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

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

Biogeochemistry 11-15

Characterization of Land Carbon and Nitrogen Fluxes
Characterization of Ocean Biogeochemical Fluxes
Land Model Development
Ocean Biogeochemical Model Development
New Model Simulations

NOAA Funding Tables 16

Progress Reports 17-117

Publications 118-121

CICS Fellows 122

CICS Administrative Staff 123

Personnel Support Information 124-127

CICS Project Awards 128
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 CO₂ 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., CO₂ 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 CO₂ 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 CO₂ 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 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 sixth 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. Ten teachers from the Princeton region participated in the Weather and Climate unit. Participating districts included: Montgomery, Burlington City, Hillsborough, Ewing and West Windsor-Plainsboro, and one teacher from the Newgrange School for children with special education needs. Burlington City is a high poverty district and Ewing has similar demographics. The others are suburban districts/school.
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

**Princeton Environmental Institute (PEI)**
Director, Stephen W. Pacala

- **Carbon Mitigation Initiative (CMI)**
- **Center for Biocomplexity (CBC)**
- **Energy Group**
- **Center for Environmental BioInorganic Chemistry (CEBIC)**

**Princeton Climate Center (PCC)**
Jorge L. Sarmiento, Director
Research Portion of CICS to be managed within PCC
Task III

Cooperative Institute for Climate Science Structure

**Cooperative Institute for Climate Science (CICS)**
Jorge L. Sarmiento, Director
Geoffrey K. Vallis, Assoc. Director

- **CICS Executive Committee**
- **CICS External Advisory Board**

**Task I: Administrative Activities**
managed by Jorge L. Sarmiento

**Task II: Cooperative Research Projects and Education**
managed by AOS Director
Jorge L. Sarmiento

**Task III: Individual Research Projects**
managed by PEI CICS Director
Jorge L. Sarmiento
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 Public and International Affairs, WWS
Denise Mauzerall – Associate Professor of Public and International Affairs, WWS

**Executive Committee**
S. George H. Philander – Professor of Geosciences
Isaac Held – GFDL Senior Research Scientist
Hiram Levy – GFDL Senior Research Scientist
V. Ramaswamy – Acting Director of GFDL, 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 Public and International Affairs, WWS
Denise Mauzerall – Associate Professor of Public and International Affairs, WWS

**Administrative Committee**
S. George H. Philander – Professor of Geosciences
Francois Morel – Professor of Geosciences
Bess Ward – Chair and Professor of Geosciences
Stephen W. Pacala – Director of PEI, Professor of Ecology and Evolutionary Biology
V. Ramaswamy – Acting Director of GFDL, GFDL Senior Research Scientist

**External Advisory Council**
Jeffrey T. Kiehl – Director of NCAR’s Climate Modeling Section
A.R. Ravishankara – Director of NOAA’s ESRL Chemical Sciences Division
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

*Note: The composition of the committees will be revised with the new CICS proposal.*
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.

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, and CICS also provides support for junior and senior research scientists. CICS continues to participate 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. One notable development has been the formulation of a new mixing parameterization for use in ocean climate models. The parameterization describes vertically non-local quasi-equilibrium shear-driven mixing and, it is hoped, captures shear-driven mixing in both gravity currents and the Equatorial Undercurrent. 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. Here, notable advances include the development of a new parameterization for the effects of submesoscale eddies in the mixed layer and the development and testing of a parameterization scheme based on a transformed Eulerian mean representation of the equations of motion.

Considerable progress has been made in the development of the next generation of ocean models at GFDL — models with arbitrary or hybrid vertical coordinates. Development of the new ocean model, GOLD (Generalized Ocean Layer Dynamics) has reached a point where we are now evaluating the new methods and configuration of the model. Various new algorithmic improvements have been developed, and we feel that this scheme represents a major step forward for layered ocean climate.
In addition to the above-mentioned work on model development and parameterization, CICS is deeply involved in studying the dynamics of the ocean itself. In one study, recently highlighted by the AGU, CICS investigators showed that the North Atlantic could have a surprisingly large impact on the climate, and in particular the zonal transport, of the ACC. This, possibly paralleled with the intensification of the Southern Ocean overturning circulation, could increase the inter-basin exchange and the ventilation rate of waters in the Southern Hemisphere. Hence, this strengthening of zonal and meridional flow around the Antarctica could have an important impact on the oceans’ capability to moderate global climate variability and change. The study also has a number of paleo-climate implications. These are all described in more detail in the individual reports.

**Large- and Meso-Scale Atmospheric Dynamics**

Atmospheric dynamics is at the core of the large-scale circulation of the atmosphere. Work in this area within CICS proceeds both through the support of graduate students and postdocs working with GFDL scientists, and by the work of University research scientists located at GFDL.

The work in this area varies between fundamental aspects of the large-scale circulation and more applied work in model development and parameterization. At the more basic end, one student has been studying the important problem of the dynamics of the Intertropical Convergence Zone, or ITCZ. Different GCMs seem to produce ITCZs with different properties and different dependencies on model parameters, and the ‘double ITCZ problem’ is a longstanding problem in climate modeling. (Models are prone to produce two ITCZs, one on either side of the equator, whereas the real atmosphere usually has only one.) Because the convergence of winds near the equator is an important component in producing El Nino, it is very important to properly simulate these winds and understanding the ITCZ is a prerequisite to that. Although we are some way from having a ‘theory of the ITCZ’, a theory has been developed that predicts precipitation distribution in certain circumstances. This theory suggests that it is smallness of gross moist stability that results in greater shift of the ITCZ with larger fraction of large scale condensation. Further, the dependence of precipitation response on cloud feedbacks suggests an important way in which uncertainties in cloud modeling can create uncertainties in regional responses to climatic perturbations.

At a somewhat smaller scale a CICS student has been investigating the fundamental dynamics of hurricanes, in particular trying to understand and verify, or not, a theory for the maximum intensity of hurricanes. Somewhat surprisingly, and even though hurricanes derive much of their energy from the latent heat of condensation, it seems that such theories can be most easily tested in the context of a dry model. It turns out that existing theories do fairly well, but that the maximum tangential wind is stronger than the theoretically predicted one. Clearly, more research remains to be done!

**Land Dynamics and Hydrology**

Land dynamics and hydrology plays an important role in climate simulations and projections, and this continues to be reflected in the range and depth of the activities funded through CICS. CICS funding is used to support research scientists located at GFDL, to provide postdoc support, and also to provide some support for researchers at other Universities. Of particular note is that the physical and biological components of the land model in GFDL’s climate modeling system continue to be 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.

Recently, and of particular note, the next version of the land model, LM3, has been initially
released. It is a descendent of two previous models (LM2 and LM3V), but adds features that
are present in neither of these, for example a high resolution model of river transport of
water, heat and other substances. The model is expected to play a major role in future
GFDL/CICS climate modeling activities. See also the section on Land Model Development
in the biogeochemistry highlights.

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. 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 investigation, CICS investigators explored the impact of Atlantic multidecadal
oscillations on Sahel rainfall and on Hurricane 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.
At one end of this spectrum, CICS researchers have been working to incorporate various
shallow convection schemes into the atmospheric models. Considerable progress has been
made in implementing both the University of Washington shallow convection scheme and the
Donner deep convection scheme. These schemes improve, among other things, the global
cloud simulation and the implied ocean heat transport compared to the earlier models. Ongoing
effort is now focusing on testing and unifying the shallow and deep convective closure,
which a primary target to improve the Amazon precipitation simulation.
At the other end of the spectrum, CICS researchers have been involved in studying various cloud-microphysical properties. For example, the relative roles of physical mechanisms for nucleation of cloud-droplets and crystals were studied in a mesoscale cloud ensemble and, relatedly, a study comparing 2D and 3D clouds was completed. Updrafts were found to be stronger in 3D, and there were related sensitivities of the microphysical and radiative properties of the cloud ensemble. Thirdly, a double-moment version of a deep convection parameterization for a global model was constructed. All of this work is, in itself, quite technical and not conducive to easy summary, yet it is vital to the ongoing efforts to improve the models that GFDL develops for climate simulation and prediction.

Radiative Forcing and Aerosols
The atmosphere is forced by radiation from the sun, and so it is crucial to accurately calculate that radiative forcing, and CICS supports this research primarily via the support of students and postdocs working with GFDL researchers. Although clear sky radiation is fairly well understood and modeled, the prediction and effects of aerosols remain a significant source of uncertainty in modeling efforts. For example, in one study CICS student has explored the climate effects of black and organic carbonaceous aerosols from anthropogenic and biomass burning sources. A particular focus of attention has been the effects of biomass burning over Southern Africa. In another study, the effects of aerosols on deep convective clouds were studied, with a goal of assessing how nucleation (for example by desert dust) modifies the microphysical and radiative properties of storm clouds.

