCC Scientific Assessment (AR4) will allow us to identify key locations where we expect to observe natural and anthropogenic trends.

Relationship to NOAA's Program Plan for Building a Sustained Ocean Observing System for Climate: (Objective 8: Ocean Carbon Monitoring Network)
Optimal design of the pCO_2 sampling network design using both the global database of pCO_2 measurements and simulations of future climate from GFDL's Earth System Model will help NOAA cost-effectively develop the infrastructure necessary to build, with national and international partners, the ocean component of a global climate observing system. The goal of this data and model-based pCO_2 sampling network design is to quantitatively assess the optimum sampling strategy based on the long-term observational requirements of the operational forecast centers, international research programs and major scientific assessments.

International Linkages:
Research strategies for global carbon cycle studies have been developed by various working groups of programs like the International Geosphere-Biosphere Programme (IGBP), the World Climate Research Programme (WCRP), the International Human Dimensions Program (IHDP), and the Intergovernmental Oceanographic Commission (IOC) working together. To achieve the goal of a global carbon synthesis, there is an immediate need for global-scale coordination of international carbon observation and research efforts. This study fulfills one component of the urgent need to critically assess the overall network of planned observations to ensure that the results, when combined, will meet the requirements of the research community. By providing an optimal network design for a global pCO_2 measurement program, we will have the potential to contribute to the International Ocean Carbon Coordination Project (IOCCP). We will also contribute to regional efforts such as CARBOOCEAN in the Atlantic and the PICES Working Group 13 in the North Pacific that are coordinating observations.

Methods and Results/Accomplishments:
Of the three integrated components of the optimal network design, we have
1.) Completed global pCO_2 database assembly for analysis-over 1.8 million measurements See Figs.2, 3).
2.) Begun analysis of seasonality, length and time scale of pCO_2 variability within the global pCO_2 database (See Fig. 4).
3.) Begun analysis of seasonality, length and time scale of pCO_2 variability within the GFDL Earth System Model.

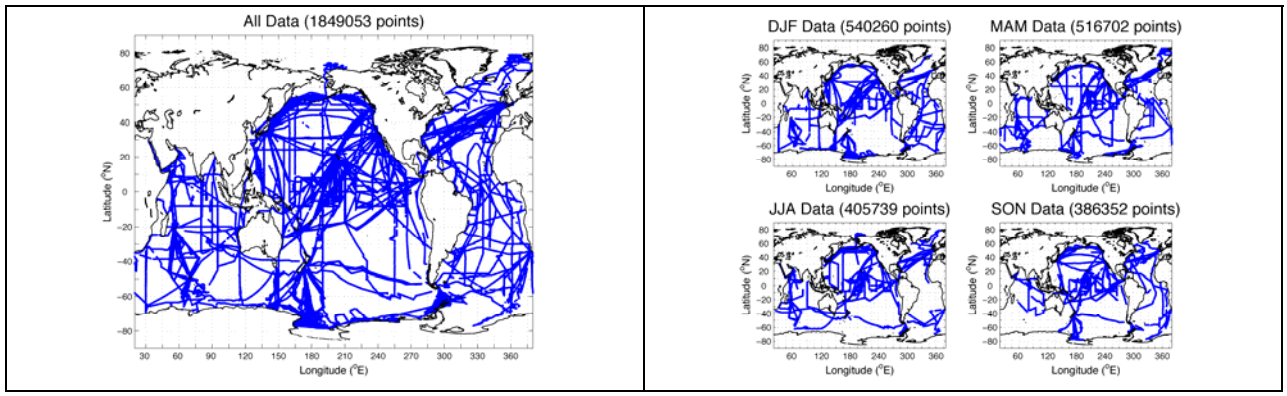

Figure 3: a) Spatial distribution of pCO_2 measurements in the global pCO_2 database; b) Seasonal distribution of pCO2 measurements in the global pCO_2 database (DJF is Dec-Feb, MAM is Mar-May, JJA is Jun-Aug, and SON is Sep-Nov).

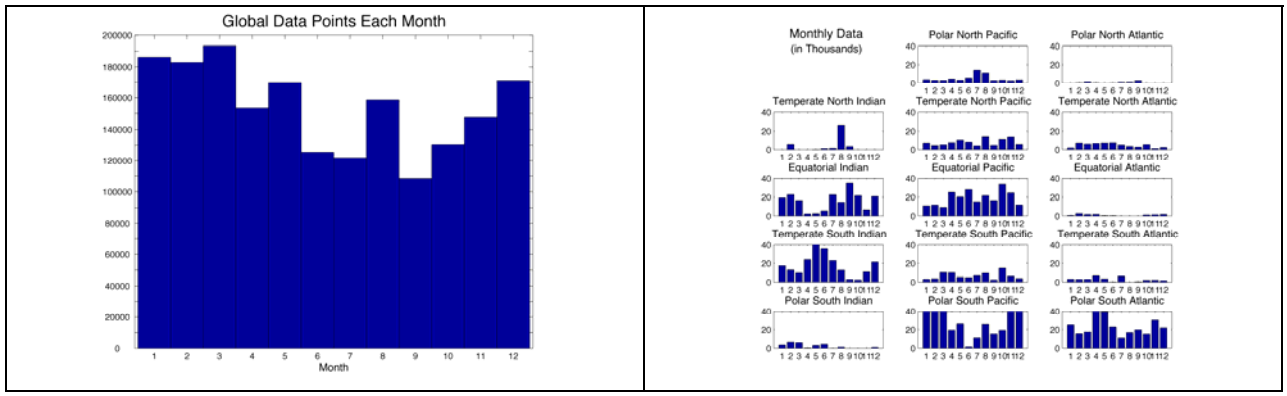

Figure 4: a) Temporal distribution of pCO_2 measurements in the global pCO_2 database (January = month 1); b) Temporal distribution of pCO_2 measurements within each region in the global pCO_2 database.

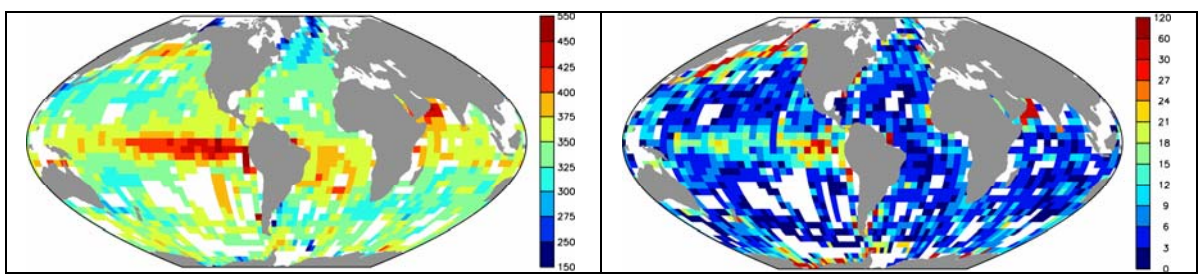

Figure 5: a) Annual average of monthly mean value of fCO_2 (ppm) in 4°x5° bins from the global database of pCO_2 measurements; b) Annual average of monthly fCO_2 (ppm) standard deviations in 4°x5° bins from the global database of pCO_2 measurements

References:

Sweeney, C., T. Takahashi and A. Gnanadesikan. 2002. Spatial and temporal variability of surface water pCO_2 and sampling strategies, p. 201. In M. Bender [ed.], A Large-scale CO_2 Observing Plan: In Situ Oceans and Atmosphere (LSCOP). NOAA, US Department of Commerce.

Takahashi, T., S. C. Sutherland, C. Sweeney, A. Poisson, N. Metzl, B. Tilbrook, N. Bates, R. Wanninkhof, R. A. Feely, C. Sabine and J. Olafsson. 2002. Biological and temperature effects on seasonal changes of pCO_2 in global surface ocean. Deep Sea Research II 49: 1601-1622.