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 two main components: (1) Characterization of the inventories and fluxes of carbon, nitrogen and other important elements. This is accomplished using model data synthesis techniques such as inverse models, as well as by analysis of in-situ and remotely sensed observations. (2) Developing models of the processes that lead to these fluxes. This involves both the development and evaluation of terrestrial ecosystem and ocean biogeochemical models. (3) Applying models to make predictions of past and future changes in climate and biogeochemistry.

Characterization of Land Carbon and Nitrogen Fluxes
The principal 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. A number of separate tasks have been undertaken during the past year. The first of these focuses on whether tropical biota compensates the carbon release by deforestation (presumably as a result of carbon fertilization). Such a sink is often assumed in models that are run to determine the target emissions required to achieve stabilization of atmospheric carbon dioxide. A series of papers published this year (Jacobson et al., 2007a,b) present results from a joint inversion of carbon concentration data in the atmosphere and the ocean that suggests that atmospheric concentrations do in fact reflect tropical deforestation. While previous models assigned some of the fluxes compensating deforestation to the land, the joint inverse (with much better constraints on oceanic fluxes) places these in the Southern Hemisphere midlatitude ocean and Northern Hemisphere land instead. An independent test of these results is the ratio of carbon-
13 as compared with carbon-12. A large carbon sink due to the terrestrial biosphere would be expected to show up in this ratio, while a sink due to the ocean would not. Simulations have been undertaken over the past year to test this idea.

If there is a significant loss of carbon over the tropics, there must be a sink somewhere over land to allow the ocean and atmosphere to come into balance. The North American Carbon Program seeks to evaluate how much of this occurs in North America, and CICS scientists are participating in this effort. A particular achievement of the past year is that a direct budgeting approach (validated in Crevoisier et al. 2007) shows a moderate carbon sink over the central North America of about 0.5 GtC/yr (Crevoisier et al. in prep.,a).

Finally, we are in the process of developing the inverse models to use more tracers (CO and CH4) and to incorporate results from different numerical models. Together this will enable us to characterize (and hopefully reduce) the uncertainties surrounding model-based estimates of atmospheric fluxes such as the NOAA carbon-tracker. It will also enable us to look at potential impacts of fire, which is increasingly thought to play a major role in explaining interannual variability in carbon fluxes. Two papers published during the past (Chedin et al, 2007, Crevoisier et al., in prep b) have help to further establish and quantify this link.

Additionally, work has begun on characterizing the terrestrial nitrogen cycle, which can couple to the carbon cycle in interesting ways (for example, nitrogen loss may limit the ability of plants to respond to carbon fertilization while fueling additional carbon sequestration in the ocean). Brookshire, in Lars Hedin’s group has begun to synthesize measurements of nitrogen loss across ecosystems, and a paper (Hedin et al., in prep) shows that climate affects this. An additional paper from the UNH group (Wollheim et al., in rev.) quantifies the impact of small rivers in moving this nitrogen to the ocean.

**Characterization of Ocean Biogeochemical Fluxes**

The oceans take up about 1/3 of the carbon put into the atmosphere each year. Understanding the relationship between future emissions and atmospheric concentrations is thus intimately linked with this process. 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. A major advance in the last year has been access to new European datasets that cover areas not included in the current GLODAP database, particularly in the Arctic Ocean and Mediterranean Sea. 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.

Inverse studies have also been carried out to constrain carbon cycling. The joint inverse also yields some interesting results about air-sea fluxes of carbon, suggesting that there is much more outgassing of carbon in the subpolar Southern Ocean (60S-44S) and much more ingassing in the mid-latitude Southern Ocean than previous models had found. Interestingly, preliminary runs with the GFDL Earth System Model and a new compilation of observational data are showing similar patterns. An inversion using bomb radiocarbon to constrain air-sea gas fluxes (Sweeney et al., 2007) was also published. When the gas transfer velocities proposed by this paper are combined with measurements of surface pCO2, the resulting uptake is around 1.8 GtC/yr in the mid-1990s.
Detecting these changes in repeat hydrographic sections has proven to be more difficult than was previously assumed. 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. These results suggest that a significant fraction of the variability may be due to changes in ventilation, gyre wobble, and Rossby wave propagation and that models may be able to help isolate the anthropogenic components. Rodgers et al. (subm.) identified an important “wintertime uptake window” that may play a significant role in this process.

Finally, a study (Sarmiento et al., 2007) was published this year examining the decoupling of the silicate and nitrate cycles. Previous work had assumed that this decoupling was due to different remineralization length scales globally, with silicate being exported much deeper than nitrate. This work demonstrated that the key location where the decoupling occurs is the Southern Ocean, highlighting the important coupling of the iron, silicon, and nitrogen cycles in this region.

**Land Model Development**

The past year has seen significant advances in the development of the LM3 land model. This model includes a dynamic vegetation model that can respond to climate and land use change and a detailed hydrological model. The Pacala, Hedin and Sarmiento groups at Princeton and the Vörösmarty and Hurtt groups at University of New Hampshire are all developing components of this model, with Pacala’s group playing the lead role in integrating these components.

A significant amount of work has gone into merging the dynamic vegetation code (LM3V) developed by Pacala’s group with the more detailed hydrological cycling code developed by Chris Milly. LM3 is currently being run by the GFDL Atmospheric Model Development Team as it develops the next-generation atmospheric model for the lab. An initial study with this model shows that while changes in the land surface do not have a major impact on the large-scale atmospheric circulation, the surface climate may be quite sensitive to such changes, and thus to biophysical-climate feedbacks (Malyshev et al., in prep.). Shevliakova et al. (in prep.) examine the impact of climate-carbon feedbacks under global warming. They show that these feedbacks depend critically on carbon fertilization, with models with strong fertilization producing a negative feedback and models with weak fertilization producing a positive feedback. Crevoisier has also been helping to tune the model by comparing the output with eddy flux and forest inventory data sets.

A particularly exciting development during the last year has been the progress towards a terrestrial nitrogen cycling model within LM3. 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. Stefan Gerber within Hedin’s group has added vegetation and soil nitrogen dynamics to the land model and a paper describing his code is in preparation. A major finding is that the balance between nitrogen inputs via biological fixation vs. nitrogen losses by fire/DON is what determines how severely nitrogen can limit productivity after a disturbance event- with important implications for the tropical forest carbon sink. Vörösmarty of the University of New Hampshire has developed a model that links changes in hydrological cycling to the riverine nitrogen cycle, with credible results for the Mississippi and Amazon basins. Hurtt is examining the impact of humans on the land N-cycle.
One issue that has emerged during the development of the land model is the role of fire. As noted above work carried out in CICS has played a role in building the case that variability in fires plays an important role in explaining interannual variability in atmospheric carbon dioxide change. Crevoisier has taken a lead role in developing a new fire model for LM3V (Crevoisier et al., in press) which is currently being incorporated into the model.

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 continued to update land-use scenarios for use in future climate change experiments as well as model development. 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. The impacts of some of these changes on the local hydrological cycles in Amazonia (D’Almeida et al., 2006, 2007) and in the Indian monsoon belt (Douglas et al., 2006) was evaluated.

Ocean Biogeochemical Model Development
Tracer distributions can be quite sensitive tracers of biases in ocean and climate models, including biases that may have important implications for the carbon cycle. CICS scientists have participated in the inclusion of a number of new biogeochemical tracers into the base code for the GFDL coupled climate model. The chlorofluorocarbon package is now being routinely used as part of the development suite for both the level and isopycnal coupled model versions. An additional climate change scenario run with anthropogenic carbon dioxide and chloroflourocarbons has been completed and added to the suite of runs being analyzed at GFDL.

One of the barriers to using tracers in coupled models is the additional computational expense. In the past year, Simeon has developed a coarse-resolution version of the GFDL coupled model which produces a simulation which is competitive with many of the models run for the AR4 assessment. This model represents a potential tool for paleoclimate simulations that will be exploited over the course of the next year.

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 CO₂, anthropogenic CO₂ 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.

New Model Simulations
A number of new simulations have been started over the past year to apply the new models to different scientific questions. Sarmiento’s group has begun a long control run to identify feedbacks between climate change and the ocean carbon cycle. A particular goal is to identify how much less carbon a warmer climate would be expected to take up, and whether such feedbacks can be identified at present. These runs will also be used to identify biases in the biogeochemical model related to biases in circulation.
Sarmiento’s group has also begun a new project involving 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. Preliminary simulations with He-3 have been carried out and reveal that the standard value of the source function is too low, a result with implications for geodynamics as well as oceanography. Discussions are now beginning about including He-3 in runs of the coarse coupled model, as part of a study examining the impact of deep mixing on global biogeochemistry.

One of the important tests of coupled climate models is whether they can simulate past changes in climate. Rodgers has begun preliminary runs with the coarse resolution coupled model to examine the role of the Indonesian throughflow in producing abrupt climate change at 2.7 million years before present. Initial results suggest that tectonic changes in this region may have helped to produce a basin-wide reorganization of the Pacific overturning circulation.

The ocean biosphere is often taken as passively responding to climate. A study published this year (Anderson et al., 2007) suggests that this is not in fact the case. The presence ocean biota change the extent to which deep waters are shaded, warming the surface and cooling the deep. The colder waters outcrop in the tropical Pacific, triggering feedbacks that spread across the entire globe.
Task I-Administrations covers the administrative activities of the Cooperative Institute and support of outreach activities. Funding during the past year included minimal support of the CICS Director and full support for the part-time administrative assistant. Funding was also provided for QUEST, a well-established 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 Univ.), Robert Hallberg (GFDL), Thomas Haine (Johns Hopkins Univ.), Stephen Griffies (GFDL), V. Balaji (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 (25%)

**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 (5%)

**Objectives:** Establish a base line ocean model for the next IPCC round

**Methods and Results/Accomplishments:**
Development of the new ocean model, GOLD (Generalized Ocean Layer Dynamics), has accelerated during the last year and reached a point where we are now evaluating the new methods and configuration of the model. Various new algorithmic improvements have been developed, including a refinement of the PPM split-explicit solver [Hallberg and Adcroft, 2007] and a robust discretization of the Coriolis terms in the presence of vanishing layers. An important development in the last year is the invention of an "analytic finite volume" treatment of the pressure gradient force (AFV-PGF). This allows the model to use accurate equations of state and incorporates compressibility properly and at the same time removes the dependence of the model on a "known" climatology; the model can now be used for different climates. AFV-PGF also avoids any pressure gradient errors that normally occur when a non-Montgomery form of the pressure gradient is used in isopycnal models. We feel that this scheme represents a major step forward for layered ocean climate models [Adcroft et al., 2007].

I have developed a new sub-grid mesoscale eddy parameterization [Adcroft and Marshall, 2007] which I have prototyped in both MOM4 and GOLD. It explicitly predicts eddy kinetic energy for the sub-grid mesoscale fields and brings a degree of closure to the energetic cycle of the resolved fields. The preliminary results are very exciting (see Figs 1 and 2); the basic features and scales diagnosed from a 1/8th degree eddy-resolving ocean model can be predicted in a non-eddying 1 degree ocean model using this parameterization. Moreover, the parameterization provides for an eddy-energy history which opens up the possibility of new modes of variability for both the ocean and coupled system. This work will be presented at the CLIVAR WGOMD 2007 meeting in Bergen as an invited speaker.

An initial study with the GOLD coupled climate model (Anderson et al., 2007) was published this year. This study demonstrated an important feedback between ocean water clarity and climate.

**References:**
CICS Annual Report 2006

**Publications:**


Fig.1: Eddy velocity scale diagnosed from an eddy resolving (1/8° resolution) ocean-only simulation.

Fig.2: Eddy velocity scale predicted in a low resolution (1°) coupled model using the new eddy energy framework. Many features from Fig. 1 are predicted even though the new scheme has not yet been optimized.
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), Piet Hut (Institute for Advanced Study), 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.
- Extension of FMS and FRE to support Mosaics and the cubed-sphere grid.
- Formulation of a draft community-wide standard specification of model grids (http://www.gfdl.noaa.gov/~vb/gridstd/gridstd.html) which is under consideration for adoption within the Climate and Forecasting conventions.
- Development of FMS infrastructure and modeling components for next generation physical climate model CM3 and Earth system model ESM3.
- Provided design oversight for Sergey Nikonov (CICS) in design and implementation of the GFDL Curator, which maintains a database of model results delivered to the public from PU/GFDL models for IPCC AR4 and other projects.
- 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), Global Organization of Earth System Science Portals (GO-ESSP) and CF Conventions groups, whose steering committees I serve on.
- Organized workshops for Earth System Curator (September 2006, Princeton NJ); GO-ESSP (June 2007, Paris)

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

Publications:


Progress Report: Cooperative Institute for Climate Science Professional Development Summer Institute in Weather and Climate
July 9-13, 2007

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

Other Participating Researchers: 10 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 9-13, 2007. 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:

The 2007 QUEST unit “Oceans and Climate” (O&C) was designed to highlight the roles of Earth’s oceans as recorders of past climates and as participants in climate and climate change. The O&C unit touched on aspects of three themes: (#1) Earth System Studies/Climate Research, (#2) Biogeochemistry, and (#4) Paleoclimate. The O&C unit also supported NOAA’s Goal #2: “Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond”. After an introduction to ocean sediments, participants examined samples of foraminifera from different depths in a core from the Atlantic Ocean with a focus on determining relative abundances of G. Menardii and how those relate to ocean surface temperatures. The depth distributions of G. Menardii were then related to data on depth distribution of δ18O in foraminifera shells of the same core. Participants were introduced to the principles of oxygen isotope fractionation through evaporation and condensation by means of a hands-on activity. The data from cores were then related to patterns of glacial cycles. A post-doc from Princeton University provided further background on uses of isotopes in climate studies and gave a tour of the mass spectrometry labs. To connect Milankovitch cycles to glacial cycles, activities were done to illustrate the basis of seasons and how orbital parameters can change. The importance of temperature and salinity in the ocean were explored through demonstrations and examinations of maps and cross-sections. Principles of ocean currents were then introduced including wind driven currents, the Coriolis effect, and thermohaline currents with an emphasis on the Ocean Conveyor. All of these studies and activities culminated with a mid-week trip to the Core Laboratory of the Lamont Doherty Earth Observatory where the participants were given a tour of the facilities, processed and examined sediment samples from cores, and were provided background on the climate research carried out.

The remaining two days focused on ocean/climate interactions and potential future climate changes. An introduction to the greenhouse effect and basic modeling was done through a simple spreadsheet model of the Earth’s radiation balance in which participants could experiment with changes in parameters that affect the radiation balance. The basics of the greenhouse effect were
also demonstrated through a hands-on activity. To understand the impacts of thermal expansion of ocean water, participants measured the thermal expansion of water and related their measurements to potential rise in sea level. Effects of melting ice were also considered through a demonstration. Participants examined topographic maps of some regions of the East and Gulf Coasts of the U.S. to discover possible impacts of sea-level rise. On the last morning the group went to NOAA’s Geophysical Fluid Dynamics Laboratory and received a tour of the supercomputer facilities as well as presentations on hurricanes, climate modeling and possible impacts of global warming. The week ended with a presentation and activity on Stabilization Wedges for reducing greenhouse gas emissions that was developed at Princeton University.

**Participating School Districts:**
Montgomery, Burlington City, Hillsborough, Ewing and West Windsor-Plainsboro and one teacher from the Newgrange School for children with special education needs. Burlington City is a high poverty district and Ewing has similar demographics. The others are suburban districts/school.
Feedback from teachers:
• “Without a doubt, QUEST is the best professional development I’ve experienced as a science teacher because it challenges my own adult understanding of concepts and allows me to determine how I can best take this back and apply it to my classroom activities.”
• “It is an incredible experience. You get to meet and talk to the scientists doing the actual research. All QUEST staff help explain concepts in a way that we can understand it.”
Progress Report: Mechanisms That Control the Latitude of Surface Westerlies

Principal Investigator: Gang Chen (Princeton Graduate Student)

Other Participating Researchers: Isaac Held-advisor (GFDL/Princeton), Pablo Zurita-Gotor (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: Understand the poleward shift of surface westerlies in response to stratospheric ozone depletion and global warming

Methods and Results/Accomplishments:
This is my fifth and final year in AOS program. I summarized my works in previous years and wrote my Ph.D. dissertation.

We further explore the tropospheric jet shift to a prescribed zonal torque in a model with high stratospheric resolution (Chen and Zurita-Gotor, 2008). The jet moves in opposite directions for the torques on the jet's equatorward and poleward flanks in the troposphere. This can be explained by different ways of modifying the critical latitudes of wave activity absorption. However, the jet moves in the same direction for the torque in the extratropical stratosphere irrespective of the latitude of the torque. The stratospheric eddies play the key role in transferring zonal wind anomalies downwards into the troposphere. We argue that these stratospheric zonal wind anomalies can affect the tropospheric jet by altering the eastward propagation of tropospheric eddies.