Progress Report: **Ocean Biogeochemistry Model Development**

Principal Investigator: Jorge L. Sarmiento (Princeton Faculty)

Other Participating Researchers: John Dunne (GFDL), Jennifer Simeon (Princeton), Richard Slater (Princeton), Anand Gnanadesikan (GFDL), Isaac Held (GFDL), Bruce Wyman (GFDL)

Theme #2: Biogeochemistry

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

Objectives:
Implementation of tracers in MOM4; development of a flux coupler for the Flexible Modeling System (FMS); and development of a coarse resolution coupled atmosphere-ocean model with biogeochemistry for use in paleoclimate studies

Methods and Results/Accomplishments:
The following biogeochemical tracers have been implemented by Slater and Simeon in the latest release of MOM4 (Memphis): a diagnostic biogeochemistry model of nutrients and carbon, chlorofluorocarbons, iron, helium, radiocarbon and inorganic carbon uptake via the solubility pump. A new generation of biogeochemistry models will take advantage of the flexible modeling system, which has required the development of a generalized module capable of handling biogeochemical fluxes between the atmosphere/land and ocean/ice models.

The FMS coupler, the code that provides fluxes and fields from one model to another at the air-sea interface, has been modified by Rick Slater to allow for an arbitrary number of user-defined gas fluxes to couple atmospheric and oceanic tracers. The first implementations of the coupler are for oxygen and carbon dioxide to be used in the Earth System Model. The new coupler has become the default coupler with the Memphis release of FMS. Further innovations with the coupler include passing tracers from the atmosphere to the ocean via wet and dry deposition, as well as tracers from the land model to the ocean via river runoff. Documentation for the FMS coupler has been included in the latest versions of the MOM4 Technical Report [Griffies et al., 2004].

A coarse resolution version of the ocean model, MOM4, is currently being tested and tuned by Jennifer Simeon with the help of Gnanadesikan and Dunne, and will ultimately provide a platform for climate simulations on the timescale of decades to millennia. The coarse ocean model has nominally 3-degree resolution and is based on the latest source code release. The coarse ocean model has the ability to support both a diagnostic and prognostic biogeochemistry model. The coarse ocean model will also be able to operate in an ocean-only or coupled mode.

In pursuit of meeting the community challenge of creating fast running climate models that accurately reproduce our past climate, the coarse resolution ocean model is being configured to run in a coupled mode with a coarse resolution (nominally 3 degrees) version of GFDL's atmosphere model with the finite-volume core that Held is helping to develop. The coarse coupled model currently compiles and computes integrations on the order of decades. Further characterization of the coarse coupled model behavior is required as well as testing and tuning. The coarse coupled model currently runs at twice the speed of the CM2 models at 20 model-years per wall clock day.

References:
Griffies, S.M., M.J. Harrison, R.C. Pacanowski and A. Rosati, with Z. Liang, M. Schmidt, H. Simmons, and R. Slater. A Technical Guide to MOM4. GFDL Ocean Group Technical Report No. 5. NOAA/Geophysical Fluid Dynamics Laboratory, 2004.
Publications:

Dunne, J. P., R. A. Armstrong, A. Gnanadesikan, and J. L. Sarmiento, 2005. Empirical and mechanistic models for the particle export ratio. Global Biogeochem. Cycles, 19, GB4026, doi:10.1029/2004GB002390.

Progress Report: **Ocean Biogeochemical Processes**

Principal Investigator: Jorge L. Sarmiento (Princeton Faculty)

Other Participating Researchers: Jennifer Simeon and Richard Slater (Princeton), Anand Gnanadesikan (GFDL), Peter Schlosser (Columbia University), Robert M. Key (Princeton)

Theme #2: Biogeochemistry

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

Objectives:
Clarifying the role ocean biogeochemical processes in the global carbon cycle with emphasis on the Southern Ocean

Methods and Results/Accomplishments:

The Southern Ocean is a key region with regard to global carbon cycling. This is where air-sea interactions occur between the atmosphere and abyssal ocean CO_2 (Toggweiler et al., 2006; Mignone et al., 2006). It is also the region that accounts for about three-quarters of the global nutrient return from the deep ocean to the surface (Sarmiento et al. [2004]; Marinov et al., 2006; and Sarmiento et al., in revision). The Southern Ocean representation and its response to climate change is thus critical for realistic climate simulations.

A series of simulations has been conducted in a previous version of the GFDL ocean model, MOM3, to understand the pathways for biogeochemical tracers in and out of the Southern Ocean. For the upper ocean circulation, which is primarily influenced by the Southern Ocean Mode Waters, a dye tracer and the nutrient, phosphate, have been implemented in the model to diagnose the formation of SAMW and the subsequent impact on low-latitude productivity.

A dichotomy of concepts exists with regard to the location of the deep-water return flow to the surface ocean. Recent data analysis studies suggest that a significant amount of deep ocean water is brought to the surface north of the Southern Ocean, while several numerical models indicate that the upwelling occurs entirely within the Southern Ocean. The simulation of helium-3 in the ocean model, in conjunction with the recent release of an extensive data set of helium-3 observations, aims to distinguish the true location of upwelling pathways. Preliminary simulations were conducted in two versions of an ocean-only MOM3 (Gnanadesikan et al., 2004), the first of which has Low vertical mixing and Low horizontal diffusion (LL) and results in an overturning circulation with the primary deep ocean return pathway via the Southern Ocean. The second version of the model has High vertical mixing and High horizontal diffusion (HH) and results in an overturning circulation that has a significant return pathway in the low latitudes. The d^3He (%) in the figure below shows the mantle helium distribution in these two models.

Future work involves dye, phosphate and helium tracer simulations in a more sophisticated ocean model, MOM4. Helium tracers implemented in MOM4 will also be used to evaluate the performance of the ocean model.

Earlier work has shown the critical importance of Southern Ocean processes in the air-sea balance of CO_2, anthropogenic CO_2 uptake, and the supplying of nutrients for biological production through Southern Ocean upwelling which feeds into the base of the main thermocline as Subantarctic Mode Water. Initial steps have begun for characterizing the Southern Ocean Mode water development and formation in the GFDL CM2.0 and CM2.1 model ensembles using the existing physical variables. Further chararcterization of the Mode Waters will be conducted with biogeochemical variables once the biogeochemisty simulation is added to the GFDL CM2.1 ensemble.

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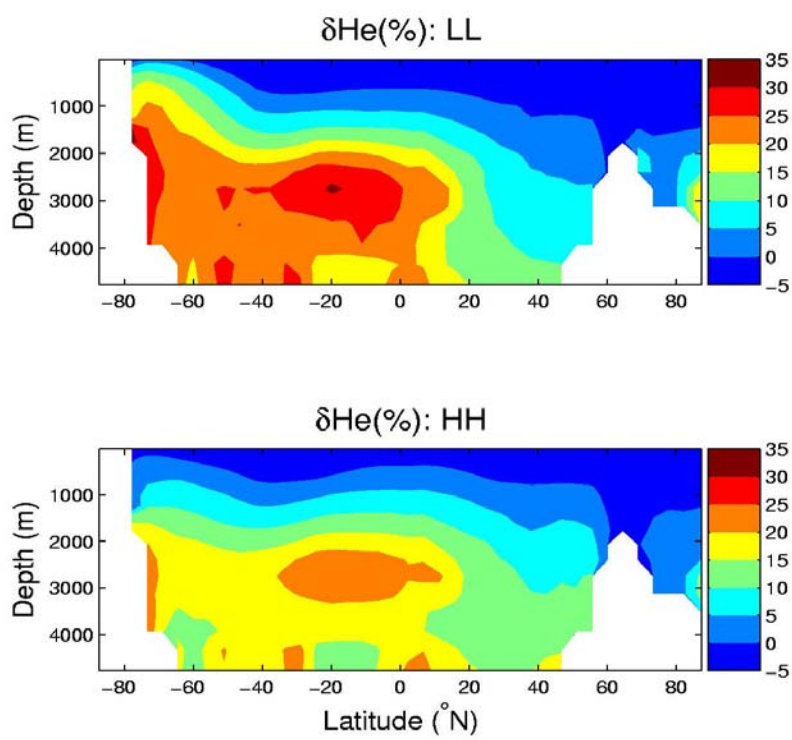

Figure. Global zonal average vertical section of d^3He (%). The LL model shows high d^3He in the Southern Ocean due to the high upwelling predicted to occur in that region by this model. The HH model has upwelling of deep water occurring primarily in low latitudes and consequently less d^3He in the Southern Ocean and higher concentrations in the main thermocline.