The tropospheric eddies display a trend towards faster eastward phase speeds in the observations and model simulations for the late 20th century, and in the model projections for the 21st century (Chen and Held 2007). We argue that the increased lower stratospheric or upper tropospheric zonal winds, associated with stratospheric ozone depletion or global warming (Miller et al. 2006), can be sufficient to increase eddy phase speeds so as to shift the circulation polewards (Chen et al. 2007). The trend is very similar in structure to the internal interannual variability due to atmospheric eddy-mean flow interactions, rather than the SST-forced variability during the ENSO cycle. This suggests that the observed and simulated shifts of surface westerlies are more related to the processes associated with the extratropical internal variability such as the variations in the stratospheric polar vortex, rather than those for the tropical-extratropical interactions.

References:

Publications:


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/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 improve the representation of boundary layer processes in the GFDL climate model

Methods and Results/Accomplishments:
Investigations of the behavior of the atmospheric boundary layer within the GFDL climate model have been focused on gaining a detailed mechanistic understanding of interactions between the boundary layer and other parameterizations, the interaction with the cloud scheme being of particular interest. Attention has mostly been directed towards a version of the model involving the Donner scheme for deep convection and the University of Washington scheme for shallow convection. A number of modifications to the boundary layer scheme have been tested. These tests have suggested that the cloud scheme quite strongly controls the model’s behavior and thus many features of the model’s climate are robust to changes in the boundary layer scheme.

The modeling of the stable nocturnal boundary layer remains problematic in large-scale atmospheric models, with models requiring more turbulent mixing in these conditions than can be justified theoretically. Traditionally, observational assessments of the simulation of such boundary layers have been based on comparisons with field studies at specific locations, but in such cases it is difficult to allow for the influence of local effects and observations on a larger scale would be desirable. Recently, satellite retrievals of radiometric surface temperatures under clear-sky conditions over the contiguous United States have become available (Sun et al. 2006) and work has been initiated to assess their ability to shed light on this problem. In general, the GFDL model reproduces the geographical pattern of variations in the diurnal temperature range well, with larger diurnal variations in the west. An interesting preliminary finding is that as a fraction of the diurnal range the fall in surface temperature between the diurnal maximum and the evening transition in the observations is rather larger than the subsequent fall between the evening transition and the minimum, whereas the relative proportions of the diurnal range are more nearly equal in the model.

References:
**Progress Report:**  Decadal to centennial climate variability and meridional energy transports in a model of the coupled ocean-atmosphere system

**Principal Investigator:** Riccardo Farneti (Princeton Postdoctoral Research Associate)

**Other Participating Researchers:** Geoffrey K. 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:** The following research project concerns the study of the mechanisms and predictability of decadal to centennial climate variability. An idealized ocean-atmosphere sector model derived from the GFDL Climate Model is proposed, with geometrical and atmospheric physics simplifications. The model, around fifty times faster than the IPCC-class GFDL CM2.1, allows for century-long and ensemble run experiments for the identification of ocean-atmosphere interaction and mechanisms and predictability of climate variability.

**Methods and Results/Accomplishments:**
We investigate the mechanisms and predictability of climate variability on the decadal to centennial timescales using an idealized coupled ocean-atmosphere model. The ocean component is a coarse resolution hydrostatic, primitive-equation model with greatly simplified geometry, while the atmospheric component is a moist primitive-equation model with simplified parameterizations of atmospheric processes.

Millennial climate simulations have been carried out with the coupled model, together with some ocean-only and atmosphere-only simulations with different boundary conditions. The long-term variability of the two systems is analyzed in an attempt to identify the mechanisms and dynamics that might lead to natural climate variability at interannual to interdecadal timescales. Specifically, we investigate the timescales on which the system can be considered as truly coupled; what, if any, is the role of ocean dynamics on redenning the atmospheric response; and if 'weather' variability in the atmosphere plays an essential role in longer term variability. The sensitivity to the poorly known parameterizations - such as the oceanic horizontal and isopycnal diffusivity - and to the effect of the ocean geometry is also considered.

With the help of the same idealized coupled model, we also explored the meridional energy transport in the coupled ocean-atmosphere fluid system. Theoretical arguments and model simulations are used in order to elucidate the dependencies of heat transport at different latitudes and in different regimes, the ability of the atmosphere to compensate for changes in the oceanic configuration and the different partitioning of the poleward energy transport in both fluids.

**Publications:**

Progress Report: Elements of the MOC-ACC Interaction in a Hierarchy of Models

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

Other Participating Researchers: Geoffrey K. Vallis - advisor (Princeton), S. George H. Philander (Princeton), Anand Gnanadesikan (GFDL) 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 nature of the combined MOC-ACC system and its role in climate dynamics.

Methods and Results/Accomplishments:

The combined MOC-ACC circulation system is an important segment of the Earth’s climate due to the associated storage and transport of heat, freshwater and dissolved substances, as well as the production and transformation of water masses. This study intends to combine the results from a hierarchy of ocean models with theoretical analysis to provide insight into the interhemispheric and interbasin aspects of an oceanic bridge connecting the MOC and the ACC. The interaction between these two global current systems could have a significant role in stabilization of climate with the respect to the natural variability and anthropogenic perturbations. One of key points of this project is investigation of oceanic remote mechanisms with a potential to influence the ACC, and in general the Southern Ocean, structure and dynamics.

The first phase of this study encompasses the use of a simplified two-hemisphere single-basin OGCM with a circumpolar channel forced by surface restoring conditions. An interhemispheric connection between the MOC and the ACC is explored through a series of sensitivity experiments and, to a certain extent, theoretical models. Some of the results are published in Geophysical Research Letters - particularly striking is a dependence of the southern hemisphere circumpolar transport on the northern hemisphere surface buoyancy conditions.

The next step includes a simplified two-basin OGCM with a circumpolar connection to examine relative importance of interhemispheric and interbasin interaction. A configuration closer to the real world bathymetry will enable us to establish robustness of key results from the previous step and expand them with analysis of additional functional links of an oceanic bridge that are more likely to operate in the real world.

Publications:

Progress Report: Transport Of Noy, O3 And Related Species From The U.S.

Principal Investigator: Yuanyuan Fang (Princeton graduate student)

Other Participating Researchers: Hiram Levy - advisor (GFDL/Princeton), Arlene Fiore and Larry Horowitz (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: Examine the composition, pathway and transport mechanism of exported NOy from the U.S during summer 2004 and evaluate how it is affected by the U.S NOy emission regulation

Methods and Results/Accomplishments:

Reactive nitrogen species (NOy) play a central role in the chemistry of the polluted and unpolluted atmosphere. They critically determine levels of O3, acidity and atmospheric oxidation potential [Crutzen, 1979; Singh et al., 2003]. Yuanyuan Fang is working with Arlene Fiore and Larry Horowitz on NOy distributions and transport within the US. She mainly uses a 3-dimensional chemical transport model (MOZART, Horowitz et al., 2003). She also applies the observational data from ICARTT campaign during summer 2004 to do model evaluation.

She finds that within the U.S boundary layer in summer, the main transport pathway for NOy is through vertical transport which is mainly due to convection. Almost 30% of total emitted nitrogen in the U.S boundary layer is exported through this pathway. On the other hand, if total column transport is considered, eastward flux in the free troposphere from the east edge of the U.S is of major importance.

Sensitivity experiment on the NOx emissions in the U.S shows that regulation of NOx emissions reduces NOy burden and exported NOy. But due to changes in NOy partitioning, this regulation relatively increases the contribution of PAN and NOx while reduces the contribution of HNO3, which in turn increases the export efficiency of NOy since HNO3 is the main sink of NOy in the boundary layer.

Most monthly mean export happens through transport episodes. These events take place under specific meteorological conditions which make export more efficient and more rapid. Therefore, they have stronger potential to affect downwind region atmospheric chemistry. For example, one of the greatest export events during ICARTT is caused by the passage of warm front. Yuanyuan's future work will focus on examining episodic transport. She plans to study the annual and interannual variation of export from the U.S, define episodes in an appropriate way, and examine the detailed physical and chemical process of these episodes and their effect on global air quality.

Yuanyuan wrote a proposal based on this idea and she is now preparing a paper on transport of NOy, O3 and related species from the U.S during summer 2004.

References:

Crutzen, P. J.(1979), the rol of NO and NO2 in the chemistry of the troposphere and the stratosphere, Annu. Rev. Earth Planet. Sci., 7,443-472


Publications:

A paper on NOy export from the U.S during summer 2004 is in preparation.

Fig 1 Latitude vs Pressure NOy flux section through East edge of the U.S. (62.5 W ), Unit: $10^{14}$ moles N/cm²/sec

Fig 2 Profiles of NOy(red), PANs(blue), NOx(green) and HNO3(black) flux though the East edge of the U.S, Unit: $10^{14}$ moles N/cm²/sec
Progress Report:  Irminger Sea/Denmark Strait Regional Ocean Circulation Model and Data Assimilation System

Principal Investigator: Thomas Haine (Johns Hopkins University Professor)

Other Participating Researchers: Alistair Adcroft (Princeton), Bob 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: Simulation and Assimilation of Irminger Sea and Denmark Strait Ocean Circulation

Methods and Results/Accomplishments:

Code Development: The model development has continued through regular collaborative visits of the PI to GFDL. In Spring 2007 a minor 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 primary improvement was in the sea-ice package.

There has also been a major upgrade in the assimilation software during the summer and Fall of 2006. This work is not yet complete, but it is a near-term priority.

New Runs: One major new solution has been integrated lasting 18 months of model time in 2003/4. The purpose of this calculation was to assess the impact of the NESDIS/NCDC Blended Sea Winds product of Zhang et al. (2006a, b). Previous calculations have used 6-hourly NCEP reanalysis winds which are known to be deficient at small scales. The Zhang et al. product merges scatterometric wind stress observations with NCEP reanalysis fields and is more realistic at small scales.

The new run has been assessed by comparing sea-surface height (SSH) variance with results from NCEP-forced calculations and also from altimetric data (T/P, Jason-1). The variance is greater with the Zhang et al. scatterometer forcing compared to the NCEP forced run, as expected. Both runs show substantial deficits in SSH variance compared to altimetry data, however. The source of this discrepancy is unknown: it could be due to altimeter noise, which is difficult to cleanly remove from the 1-second along-track data being used. Alternatively, the GCM results might really underestimate the SSH variance, despite the fact that the GCM is very well resolved (2km horizontal, 100 vertical levels) and is forced with a realistic wind product. If this latter possibility is true, there are important repercussions for comparing along-track altimetry data with GCMs using data assimilation. Further investigation is ongoing.

Denmark Strait Overflow Volume Transport Results: The intriguing and potentially-important connection between Denmark Strait SSH and Denmark Strait overflow transport has been explored further. The new run with more energetic wind forcing (see above) actually shows an improved correlation between SSH and overflow transport. This important result strongly suggests that SSH from the real Denmark Strait can be used to diagnose overflow transport in real time on a 12-hourly timescale. Furthermore, this statement still applies given the sparse sampling of real altimeter data such as T/P and Jason-1 (if the data are processed carefully). The reconstructed overflow transport signal is sensitive to noise in the altimetry data, however. Although noise-reduction techniques are still being tested, it appears that the noise level in T/P and Jason-1 is too great to allow a useful overflow timeseries to be extracted from the satellite data. In any case, bottom pressure is very likely also well-correlated with overflow transport and
this possibility suggests a cost-effective and efficient method to monitor the Denmark Strait overflow. A research article on these topics is now in preparation and a paper was recently presented at an international meeting (Haine, 2007).

Related Field Work: Two important related field work campaigns have begun in the last year. First, an atmospheric field expedition to the Irminger Sea, Denmark Strait, and Iceland Sea occurred in winter 2007 (the Greenland Flow Distortion Experiment, GFDEEx; http://lgmacweb.env.uea.ac.uk/e046/research/gfdeex/index.htm). The PI participated in this aircraft campaign and is working with the GFDEEx PIs to produce an air/sea flux dataset of unprecedented accuracy and resolution. During the campaign several very intense sub-mesoscale polar low systems were sampled. The air/sea forcing during these events was especially strong and preliminary analysis shows substantial biases in NCEP reanalysis data, for example. The unique dataset from the GFDEEx will be used as a case study to drive the PI's ocean model and data assimilation system in the coming year.

Second, the PI has been funded by NSF to collaborate on an oceanographic field project to study shelf/basin exchange off the east Greenland shelf. The project involves a high-resolution mooring array being deployed for a year in summer 2007 focusing on the East Greenland Spill Jet (Pickart et al., 2005). The PI's high-resolution Irminger Sea model will be used extensively in this project to place the field data in context, to explore dynamical mechanisms of the shelf-basin exchange, and to study the large-scale consequences for the Atlantic meridional overturning circulation.

References:


Publications:

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

**Principal Investigator:** Arno Hammann (Princeton graduate student)

**Other Participating Researchers:** Anand Gnanadesikan-advisor (GFDL/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 understand the role of ocean eddies in the dynamics of the Antarctic Circumpolar Current (ACC), and to improve our ability to parameterize their effects in non-eddy-resolving ocean climate models.

**Methods and Results/Accomplishments:**
A two-layer isopycnal ocean model is set up in a wind-forced channel configuration with a meridional ridge, using the Hallberg Isopycnal Model (HIM) code. Diabatic effects are included through interface damping near the channel boundaries. This provides the simplest model of ACC dynamics that encompasses all processes which we believe important (Hallberg and Gnanadesikan, 2001).

The model was run at different grid resolutions with and without an eddy parameterization to study the effects of parameterizing versus resolving eddies. It was found that in the presence of topography, the common practice of diffusing layer interface height degrades the model solution due to its adverse effect on standing eddies. Moreover, it appears that bottom and horizontal frictional stresses are more important in the overall momentum balance than previously thought, a point whose implications will have to be studied in more detail.

Future work will focus on the attempt to parameterize ocean eddies by means of statistical learning methods. High-resolution runs of the model set up will provide the data necessary to train such methods, which are intended to relate the non-resolved dynamics in low-resolution experiments to the spatial mean fields.

**References:**
**Progress Report:** Diagnostic Investigation of Satellite-Observed and Model-Simulated Spectral Longwave Radiances: Spectral Signatures of External (Natural, Anthropogenic) Climate Forcings and Internal Variability

**Principal Investigator:** Yi Huang (Princeton graduate student)

**Other Participating Researchers:** V. Ramaswamy - advisor (GFDL/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:** 1) to conduct a comparison between GCM simulation and satellite observation to assess the model’s capability in simulating the outgoing longwave spectrum; 2) to detect signature of climate forcing and associated feedbacks in the infrared spectrum.

**Methods and Results/Accomplishments:**

The synthetic spectra are simulated from GFDL GCM, AM2, by using a moderate resolution radiative transfer code, MODTRAN. The observational spectra are from the AIRS instrument aboard NASA satellite, Aqua. Model deficiencies in at least two aspects have been highlighted by the disagreements.

First, the model has a positive bias (prominent in the total-sky case but smaller in the clear-sky case) in the window region, and a negative bias in the water vapor vibration-rotation absorption band (1200-1650 cm-1). When decomposed in terms of different latitude belts, the cold bias in the water vapor band is persistent at all latitudes, and is largest in the tropics (30S-30N). This indicates that there exists a significant cold temperature bias and a strong wet bias in the model simulated upper troposphere, which is confirmed by the reconstruction of the biases with the radiative Jacobians [Huang et al., 2007]. Such a cold bias in the water vapor band also shows up when the NCAR atmospheric model CAM3 is compared to AIRS [communicated by the AIRS science team].

The existence of errors of opposite signs at different spectral regions suggests that an agreement of broadband OLR fluxes between model and observation might be due to fortuitous cancellation of errors.

The second model deficiency concerns the diurnal cycle in the equatorial oceans where deep convection is prevalent. The GFDL GCM shows a persistent diurnal contrast of total-sky outgoing radiation at the two satellite overpassing times (1:30A.M./P.M.) which doesn’t exist in the observation. This spurious contrast shows up in both broadband flux and radiance comparisons. In the same region, CERES has a day-night difference of -2.82 W m-2 while AM2 yields 8.17 W m-2. Such spurious diurnal contrast exists in NCAR CAM and NCEP reanalysis too.

**References:**


**Publications:**

Huang, Y., V. Ramaswamy, X. Huang, et al., A strict test in climate modeling with spectrally resolved radiances: GCM simulation versus AIRS observations, to be submitted to Geophysical Research Letters.
**Progress Report:** Gravity Current Entrainment Climate Process Team

**Principal Investigator:** Laura Jackson (Princeton Associate Research Scholar)

**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 the GCE Climate Process Team in developing parameterizations of gravity current entrainment and in testing these in regional and global climate models.