Progress Report: **Feedbacks Between Climate Change and the Ocean Carbon Cycle**

Principal Investigator: Jorge L. Sarmiento (Princeton Faculty)

Other Participating Researchers: Robbie Toggweiler (GFDL), John Dunne (GFDL), Ronald Stouffer (GFDL), Anand Gnanadesikan (GFDL), Keith Dixon (GFDL), Richard Slater (Princeton), Jennifer Simeon (Princeton)

Theme #2: Biogeochemistry

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

Objectives:
Implementation of ocean biogeochemical tracers in CM2.1 to diagnose climate feedbacks

Methods and Results/Accomplishments:

GFDL's CM2 climate model is being utilized to conduct simulations to identify the feedbacks between climate change and the ocean carbon cycle. To complement the GFDL CM2 simulations conducted for the IPCC report, further global warming simulations will include an ocean biogeochemistry model within the framework of the CM2 model as well as predictions of the uptake of anthropogenic CO_2 by the ocean. The initial ocean biogeochemistry model planned for these simulations is a diagnostic model following the Ocean Model Intercomparison Project, Phase II (OCMIP2) protocols, but with an expanded suite of tracers. Other biogeochemical tracers that will be included are: chlorofluorocarbons (CFCs), radiocarbon and a perturbation CO_2 tracer used to estimate the oceanic uptake of anthropogenic carbon (Sarmiento et al., 1992; Siegenthaler and Joos, 1992).

A series of simulations has been planned to identify the various feedbacks in the climate system. The initial effort is geared towards a 500-year spin-up of CM2.1, starting from 1860. The figure shows results from tests we have been running to determine how to best initialize the spin-up simulation. After the model spin-up, three additional simulations will be carried out: (1) a 240-year run with the IPCC emissions scenario, SRESA1B, (2) a 240-year run without the emissions forcing, (3) a 240-year run with emissions, but without climate feedbacks. The scenario, SRESA1B, represents a balanced use between fossil fuels and other energy sources (such as high-tech renewables) in a world of rapid economic growth, moderate population growth and substantial reduction in regional differences of per capita income, and increased socio-economic globalization.

The accomplishments to-date include code revisions of the biogeochemistry module required for the update to the Memphis-release version of MOM4, as well as reconfiguration of the biogeochemistry model to the CM2.1 grid. The biogeochemistry module has been run successfully for two years in a configuration similar to CM2.1. A further test will be conducted in the CM2.1 experimental set-up. With regard to the anthropogenic CO_2 tracers, the perturbation CO_2 tracer module is pending. The module including radiocarbon has been coded and compiled, but execution and testing of the module remains to be completed. The OCMIP2 CFC module is complete and has been compiled and run.

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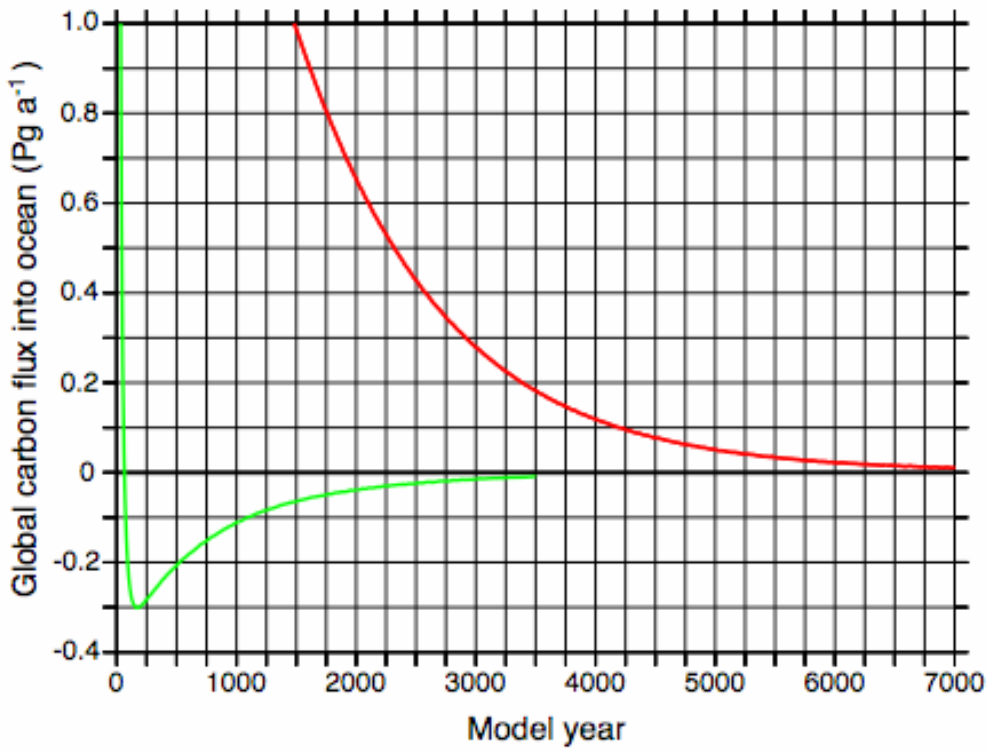

Figure 1a. The figure shows results from a set of simulations that have been carried out to analyze how to initialize the new GFDL Earth System Model so as to avoid long and costly spin up times. The ecosystem model used is the OCMIP-2 version of the BIOTIC model. Positive values denote CO_2 fluxes from the atmosphere into the ocean. An asymptotic flux of zero indicates model convergence. The red line is for a model that was initialized with uniform initial concentrations of 2370 meq/kg and 2000 mmol/kg for alkalinity and dissolved inorganic carbon (DIC), respectively. The green line is for a model that was initialized at observations using the GLODAP datasets with initial mean concentrations for alkalinity and DIC of 2363 meq/kg and 2249 mmol/kg, respectively. The model initialized at observations is clearly superior to the model initialized with uniform concentrations, though it still does not converge to a solution until it has been run out for several thousand years. Additional tests show that the model initialized at observations gives almost the same anthropogenic CO_2 uptake regardless of whether these perturbation simulations are run at year 500 or after the model has converged to a solution (see Figure 1b).