**Methods and Results/Accomplishments:**

I have been developing a shear-driven diapycnal mixing parameterization for use in ocean climate models. This new parameterization describes vertically non-local quasi-equilibrium shear-driven mixing which we believe will capture shear-driven mixing in both gravity currents and the Equatorial Undercurrent.

I have submitted a paper describing this new theory and comparing it to high resolution numerical simulations of shear-driven stratified turbulence. Our parameterization captures the mixing well and is simpler (and more appropriate for climate studies) than two equation models such as k-epsilon and Mellor-Yamada. Our parameterization has been implemented in the GFDL isopycnal coordinate ocean model GOLD where it has proved to be robust and efficient. Idealized simulations (Legg et al, 2007) have shown that our parameterization gives reasonable amounts of mixing, and follow up work describing our parameterization's performance in a global climate model is in progress. I presented this work at the 2007 Turbulence Colloquium in Liege, Belgium.

Additionally I have been examining the mixing in a regional model of the Mediterranean overflow, both with and without barotropic tides. With the tides there is slightly more mixing, giving a lighter plume, with the majority of the extra mixing occurring at the sill.

**Publications:**


Progress Report: Intraseasonal Teleconnection Between North American and Western North Pacific Monsoons with A 20-Day Time Scale

Principal Investigator: Xianan Jiang (Princeton Postdoctoral Research Associate)

Other Participating Researchers: Ngar-Cheung Lau (GFDL/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: This study aims to understand physical mechanisms responsible for the low-frequency variability of the North American Monsoon with an intraseasonal time-scale.

Methods and Results/Accomplishments:
We found that local low-level circulations associated with intraseasonal variability (ISV, with a time-scale of about 20 d) of the North American Monsoon (NAM) are part of a prominent trans-Pacific wave-train extending from the western North Pacific (WNP) to the Eastern Pacific/North America along a “great circle” path. The circulation anomalies along the axis of this wave-train exhibit a barotropic vertical structure over most regions outside of the WNP, and a baroclinic structure over the WNP, thus suggesting the important role of convective activities over the WNP in sustaining this wave-train. This inference of teleconnection between North American and WNP monsoons is further substantiated by an analysis of the pattern of wave activity-flux vectors. A manuscript containing the results of this study is in revision for Journal of Climate.

Publications:
Progress Report: The Response Of The Itcz To Extratropical Thermal Forcing

Principal Investigator: Sarah M. Kang (Princeton Graduate Student)

Other Participating Researchers: Isaac Held -advisor (GFDL/Princeton), Dargan Frierson (University of Chicago), Ming Zhao (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 understand what determines the boundary of rainbelt in the tropics which is applicable to recent Sahel drought or paleoclimate studies related with LGM

Methods and Results/Accomplishments: The idealized moist GCM by Frierson et al. and aquaplanet version of AM2 are used to see how sensitive the position of the ITCZ is to extratropical thermal forcing. Heating is imposed poleward of 40S and equal and opposite cooling is imposed to poleward of 40N. The main difference of AM2 from the idealized model is the existence of water vapor feedback and clouds. These differences are important in enhancing the degree of compensation between the imposed oceanic flux and the resulting response in the atmospheric energy fluxes. Thus with the same magnitude of cross-equatorial heat flux, there is larger response in AM2. Also, additional simulations were designed to investigate how sensitive the response of the ITCZ is to aspects of the model's moist convection scheme. One of the parameters in the convection scheme is altered to modify the fraction of large scale condensation versus convective precipitation. In the idealized model, the ITCZ was displaced more poleward with larger fraction of large scale condensation. With larger fraction of large scale condensation, gross moist stability becomes smaller and the Hadley circulation becomes stronger to transport as much energy poleward which is responsible for greater response in precipitation. We have developed a simple theory to predict precipitation distribution if the compensation percentage and gross moist stability of the control case are given. This theory supports that it is smallness of gross moist stability that results in greater shift of the ITCZ with larger fraction of large scale condensation. However in AM2, the ITCZ is displaced more with less fraction of large scale condensation opposite to the idealized model. This is because, say in warmed southern hemisphere, with smaller fraction of large scale condensation, deep convection is enhanced which directly contributes to reduction in lower tropospheric cloud and it leads to more warming through the feedback of cloud forcing on TOA energy fluxes. Therefore imposed oceanic flux is amplified more in smaller fraction of large scale condensation and it is responsible for greater response with smaller fraction of large scale condensation in AM2. The dependence of precipitation response on cloud feedbacks suggests an important way in which uncertainties in cloud modeling can create uncertainties in regional responses to climatic perturbations.


Principal Investigator: Seoung Soo Lee (Princeton Graduate Student)

Other Participating Researchers: Leo J. Donner - advisor (GFDL) and Vaughan Phillips (Univ. 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 (80%)
NOAA’s Goal #3: Serve Society’s Needs for Weather and Water Information (20%)

Objectives: 1. Understanding the aerosol effects on aerosols
2. Comparison of single- and double-moment microphysics

Methods and Results/Accomplishments:
Aerosol effects on a mesoscale cloud ensemble (MCE) were simulated. Double-moment microphysics coupled with explicit nucleation schemes, taking into account spatiotemporally varying aerosol properties, were used. Increasing aerosol number led to smaller cloud particle size and larger water content for an increase in outgoing shortwave radiation and a decrease in outgoing longwave radiation at the top of the model domain. It was notable that 41% of the increase in outgoing shortwave radiation was offset by the decrease in outgoing longwave radiation. Increases in ice mass as well as liquid mass played an important role in the decrease in outgoing longwave radiation at high aerosol. This indicated a need to consider aerosol effects on ice physics to better assess aerosol effects on radiation budget.

The temporal evolution of precipitation rate with single-moment microphysics was different from that with double-moment microphysics. Generally, double-moment microphysics showed better agreement between simulated precipitation and its observed counterpart. The difference was mostly caused by the different treatments of autoconversion, saturation and nucleation. Even when the same autoconversion parameterization was used, the prediction of cloud droplet number concentration (CDNC) for autoconversion can result in significantly different precipitation patterns. The initiation and duration of precipitation were significantly affected by how autoconversion was treated. When the key processes, autoconversion, saturation and nucleation, were treated in the same manner, precipitation differences between single- and double-moment microphysics became negligible. Sensitivity of precipitation to different treatments of the other processes for single- and double-moment microphysics was not significant. More attention needs to be paid to numerical parameterizations of the key processes for the improvement of precipitation simulation in double-moment microphysics.

The mass of cloud particles and prescribed effective sizes in the run with single-moment microphysics were significantly different from those predicted using double-moment microphysics. The predicted size and mass of cloud particles in the double-microphysics run better represented cloud radiative properties than the prescribed size and predicted mass of cloud particles in the single microphysics.

References:
**Publications:**


**Progress Report:** Ocean Tidal Mixing

**Principal Investigator:** Sonya Legg (Princeton Research Oceanographer)

**Other Participating Researchers:** Jody Klymak (Univ of Victoria), Jonathan Nash (Oregon State) and other members of Hawaiian Ocean Mixing Experiment, GFDL researchers, Matthias Green and John Simpson (University of Bangor).

**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 manuscript describing numerical simulations of tidal mixing occurring near the top of the flanks of tall topography such as the Hawaiian Ridge. Included in this manuscript is a theoretical analysis of the regimes in which mixing by internal hydraulic jumps can occur, and an examination of global data to identify other topographic features where such mixing is likely. This study has been carried out in collaboration with members of the Hawaiian Ocean Mixing Experiment, especially Jody Klymak. 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 stratification 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. The manuscript has been reviewed for Journal of Physical Oceanography, and is currently under revision. A second manuscript, describing a more detailed comparison between model and data and using the model to aid the interpretation of the data, is currently in progress. Other related collaborations include sharing the model simulation data with Jonathan Nash, another member of the HOME team, to identify the baroclinic energy fluxes in the HOME region.

A second, smaller collaboration involving tidal mixing has been carried out with researchers from Bangor University, Wales. 2D simulations of internal tide generation on the Celtic Sea shelf have been carried out, and results documented as part of a manuscript submitted to Continental Shelf Research. The manuscript is currently under revision.

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 coordinating the effort to implement mixing parameterizations in the new GOLD model.

**Publications:**


Progress Report: Dense Overflows

Principal Investigator: Sonya Legg (Princeton Research Oceanographer)

Other Participating Researchers: Robert Hallberg (GFDL/Princeton), Laura Jackson (Princeton), Ulrike Riemenschneider (WHOI postdoc), Steve Griffies (GFDL), 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:
Legg has carried out a variety of project related to mixing in dense overflows as part of the Gravity Current Entrainment Climate Process Team. One focus this year has been an evaluation of the influence of vertical viscosity and tracer advection scheme on the numerical diffusion in z-coordinate simulations of overflows. Numerous idealized simulations at different resolutions have been carried out, with the principal finding that numerical diffusion is inversely related to vertical viscosity, and the use of more sophisticated advection schemes produce only a small change in numerical diffusion. These results have been documented in an article written as a chapter for an AGU monograph on eddy-resolving ocean modeling. Also included in this chapter is a comprehensive review of existing modeling of overflows, and the behavior of eddies in overflows.

Legg has been assisting Laura Jackson and Robert Hallberg in the development of a new parameterization of shear driven mixing by configuring the MITgcm for high resolution simulations of shear-driven turbulence. The new parameterization has now been calibrated against these simulations and documented in Jackson et al, 2007. The parameterization is now implemented in HIM, and idealized overflow simulations carried out using the new parameterization are described in the AGU chapter by Legg et al (2007).

Legg has been supervising the work of postdoctoral researcher Ulrike Riemenschneider at Woods Hole for the past three years. Riemenschneider and Legg have examined the ability of z-coordinate models such as the MITgcm to simulate the Faroe Bank Channel overflow with a thorough comparison of simulations and data, now published in Ocean Modeling (Riemenschneider and Legg, 2007). A principal result is that the MITgcm can reproduce the observations 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. As a follow-on to this study, the Marginal Sea Boundary Condition, a representation of overflows for coarse resolutions implemented in the NCAR POP as part of the CPT, is evaluated for the Faroe Bank Channel, by comparison with the high resolution regional simulations. Significant problems with the MSBC for this particular overflow are highlighted in a manuscript under preparation for Ocean Modeling (Riemenschneider et al, 2007).

Finally, Legg is taking the lead in coordinating a synthesis manuscript for submission to the Bulletin of the American Meteorological Society describing the achievements of the CPT (Legg et al, 2007b).
Publications:


Progress Report:  Dynamics of an Enhanced Brewer-Dobson Circulation

Principal Investigator:  Feng Li (Princeton Postdoctoral 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:  To understand the mechanisms of an enhanced Brewer-Dobson circulation in GFDL coupled chemistry-climate model simulations and to quantify the relative importance of ozone depletion and greenhouse gas increase in driving an enhanced Brewer-Dobson circulation.

Methods and Results/Accomplishments:

Li has continued the study on the dynamics of an enhanced Brewer-Dobson circulation (BDC) in a changing climate in his second year at GFDL.

Li’s first year’s work at GFDL found that the tropical upwelling in the lower stratosphere increases by about 30% for the period 1960-2100 in ensemble simulations in the GFDL coupled chemistry-climate model (AMTRAC). A downward control analysis identified that the increase in the Southern Hemisphere (SH) downward mass flux is caused primarily by planetary waves, whereas the increase in the Northern Hemisphere (NH) downwelling in the lower stratosphere is primarily attributed to enhanced gravity wave forcing. This project is continued in the second year. The purpose is to understand the mechanism of the increase of the orographic gravity wave forcing in the NH lower stratosphere and to explore the relative importance of greenhouse gas (GHG) increase and ozone depletion in driving the intensification of the BDC during the past 3 decades.

It is found that the increase of the orographic gravity wave forcing in the NH is not due to a strengthening of the wave source, but is due to an increase in the wave saturation flux which leads to decreased wave filtering in the lower stratosphere and enhanced gravity wave deposition above the lower stratosphere. An increase in wind speed and a decrease in static stability in the lower stratosphere cause the increase of the gravity wave saturation flux (Fig. 1). This work is the first detailed quantified study of the impact of parameterized orographic gravity waves on the strength of the BDC. The results provide a possible mechanism for the interactions between climate change and gravity waves.

A past climate simulation with fixed 1960 levels of chlorofluorocarbons (CFCs) was performed in an attempt to separate the effects of ozone depletion versus GHG increase in driving an enhanced BDC. The results show that about 60% of the increase in the tropical upwelling is caused by ozone depletion, and the remaining 40% is attributed primarily to GHG increase. While the model may overestimate the impact of ozone depletion because of the model ozone bias, the results certainly highlight the importance of including ozone change in BDC studies.

Li has been collaborating with scientists outside GFDL in diagnosing and comparing AMTRAC model results. Li have worked with Prof. Qiang Fu of University of Washington in a comparison study of the tropical stratosphere vertical mass flux profiles between radiosonde data and the AMTRAC. The results are very encouraging, especially that both show a nearly constant mass flux in the height range 20-30 km, consistent with the “tropical pipe” model (Plumb, 1996). Furthermore, Li’s analysis of the thermal budget in the tropical lower stratosphere provides a strong support of Prof. Fu’s idea that the top of the tropical tropopause layer is the height where the cooling due to eddy vertical mixing becomes negligible. In addition, Li has worked with Dr. Andrew Charlton and Prof. Lorenzo Polvani of Columbia University in looking at the frequency
of stratospheric sudden warming under climate change. Three papers are being prepared on these subjects.

**Figure 1.** Diagnostics of the orographic gravity wave parameterization at 27°N and 86 hPa in December-January-February (DJF). All results are daily-averaged values for DJF. The dotted line in year 2005 in all panels indicates that data for the period 1960-2004 and 2005-2099 are from past and future runs, respectively. (a) The zonally-integrated orographic gravity wave source flux (red), and the zonally-integrated flux of all waves (black), unsaturated waves (blue) and saturated waves (green). Note that the black curve is the sum of the blue and green curves. For clarity, the curve representing source flux has been offset downward by 2.8 kg/m/s²; (b) The zonal-mean zonal wind speed (blue) and Brunt-Vaisala period (green); (c) The saturation ratio, which is defined as the ratio of the number of longitude grids at which the wave flux is saturated to the number of longitude grids at which the wave flux is either saturated or unsaturated; (d) The zonally-normalized flux of unsaturated (blue) and saturated (green) waves. The normalization is calculated by dividing the zonally-integrated flux of saturated and unsaturated waves shown in (a) with the number of longitudinal grids at which the fluxes are saturated and unsaturated, respectively.

**Publications:**


Progress Report: The Distribution, Transport, and Deposition of Mineral Dust in
The Southern Ocean and Antarctica: Contribution of Major
Sources

Principal Investigator: Fuyu Li (Princeton graduate student)

Other Participating Researchers: V. Ramaswamy-advisor (GFDL/Princeton), 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 Southern Ocean and Antarctica, in
particular evaluating the contributions from different sources.

Methods and Results/Accomplishments:
As a continuation of pre-general work, I have been working with V. Ramaswamy and Paul
Ginoux to study the distribution, transport, and deposition of mineral dust in the Southern Ocean
and Antarctica by using the GFDL Atmosphere Model (AM2). The dust in high latitude Southern
Hemisphere is of particular interests (1) as indicators of climate change as observed from the
marine sediments and ice cores [Basile, 1997], (2) as fertilizer for ocean phytoplankton and thus
contributing to the fluctuation of CO₂ in climatic timescales [Martin et al., 1990]. The study
represents the first GCM attempt to quantify the contribution of the major sources by tagging dust
based on its origin.

We evaluate the contribution of each source to the emission, distribution, mass burden and
deposition of dust in the Southern Ocean and Antarctica, and show that each source produces
distinctive meridional transport, vertical distribution, and deposition patterns. The dust in SH
originates primarily from Australia (120 Tgyr⁻¹), Patagonia (38 Tgyr⁻¹) and the inter-
hemispheric transport from Northern Hemisphere (31 Tgyr⁻¹). A small fraction of it (6.8 Tgyr⁻¹)
is transported and deposited in Southern Ocean and Antarctica, where dust from South America,
Australia, and Northern Hemisphere are essentially located in the boundary layer, mid-
troposphere, and upper-troposphere, respectively. These three sources contribute to nearly all the
dust burden in the Southern Ocean and Antarctica while South Africa dust concentration is one
order of magnitude less than other sources. South America and Australia are the main sources of
the dust deposition, but they differ zonally, with each one dominating half of a hemisphere along
120° E - 60° W: the half comprising the Atlantic and Indian oceans in the case of the South
American dust and the Pacific half in the case of the Australian dust [Figure 1]. Our study also
indicates a potentially important role of Northern Hemisphere dust, as it appears to be a
significant part of the dust burden but contributing little to the dust deposition in Antarctica.