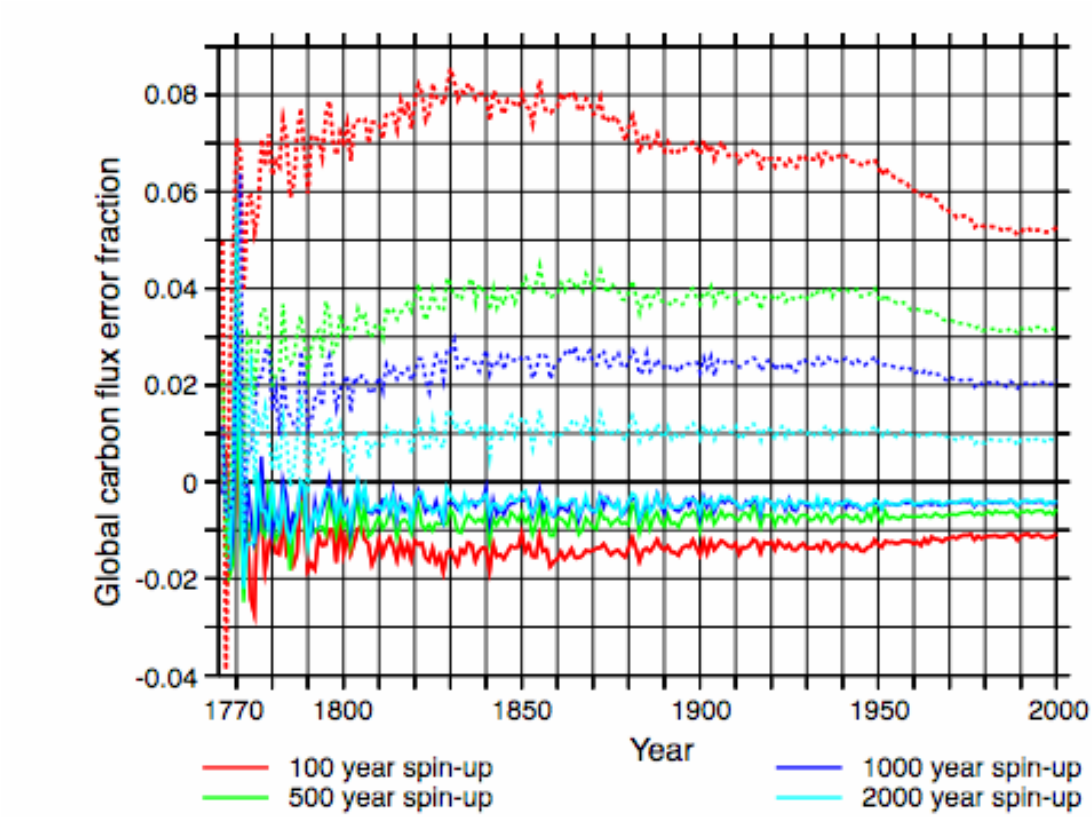

Figure 1b. Fractional error for OCMIP-2 historical (1765-2000) anthropogenic carbon simulations between simulations starting after a spin-up of the given number of years, and simulations starting from a completely spun-up carbon model. The dashed lines are for spin-up from constant DIC and alkalinity (red line in Fig. 1a), and solid lines for spin-up from data (green line in Fig. 1a). The fractional error is calculated as (partial – complete) / complete.

Progress Report: **Land Cover and Carbon Dynamics and Their Interactions with Climate**

Principal Investigators: Elena Shevliakova and Sergey Malyshev (Princeton Research Staff, EEB)

Other Participating Researchers: M. Spellman, K. Findell and R.J. Stouffer (GFDL), P.C. D. Milly (USGS), S. Pacala, S. Gerber, L. Hedin and C. Crevoisier (Princeton), S. Klein, X. Jiang and S. Xie (LLNL)

Theme #2: Biogeochemistry and also contributes to:
Theme #1: Earth System Studies/Climate Research

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

Objectives:
Develop modeling and analysis capabilities to understand past and project future changes in land cover and carbon.

Methods and Results/Accomplishments:
A. Development of Earth System Model Components.

A.1 Land model LM3V. During the past year Shevliakova in collaboration with S. Malyshev, M. Spellman (GFDL), R.J. Stouffer (GFDL), and P.C.D. Milly (USGS) evaluated a coupled equilibrium climate-land model (SM2.1-LM3V), including the full range of the land–climate biophysical interactions. Experiments with different settings of land parameters were carried out to evaluate the differences between the climate from the standard SM2.1 configuration (with LM2) and the climate from the SM2.1-LM3V configuration. Subsequent tunings of the land radiation and biophysical parameterizations significantly reduced the annual temperature and precipitation biases.

LM3V is already coupled and fully interactive with the GFDL ESM2.1 model. Shevliakova and Malyshev contributed to the model configuration, the experiment design and analysis of the results from the first 200 year simulation with ESM2.1. Shevliakova and Malyshev evaluated LM3V performance in ESM2.1.

Additionally, Shevliakova and Malyshev collaborated with S. Gerber and L. Hedin on development of a nitrogen branch of LM3V, with C. Crevoisier on development of the new seasonal fire model, and with G. Hurtt (UNH) on the integration of the improved scenarios of land use change.

A.2 Land model LM3. During the last year we continued to focus on enhancement of the land model capabilities. Malyshev lead the design of LM3 architecture and integration of LM3V and LM3W capabilities in the newly developed modeling system. The merge of these models required development of a new design and code infrastructure that allowed both dynamic tiling and modular treatment of vegetation, snow, soil, lake, glacier and canopy air components. Shevliakova has contributed to the design of LM3 and worked on modifications of LM3V parameterizations required for the integration. At various stages the merged code has been tested against LM2, LM3W and LM3V codes in stand alone and coupled to AM2 configurations.

A.3 FMS flux exchange module. During the past year Malyshev has continued working, in collaboration with other FMS developers, on the enhancements of the FMS flux exchange module, including the provisions for dynamic land tiling and the implicit tracer exchange (including CO_2) between the land and atmosphere models. This joint work contributed to the successful release of the "Memphis" version of GFDL's FMS that specifically targets ESM2.1 development.

B. Scientific Applications.

B.1 Analysis of effects of land-use on the terrestrial carbon dynamics in the stand-alone LM3V model. Shevliakova in collaboration with S. Pacala, S. Malyshev and G. Hurtt (UNH) performed a set of experiments with LM3V, forced with the output from the GFDL atmospheric model AM2 and observed precipitation under two different land-use scenarios. The analysis of the experiments indicates that LM3V adequately simulates current global gradients of net primary productivity, leaf area index, biomass accumulation, and runoff in response to both climate forcing and land-use changes. The analysis of these experiments revealed high model sensitivity to the choice of land-use scenarios, particularly the assumptions about harvesting practices in different land use categories.

B.2 Analysis of the coupling between LM3V and the GFDL atmospheric model AM2. Malyshev is leading a study in collaboration with E. Shevliakova, P.C. D. Milly (USGS) and S. Pacala to asses the effect of the new parameterizations of land surface processes in LM3V on the GFDL atmospheric model AM2. The analysis focuses on the sensitivity of the atmosphere/land interactions to the land surface scheme, specifically replacement of LM2 with LM3V model. Malyshev has performed numerical experiments in AM2p14/LM2 configuration with the prescribed Hurrell 50-year record of sea surface temperature and Matthews potential vegetation land cover dataset. The results of this experiment will be the base for comparison of climate. Additionally, the output of this experiment was used as the forcing for the multi-decadal LM3V spin-up.

B.3 Initialization of coupled land/atmosphere/ocean models for seasonal forecasts. Malyshev collaborated with C. T. Gordon (GFDL) and other scientists from NASA and NOAA on the study of the coupling strength between the land and the atmosphere. Specifically, the study explored the potential influence of the land model initialization on forecasts on seasonal and shorter time scale. As a result, the initialization schemes for the land properties, in particular soil moisture has been developed. Malyshev also collaborated with C. T. Gordon in a related study that focuses on initialization of the state of the atmosphere for ensemble seasonal forecasts. He implemented a flexible system that generates and uses "bred vectors" (or fastest growing perturbations) to produce atmospheric initial conditions that, while close to the actual reanalysis data, provide enough spread in the atmosphere to cover error space and thereby potentially improve the quality of the ensemble forecast.

B.4 Impact of Cumulative Anthropogenic Land Cover Change on Climate. Shevliakova collaborated with K. Findell, P.C.D. Milly, and R. Stouffer on a study about the impact of 300 years of cumulative anthropogenic land cover change on climate. The equilibrium climate model suggests that observed land cover changes have little or no impact on globally averaged climatic variables. Differences are very small and field significance is not achieved in annual mean global representations of the climatic fields analyzed. Within some of the regions of land cover change, however, there are relatively large changes to many climatic variables at the earth's surface. These changes are highly significant in the annual mean and in most months of the year in Eastern Europe and Northern India, and can be explained through physical mechanisms resulting from the prescribed differences in land surface properties.

B.5 Diagnosis of the atmospheric model biases. Malyshev collaborated with S. Klein (LLNL), X. Jiang and S. Xie in a study of possible reasons for the warm and dry climate biases exhibited by GFDL atmospheric model in the central US. The study used short-term weather forecasts with prescribed initial conditions to untangle cause and effect relationship in land-atmosphere interactions. With the model simulating realistic evaporation but underestimated precipitation, a deficit in soil moisture results which amplifies the initial temperature bias through feedbacks with the land surface. The underestimate of precipitation is associated with an inability of the model to simulate the eastward propagation of convection from the front-range of the Rocky Mountains and is insensitive to an increase of horizontal resolution.

B.6 Evaluation of biophysical processes governing air-land exchanges over North America. Shevliakova and Malyshev have contributed to the development of a proposal that won a financial support from DOE/NICCR. This project proposes to simultaneously use eddy flux data, atmospheric CO_2 data and forest inventories to estimate biophysical parameters for the new process-based vegetation model LM3V. To initiate the project, Malyshev has developed a computationally efficient runtime environment to gather information about the model performance with a numerous sets of parameter combinations. He has designed and implemented changes to the FMS infrastructure to accommodate the specific requirements for the parameter estimation in LM3V experiments.

B.7 Last Glacial Maximum Simulation. A project led by T. Delworth (GFDL) aims to simulate the climate of last glacial maximum (LGM) using GFDL's CM2.1. Malyshev has contributed to the preliminary set-up of the model by providing updated land properties, in particular river routing map suitable for LGM continent boundaries.

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Malyshev, S., E. Shevliakova, S.W. Pacala, and P.C.M. Milly (in preparation). The impact of the new land model LM3V on the GFDL Atmospheric Model Simulation of Climate and Climate Sensitivity.

Randal D. Koster, Zhichang Guo, Paul A. Dirmeyer, G. Gordon Bonan, Edmond Chan, Peter Cox, C.T. Gordon, Shinjiro Kanae, Eva Kowalczyk, David Lawrence, Ping Liu, Cheng-Hsuan Lu, Sergey Malyshev, Bryant McAvaney, J.L. McGregor, Ken Mitchell, David Mocko, Taikan Oki, Keith W. Oleson, Andrew Pitman, Y.C. Sud, Christopher M. Taylor, Diana Verseghy, Ratko Vasic, Yongkang Xue, and Tomohito Yamada, (Submitted to *J. of Hydrometeorology*).GLACE: The Global Land-Atmosphere Coupling Experiment. 1. Overview.

Zhichang Guo, Paul A. Dirmeyer, Randal D. Koster, Gordon Bonan, Edmond Chan, Peter Cox, C.T. Gordon, Shinjiro Kanae, Eva Kowalczyk, David Lawrence, Ping Liu, Cheng-Hsuan Lu, Sergey Malyshev, Bryant McAvaney, J.L. McGregor, Ken Mitchell, David Mocko, Taikan Oki, Keith W. Oleson, Andrew Pitman, Y.C. Sud, Christopher M. Taylor, Diana Verseghy, Ratko Vasic, Yongkang Xue, and Tomohito Yamada, (Submitted to *J. of Hydrometeorology*). GLACE: The Global Land-Atmosphere Coupling Experiment. 2. Analysis.

Stephen A. Klein, Xianan Jiang, Jim Boyle, Sergey Malyshev, and Shaocheng Xie (Submitted to *Geophysical Research Letters*). Diagnosis of the summertime warm and dry bias over the U. S. Southern Great Plains in the GFDL climate model using a weather forecasting approach.

Progress Report: **Development Of Freshwater Biogeochemical Model For The Princeton/GFDL Earth System Model**

Principal Investigator: Charles Vörösmarty (University of New Hampshire Faculty)

Other Participating Researchers: Balazs Fekete (UNH), Wilfred Wollheim (UNH)

Theme #2: Biogeochemistry

NOAA's Goal #1: Protect, Restore, and Manage the Use of Coastal and Ocean Resources through Ecosystem-based Management 33%
NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond 33%
NOAA's Goal #3: Serve Society's Needs for Weather and Water Information 33%

Objectives:
To develop a process-based freshwater biogeochemical model for the GFDL Earth System Model that incorporates the role of inland aquatic ecosystems in global biogeochemical cycles and in regulating material fluxes from land to ocean.

Methods and Results/Accomplishments:
During the past year we completed the initial phase of familiarizing ourselves with the Princeton/GFDL Earth System model and incorporating a preliminary version of FrAMES (Framework for Aquatic Modeling in the Earth System) into the ESM to model freshwater biogeochemical processes. Among the specific accomplishments were:

1) Porting and application of parts of the GFDL Earth System Model (River_Solo component of the larger LM3 model provided by Kirsten Findell) on the UNH computer cluster. This enabled us to better understand the GFDL modeling environment, parallelization, etc. in order to begin incorporating the aquatic biogeochemical routines.

2) Implementation of single species nutrient processing (nitrogen) in aquatic systems. We used the runoff and river routing results from the 25 year (1980-2004) application of the Land Model (LMW; from Chris Milly and Kirsten Findell). We implemented kinetic parameters for denitrification based on empirical work (Garcia-Ruiz et al. 1998; Mulholland et al. 2004). For the current model development phase, we assumed that N loading concentrations were uniform in time and space (1 mg N/L). Preliminary results suggest that temporal variability in N fluxes and N removal are consistent with observations (based on USGS measurements at the Mississippi mouth, Figure 1A, B). Temporal variability is consistent with expectations based on previous reports (Figure 1C; Donner et al. 2004). The underprediction of TN flux from the Mississippi arises from 1) underprediction of annual discharge, 2) lack of true N input concentrations (we assumed a uniform 1 mg N / L, though true input concentrations are likely greater), and 3) simplicity of the N processing routines currently incorporated. The proportion of inputs removed by aquatic systems are relatively low (4-12% depending on annual moisture conditions, Figure 1C), resulting from the coarse 30 minute river network resolution (i.e. smaller streams and rivers are not accounted for), lack of lake and reservoir processing, and from the hydraulic assumptions (relatively narrow channels are assumed), consistent with the analysis of Wollheim et al. (2006; in Revision). In the coming year we will introduce more realistic aquatic N input data sets (based on Green et al. 2004, and eventual predictions from LMveg) and add complexity to the aquatic N processing routines (e.g. varying processing rates based on temperature and N form). We will also begin to incorporate C and P processing modules that will allow us to couple biogeochemical cycles and allow us to quantify the role of aquatic systems in the carbon cycle as well.

3) Provided data sets of monthly TN and DIN fluxes from continents to oceans for phase 1 of the N demonstration project currently underway. The data sets are being used by John Dunne to drive the ocean biogeochemical model in pre-industrial and contemporary setting. These data sets were based on an existing whole basin empirical model developed by UNH (Green et al. 2005)

4) One paper was published (Wollheim et al. 2006) , and another is in revision (Wollheim et al. in revision). These were partially funded by the Princeton/GFDL collaboration. The papers explore the factors that define river network capacity to control nutrient exports and will be useful for further developing FrAMES in the ESM.

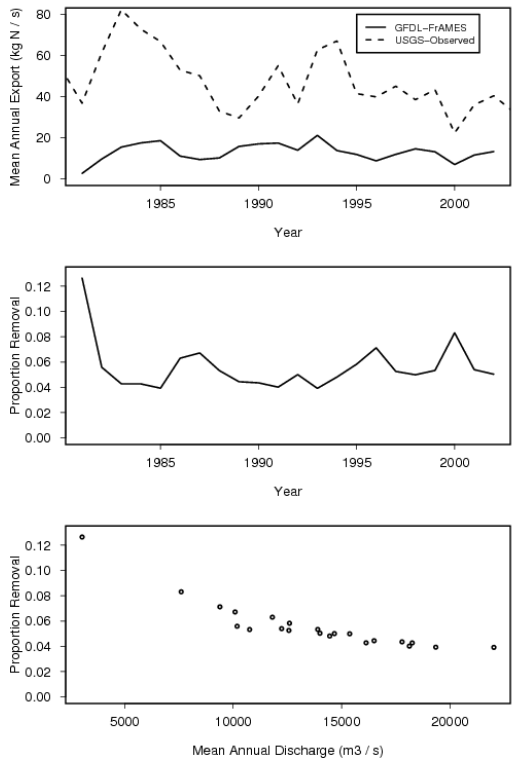

Figure 1. FrAMES/GFDL results for the Mississippi Basin showing A) predicted and observed annual TN flux at the mouth , B) predicted proportion of aquatic inputs removed, and C) relationship between annual aquatic removal and mean annual discharge. Note that these are preliminary results using model development data sets that will require further refinement, but show the dynamics that FrAMES will provide.

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Progress Reports:

Coastal Processes

Progress Report: **Ecological Forecasting In The Coastal Zone: Demonstration On The Northeast North American Continental Shelves**

Principal Investigator: Dale B. Haidvogel (Professor, IMCS, Rutgers University)

Other Participating Researchers: Katja Fennel (Rutgers), Mike Previdi (Rutgers), John Wilkin (Rutgers)

Theme #3: Coastal Processes

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

Objectives:
This project has multiple science and technical development themes (S1-S2 and D1-D3, respectively). The objectives for AY2005/2006 included: (S1) to conduct retrospective simulations of bio-geochemical cycles in the Western North Atlantic, and to assess the processes responsible for the simulated variability; and (D1) to evaluate the sensitivity of the ROMS U.S. East Coast model to the dynamical formulation of its open boundary conditions, and the manner in which boundary data from the exterior circulation model are sampled and preprocessed.

Methods and Results/Accomplishments:
(S1) We are currently using the Regional Ocean Modeling System (ROMS) to study interannual variability in the air-sea exchange of carbon dioxide (CO_2) in the Middle Atlantic Bight (MAB). Model implementation and preliminary validation has been described in Fennel *et al.* (2006). In our more recent work, two years marked by opposite phases of the North Atlantic Oscillation (NAO) were selected and the ocean state during these years was then simulated with ROMS. Model results indicate an increase in the uptake of atmospheric CO_2 by the ocean over most of the MAB during the low phase of the NAO relative to the high phase (Fig. 1). We are working to attribute these differences in air-sea flux to various physical and biological processes. The difference in the annually-integrated CO_2 air-sea flux, δF, between opposite phases of the NAO can be approximated using a second-order Taylor series expansion:

$$\delta F = \sum_{i=1}^{n} \frac{\partial F}{\partial X_i} \delta X_i + \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{\partial^2 F}{\partial X_i \partial X_j} \delta X_i \delta X_j + e$$

where e is a residual term of order $\partial^3 F/\partial X_i^3$ and $X_1,\ldots,X_n$ are parameters in the equation for F (i.e., $F = F(X_1,\ldots,X_n)$). This method allows us to estimate the sensitivity of F to various changes in the system, and incorporates the effects of non-linear interactions between different processes (by including estimates of the second-order partial derivatives of F). Figures 2 and 3 highlight some preliminary results from this analysis, namely the contributions of interannual differences in surface wind speed and air-sea pCO_2 (CO_2 partial pressure) gradient (ΔpCO_2) to δF. Wind speed changes between the high and low phases of the NAO act to increase oceanic uptake of CO_2 during the latter over nearly all of the MAB (Fig. 2). The effects of interannual differences in ΔpCO_2, on the other hand, are much more spatially variable, with these differences contributing to an overall increase in CO_2 uptake by the ocean during the low phase of the NAO over the northern MAB and an overall decrease in CO_2 uptake over the southern MAB (Fig. 3). This sub-project will be completed in AY2006/2007 by examining interannual differences in ΔpCO_2 by way of accompanying changes in sea surface temperature, biological activity, and the physical transport of carbon by the ocean circulation.

(D1) The first development theme entails a systematic study of how large-scale climate models can best be sampled, averaged or interpolated for effective nesting applications. With NOPP support for a graduate student at Rutgers University, we have first performed an initial "proof of concept" using the GODAE HyCOM (Hybrid Coordinate Ocean Model) data-assimilating North Atlantic basin model http://hycom.rsmas.miami.edu, using it as the source of open boundary conditions for the ROMS NENA model. Circulation within the MAB is found to be degraded, relative to observations, by biases in the tracer fields provided as boundary conditions by HyCOM. Statistical procedures, involving *ad hoc* correction of the HyCOM data using the World Ocean Atlas, improve the MAB circulation substantially. Further improvements await more rigorous, assimilation-based correction procedures (development theme D2). This sub-project will be extended in AY2006/2007 by embedding the ROMS NENA model within the GFDL global climate model, initially using asynchronous one-way coupling.

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Fennel, K., J. Wilkin, J. Levin, J. Moisan, J, O'Reilly and D. Haidvogel, 2006. Nitrogen cycling in the Middle Atlantic Bight: Results from a three-dimensional model and implications for the North Atlantic nitrogen budget. *J. Geophys. Res.,* in press.

Publications:

Fennel, K., J. Wilkin, J. Levin, J. Moisan, J, O'Reilly and D. Haidvogel, 2006. Nitrogen cycling in the Middle Atlantic Bight: Results from a three-dimensional model and implications for the North Atlantic nitrogen budget. *J. Geophys. Res.*, in press.

Related synergistic activities:

ROMS has recently been adopted by the NOAA National Ocean Service (NOS) for utilization as an operational platform for (e.g.) water level forecasting in shallow seas and estuaries. The transitioning of ROMS to operational use at NOAA NOS will begin in AY2006/2007.

Efforts to implement one- and two-way coupling of ROMS to the NCAR Community Climate System Model via the Modeling Coupling Toolkit (MCT) and the Earth System Modeling Framework (ESMF) are underway.

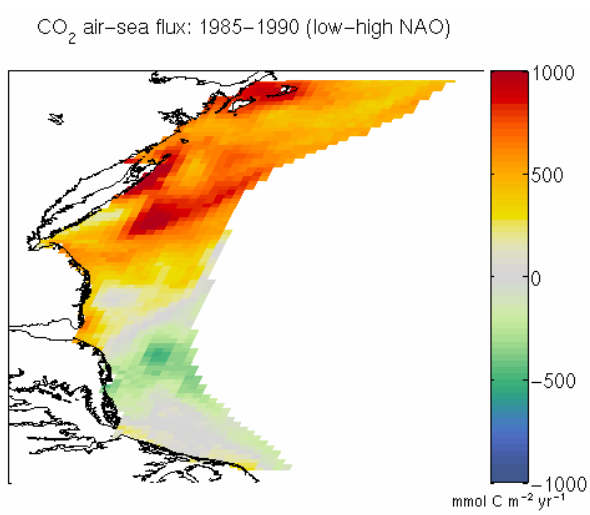

Figure 1. Difference in the annually-integrated CO_2 air-sea flux (in mmol C m^{-2} yr^{-1}) between 1985 (low NAO) and 1990 (high NAO). Positive values denote increased uptake of atmospheric CO_2 by the ocean.

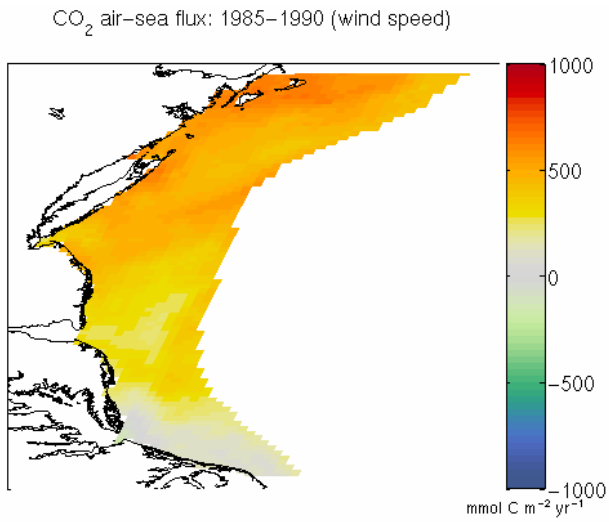

Figure 2. Difference in the annually-integrated CO_2 air-sea flux (in mmol C m^{-2} yr^{-1}) between 1985 (low NAO) and 1990 (high NAO) associated with interannual differences in surface wind speed.

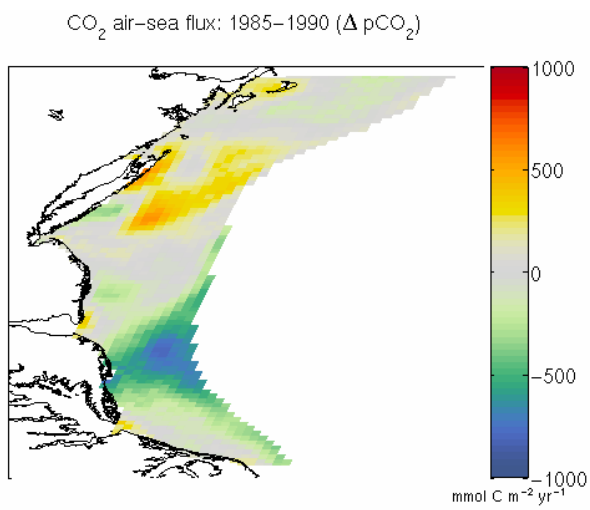

Figure 3. Difference in the annually-integrated CO_2 air-sea flux (in mmol C m^{-2} yr^{-1}) between 1985 (low NAO) and 1990 (high NAO) associated with interannual differences in the air-sea pCO_2 gradient, ΔpCO_2.

Progress Reports:

Paleoclimate

Progress Report: **The Effect Of Whole Ocean Temperature Change On Deep Ocean Ventilation**

Principal Investigator: Agatha M. de Boer (Princeton Research Associate)

Other Participating Researchers: Daniel M. Sigman (Princeton Univ) and J. Robert Toggweiler (GFDL)

Theme #4: Paleoclimate

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

Objectives:

A growing number of paleoceanographic observations suggest reduced overturning in the Antarctic and Subarctic North Pacific during colder times over the last 3 million years (Sigman et al., 2004). The objective of this study is to test, using an ocean general circulation model, whether this could simply be a consequence of the seawater's non-linear equation of state, which indicates that the density of seawater is less sensitive to temperature at low temperatures. Several implications follow from this non-linearity. First, polar regions are stratified by freshwater, especially in the summer, but sufficient winter cooling and sea ice formation can destabilize the water column and initiate deep convection. At the freezing point, the change in density with temperature, $\Delta\rho/\Delta T$, approaches zero. In this limit, the surface thermal forcing becomes impotent, and convection cannot occur if a fresh surface layer exists. In contrast, a homogenous warming would increase $\Delta\rho/\Delta T$ and thereby promote the formation of deep water. Second, the equator-pole density gradient is enhanced in a warm world, again because of a larger $\Delta\rho/\Delta T$. Scaling analysis suggests that the thermocline will shoal and sharpen, thereby enhancing the downward mixing of heat at low latitudes. As a consequence, deep convection can take place more easily to replace the warm water in the abyss. Third, geostrophic currents are driven by across-stream density gradients. Where the flow is moving in accordance with the temperature-induced density gradient (cold water on the right in the southern hemisphere), one can expect an increase in velocity with an increase in mean temperature (given the same surface temperature gradients). The Antarctic Circumpolar Current (ACC) is the strongest current of this type, and one would expect an increase in its transport during warm climates. Our goal is to determine the importance and implications of the above mentioned expected effects of the non-linearity of the equation of state.

Methods and Results/Accomplishments:

We use a general ocean circulation model (MOM4) coupled to an energy moisture balance for the atmosphere to test the hypothesis that the mean temperature-ventilation relation is due to the reduced sensitivity of seawater density to temperature at low mean temperature; that is, at lower temperatures, the surface cooling is not as effective at densifying fresh polar waters and initiating convection. In order to isolate the effect of the non-linearity of the equation of state from other climate-related feedbacks, we changed the model ocean temperature only where it is used to calculate the density (to which we refer below as 'pseudo–' temperature change). We find, in agreement with scaling analysis, that a pseudo-cold ocean is globally less ventilated than a pseudo-warm ocean. With pseudo-cooling, convection decreases markedly in regions that have strong haloclines (i.e., the Southern Ocean and the North Pacific, while overturning increases in the North Atlantic, where the positive salinity buoyancy is smallest among the polar regions. We propose that this opposite behavior of the North Atlantic to the Southern Ocean and North Pacific is the result of an energy-constrained overturning.

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Ph.D. Thesis:

E. P. Gerber, December 20, 2005. A Dynamical and Statistical Understanding of the North Atlantic Oscillation and Annular Modes, PhD Thesis, Princeton University.

Dargan Frierson July 11, 2005. Studies of the General Circulation of the Atmosphere with a Simplified Moist GCM, PhD Thesis, Princeton University.

Huiyan Yang, July 12, 2005. The Modeling of Tropospheric Photochemistry and Black Carbon Aerosol: Examinations of Radiation, Transformation, Concentrations and Emission Reduction Aspects, PhD Thesis, Princeton University.

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	JI Lead Author				NOAA Lead Author				Other Lead Author			
	FY03	FY04	FY05	FY06	FY03	FY04	FY05	FY06	FY03	FY04	FY05	FY06
Peer-reviewed	4	12	30	26	1		3	5	1	10	14	22
Non Peer-reviewed	2	4	6	3							2	
Chapters in books		2									3	1
Ph.D. Thesis		1	1	3								

CICS Fellows - Princeton University

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 CICS Fellows include senior research staff at GFDL and the following faculty members at Princeton University:

Lars O. Hedin, Professor of Ecology and Evolutionary Biology and Princeton Environmental Institute, a biogeochemist who does research on the terrestrial nitrogen cycle.

Sonya A. Legg, Lecturer of Geosciences and Research Oceanographer in the Program of Atmospheric and Oceanic Science, who does research on turbulent mixing in the ocean, with primary tools being numerical simulation and theory.

Michael Oppenheimer, Albert G. Milbank Professor in Geosciences and International Affairs, Woodrow Wilson School, an atmospheric chemist who does research on the impacts of climate change and also the nitrogen cycle.

Stephen W. Pacala, Frederick D. Petrie Professor in Ecology and Evolutionary Biology, Acting Director of Princeton Environmental Institute, a biogeochemist who does research on the terrestrial carbon cycle and is co-Director of the Carbon Mitigation Initiative of Princeton University.

S. George H. Philander, Knox Taylor Professor in Geosciences, Director of the Program in Atmospheric and Oceanic Sciences, who does research on ocean dynamics and paleoclimate.

Ignacio Rodriguez-Iturbe, Theodora Shelton Pitney Professor in Environmental Sciences, Professor of Civil and Environmental Engineering, who does research on hydrology.

Jorge L. Sarmiento, Professor of Geosciences, Director of CICS, a biogeochemist who does research on the ocean carbon cycle and biological response to climate change.

Daniel M. Sigman, Professor of Geosciences, Dusenbury University Preceptor of Geological and Geophysical Sciences, a biogeochemist who does research on paleoceanography.

Eric F. Wood, Professor of Civil and Environmental Engineering, who does research on hydrology.

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Task I: Administrative Activities and Outreach Supported Personnel

Name	Rank	Advisor
Carson, Steve	Chemistry Teacher at Princeton Regional Schools	
Curcio, Joanne	Administrative Assistant	Sarmiento
Rossi, Laura	CICS Administrator	Sarmiento
Sarmiento, Jorge L.	CICS Director	-

Departures - Task II and Task III:

Research Associates/Research Staff

Erwan Gloaguen - 8/1/05 Research Associate McGill University
Gwendal Riviere - 1/1/06 CNRS scientist Centre National de Recherches Meteorologiques
Joellen Russell - 1/1/06 Assistant Professor University of Arizona
Youlong Xia - 1/19/06 Scientist NOAA's National Weather Service
Agatha deBoer - 3/6/06 Assistant Professor University of East Anglia, UK

Ph.D. Defenses

Student: Dargan Frierson *Advisor:* Geoffrey Vallis - *July 11, 2005*
Dissertation: Studies of the General Circulation of the Atmosphere with a Simplified Moist GCM (Applied Math Student) - *University of Chicago Postdoctoral Associate*

Student: Huiyan Yang *Advisor:* Hiram Levy II - *July 12, 2005*
Dissertation: The Modeling of Tropospheric Photochemistry and Black Carbon Aerosol: Examinations of Radiation, Transformation, Concentrations and Emission Reduction Aspects - *Rutgers University Postdoctoral Associate*

Student: Edwin Gerber *Advisor:* Geoffrey Vallis - *December 20, 2005*
Dissertation: A Dynamical and Statistical Understanding of the NAO and Annular Modes (Applied Math Student) - *Columbia University Postdoctoral Associate*

Task II: Cooperative Research Projects and Education Supported Personnel

Name	Rank	Advisor
Adcroft, Alistair	Research Oceanographer	Leetmaa
Balaji, Venkatramani	Prof. Technical Staff	Leetmaa
Chen, Gang	Graduate Student	Held
deBoer, Agatha	Research Associate	Toggweiler
Edwards, John	Visiting Research Staff	Donner
Farneti, Riccardo	Research Associate	Vallis
Frierson, Dargan	Graduate Student	Vallis
Fučkar, Neven S.	Graduate Student	Vallis
Gebbie, Jake (Harvard)	Research Associate	Tziperman
Gerber, Edwin	Graduate Student	Vallis
Haine, Thomas (JHU)	John Hopkins Faculty	-
Hammann, Arno	Graduate Student	Philander
Huang, Xianglei	Research Associate	Ramaswamy
Huang, Yi	Graduate Student	Ramaswamy
Jackson, Laura	Research Associate	Hallberg
Jiang, Xianan	Research Associate	Lau
Kang, Sarah	Graduate Student	Held
Lee, Seoung-soo	Graduate Student	Donner
Legg, Sonya	Research Oceanographer	Leetmaa
Li, Feng	Research Associate	Wilson/Ramaswamy
Li, Fuyu	Graduate Student	Ramaswamy
Little, Christopher	Graduate Student	Gnanadesikan/Sigman
Pauluis, Olivier	Research Staff	Held
Phillips, Vaughan	Research Staff	Ramaswamy
Randles, Cynthia	Graduate Student	Ramaswamy
Riviere, Gwendal	Research Associate	Orlanski
Russell, Joellen	Research Staff	Toggweiler
Smith-Mrowiec, Agnieszka	Graduate Student	Garner
Song, Qian	Research Associate	Rosati
Tziperman, Eli (Harvard)	Harvard Faculty	-
Vallis, Geoffrey	Research Oceanographer	Leetmaa
West, James	Research Staff	Ramaswamy
Xia, Youlong	Research Staff	Milly
Yang, Huiyan	Graduate Student	Levy
Yin, Jianjun	Research Associate	Stouffer
Zhang, Rong	Research Staff	Vallis
Zhao, Ming	Research Associate	Held
Zhao, Rongrong	Research Associate	Vallis

Task III: Individual Projects Supported Personnel

Name	Rank	Advisor
Barreiro, Marcelo	Research Associate	Philander
Crevoisier, Cyril	Research Associate	Sarmiento
deBoer, Agatha	Research Associate	Sigman
Douglas, Ellen (UNH)	UNH Research Scientist	Vorosmarty
Fearon, Matthew (UNH)	UNH Research Scientist	Hurtt
Fekete, Balazs (UNH)	UNH Senior Research Scientist	Hurtt
Fennel, Katja (RUTGERS)	RUTGERS Faculty	Haidvogel
Frolking, Steve (UNH)	UNH Research Assoc. Professor	Hurtt
Gerber, Stefan	Research Associate	Hedin/Oppenheimer
Glidden, Stanley (UNH)	UNH Information Technologist	Vorosmarty
Gloaguen, Erwan	Research Associate	Sarmiento
Gloor, Emanuel	Research Scholar	Sarmiento
Haidvogel, Dale (RUTGERS)	RUTGERS Faculty	-
Hurtt, George (UNH)	UNH Faculty	-
Key, Robert	Research Oceanographer	Sarmiento
Li, Changsheng (UNH)	UNH Research Professor	Hurtt
Luo, Lifeng	Research Staff	Wood
Malyshev, Sergey	Research Staff	Pacala
Manfreda, Salvatore	Research Associate	Rodriguez-Iturbe
Mikaloff-Fletcher, Sara	Research Staff	Sarmiento
Previdi, Michael (RUTGERS)	RUTGERS Postdoctoral Assoc.	Haidvogel
Rodgers, Keith	Research Staff	Sarmiento
Rodriguez-Iturbe, Ignacio	Princeton Faculty	-
Russell, Joellen	Research Staff	Sarmiento
Sarmiento, Jorge L.	Princeton Faculty	-
Shevliakova, Elena	Research Staff	Pacala
Simeon, Jennifer	Prof. Technical Staff	Sarmiento
Slater, Richard	Prof. Technical Staff	Sarmiento
Vörösmarty, Charles (UNH)	UNH Faculty	-
Wilkin, John (RUTGERS)	RUTGERS Faculty	Haidvogel
Wollheim, Wilfred (UNH)	UNH Research Scientist	Vörösmarty
Wood, Eric F.	Princeton Faculty	-

Personnel				
Category	Number	B.S.	M.S.	Ph.D.
Research Scientist	6			6
Visiting Scientist	1			1
Postdoctoral Fellow (Research Associate)	15			15
Professional Technical Staff	3		2	1
Research Staff	9			9
Administrative	1			
Total (≥ 50% support)	**35**	**0**	**2**	**32**
Graduate Students	13	9	1	3
Employees that receive < 50% NOAA funding (not including graduate students)	24			12
Located at the Lab (include name of lab)	31-GFDL	7		24
Obtained NOAA employment within the last year	*1 NWS/NCEP			

*Youlong Xia, Support Scientist
NOAA-National Weather Service/National Centers for Environmental Predictions
Start Date: August 25, 2004

CICS FY'06 List of Awards

Amount	PI	Project Title
$ 282,917	Jorge L. Sarmiento	Determination of Carbon Source & Sink Distributions (Task III)
$ 155,200	Jorge L. Sarmiento	Ocean and Atmospheric Inverse Modeling for Global Carbon Flux Determinations (OGP-Task III)
$ 230,286	Stephen W. Pacala	Development of Carbon Sink Models (Task III)
$ 76,690	Eric F. Wood	Improved Parameterization for Sub-grid-scale Heterogeneity in Topography for use in Hydrologic Models (Task III)
$ 44,285	Lars Hedin	Modeling Terrestrial Nutrient Cycling (Task III)
$ 44,285	M. Oppenheimer	Modeling Terrestrial Nutrient Cycling (Task III)
$ 166,489	Robert M. Key	Understanding the Temporal Evolution of the Global Carbon Cycle Using Large-Scale Carbon Observations (OGP-Task III)
$ 61,818	Joellen Russell	Optimal Network Design to Detect Spatial Patterns and Variability of Ocean Carbon Sources and Sinks for Underway Surface CO_2 Measurements (OGP-Task III)
$ 102,700	Eric F. Wood	A Hydrologic Ensemble Seasonal Forecast System Over the Eastern U.S. (OGP-Task III)
$ 11,000	Steve Carson	QUEST (Task I)
$ 43,300	Jorge L. Sarmiento	Administration (Task I)
$ 131,005	Charles Vörösmarty (New Hampshire)	Global Methods of Constituent Flux in Continental Aquatic Systems (Task III)
$ 114,500	Dale Haidvogel (Rutgers)	Development of a Multi-Scale, Coupled Climate Modeling System for the Coastal Zone: Demonstration on the North American Continental Shelf (Task III)
$ 76,688	Lars Hedin	N-fixation and Atmospheric Inputs of N (Task III)
$ 20,000	Jorge L. Sarmiento	Fisheries Workshop-Ecosystems and Climate (Task III)
$2,864,850	S. George Philander	Cooperative Research Projects and Education (Task II)