Based on current AM2 simulations, future studies will be complemented by satellite
observations through an integrated approach taking advantage of both AM2 and six satellite
instruments, e.g. MODIS and TOMS. We will first focus our analysis on the sensitivity of the
emission, transport and deposition of mineral dust to surface characteristics over source regions.

References:
Basile, I., F. E. Grousset, M. Revel, J. R. Petit, P. E. Biscaye, and N. I. Barkov (1997),
Patagonian origin of glacial dust deposited in East Antarctica (Vostok and Dome C) during
glacial stages 2, 4 and 6, Earth and Planetary Science Letters, 147, 573-589.
Martin, J. H. (1990), Glacial-interglacial CO₂ change: The Iron hypothesis,
**Publications:**

Li, F., P. Ginoux, and V. Ramaswamy, The Distribution, Transport, and Deposition of Mineral Dust in the Southern Ocean and Antarctica: Contribution of Major Sources, submitted to JGR.

**Figure 1.** Relative contribution (fraction) from the three Southern Hemisphere (SH) sources to dust deposition in high latitude SH. Only contributions larger than 40% are plotted with the thick yellow, green and red lines representing the boundaries for South America, South Africa, and Australia, respectively. The white triangle is the Vostok station (78°S, 106°E).
Progress Report: Constraining Ocean Circulation and Basal Melting Under Ice Shelves

Principal Investigator: Christopher Little (Princeton graduate student)

Other Participating Researchers: Anand Gnandesikan-advisor (GFDL/Princeton), Robert Hallberg (GFDL), Michael Oppenheimer (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: 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 dynamics. My research goal is to extend our knowledge of the ocean dynamics that control the location and rate of basal melting, as well as its sensitivity to changing oceanic conditions. I utilize numerical models to isolate the mechanisms -- sub-shelf thermodynamic and dynamic controls, tides, winds, and open ocean dynamics -- by which heat drives basal melting. The understanding and representation of basal melting derived from my research will illuminate its role in the regulation of ice sheet stability, oceanic freshwater balance, and global climate.

Methods and Results/Accomplishments:
To enable this research, I have modified a NOAA Geophysical Fluid Dynamics Laboratory ocean model (the Hallberg Isopycnal Model, or HIM) to represent the unique conditions under ice shelves (including a solid surface boundary and a thermodynamically active ice interface). My initial experiments have focused on the mechanisms by which cavity shape and sub-shelf topography influence heat transport within the ice shelf cavity. A paper, currently in preparation, utilizes theory and numerical models to clarify the interaction of topography and buoyancy driven flow in determining melting locations, especially near grounding lines. While flow in the interior is influenced by cavity shape, near the base of the ice shelf (where melting rates are highest), the location of melting is found to be insensitive to topography.

A recent cruise to the Amundsen Sea (NBP-0702, February-March, 2007) has led me to focus my next set of experiments on processes that may limit and/or stabilize small ice shelf melt rates, beginning with the slope and shape of the ice shelf. In cavities characterized by high temperatures relative to the in-situ freezing point, melting may be limited by the ability of meltwater to flow away from the ice interface. Ice shelf shape (including large scale gradients and smaller-scale roughness) likely influences the vertical velocity and temperature profiles of these outflows. Oceanographic observations taken near ice shelf fronts on NBP-0702 and other cruises may offer support to model results.

Publications:
Progress Report: Evaluating Current and Historical Biomass Burning In Africa

Principal Investigator: Brian Magi (Princeton Postdoctoral Research Associate)

Other Participating Researchers: V. Ramaswamy (GFDL/Princeton), P. 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: Use observational data sets together with the GFDL general circulation model (GCM) to constrain emissions from biomass burning in Africa

Methods and Results/Accomplishments:
Past studies have shown that there are discrepancies between aerosol optical properties (AOP) derived from measurements with AOP output from the GFDL GCM, particularly in the Southern Hemisphere and in Africa (e.g. Ginoux et al, 2006). I am exploring whether the discrepancies are linked to emissions inventories used by the GFDL GCM. The question requires that the emissions inventories be examined in the context of observations of various characteristics of biomass burning. This method is based on published studies that are scattered throughout the literature and a few independent attempts to build emissions inventories from first principles (i.e. starting with a fire). A separate constraint is to compare AOP output from the GCM with independently derived AOP from either in situ instruments or satellites like MODIS and MISR. The most commonly reported AOP is aerosol optical depth (AOD) in the visible wavelengths (AODvis) or at a wavelength of 550 nm (AOD550). The base case comparison of GFDL GCM Atmospheric Model Version 2 (AM2) AODvis with AOD550 measured from the University of Washington (UW) research aircraft during the SAFARI-2000 southern African field campaign (Magi et al., 2003, 2007) is shown in Fig. 1, with the root-mean-squared (RMS) agreement and linear correlation coefficient (r2) listed as well. The horizontal error bars in Fig. 1 are derived from measurement uncertainties in UW AOD550, while the vertical error bars representing neighboring gridcell variability of AM2 AODvis. The important result from this comparison is that although there is agreement in the extratropical latitudes of southern Africa, there is a low bias in AM2 AOD compared to the UW measurements. As I continue to explore this discrepancy, I will also be working on understanding the historical trends in biomass burning emissions and assessing the long term climate impact using the GCM.

References:


Publications:
Progress Report: Observational Constraints on the Tropospheric Ethanol Budget: Implications for U.S. Air Quality, Global Chemistry and Climate

Principal Investigator: Vaishali Naik (Princeton Associate Research Scholar)

Other Participating Researchers: Arlene Fiore (GFDL), Larry Horowitz (GFDL), Michael Oppenheimer (Princeton), Hiram Levy (GFDL/Princeton), J. de Gouw (NOAA), D. Millet (Harvard University), Hanwant B. Singh (NASA), and C. Wiedinmyer (NCAR)

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 atmospheric observations of ethanol together with the MOZART-4, three-dimensional global model of tropospheric chemistry, to advance our understanding of the present-day ethanol budget and its implications for atmospheric chemistry.

Methods and Results/Accomplishments:

Energy security and climate change concerns have led to the promotion of biomass-derived ethanol, a nearly ubiquitous oxygenated volatile organic compound (OVOC) in the troposphere (Singh et al., 2001), as a viable substitute for fossil fuels. However, we have very limited understanding of the current global atmospheric distribution and budget of ethanol. We used the global three-dimensional chemical transport model, MOZART-4 (Emmons et al., 2006), to examine the consistency between atmospheric observations and the current understanding of the global ethanol budget and .

Application of a global ethanol source of 5.8 Tg/yr (including emissions from industrial and biofuel sources, biomass burning, and in-site atmospheric production) and the atmospheric sinks of ethanol (oxidation with hydroxyl radical, dry deposition, and wet scavenging) in MOZART-4 produced ethanol concentrations that are at least an order of magnitude lower than measurements in the boundary layer over the eastern United States in summer 2004, downwind of Asia in spring 2001, and over the remote Pacific in spring 1999 (Figure 1; BASE). Surface observations of ethanol at various locations in North America and off the New England coast are also underestimated by factors ranging from two to ten.

To reconcile model-simulated ethanol concentrations with observations, we performed a second MOZART-4 simulation (BIOGENIC) which included a first estimate of the biogenic ethanol emissions, and a revised spatial distribution of surface ethanol emissions. The comparison of boundary layer ethanol concentrations with observations over the eastern United States improved to within a factor of 2 in the BIOGENIC simulation, implying an important role of ethanol emitted from plants in the U.S. (Figure 1). The large mismatch between simulated and observed ethanol concentrations off the coast of China and over the remote Pacific was maintained in the BIOGENIC simulation.

Our analysis confirms the significant role of emissions from vegetation in the atmospheric ethanol abundance, and suggests that an in situ atmospheric source will be needed to explain the observed ethanol concentrations in remote regions (Naik et al., in preparation, 2007).

References:


Figure 1. Comparison of the observed boundary layer ethanol concentration with MOZART-4 predictions a) over North America and the Atlantic during July-August 2004 (ICARTT), b) in the Pacific troposphere in spring 2001 (TRACE-P), c) over the remote Pacific ocean in spring 1999 (PEMT-B), along the northeastern U.S. coast in d) summer 2002 (NEAQS02) and e) summer 2004 (NEAQS04), f) over Chebogue Point in summer 2004, in Pittsburgh g) summer and h) winter of 2002, i) Trinidad Head in spring 2002, j) Granite Bay summer 2001, and k) in spring 2000 over Alert, Canada.
Progress Report: Effects from Aerosols on Deep Convective Clouds

Principal Investigator: Vaughan Phillips (former Associate Research Scholar at Princeton University; currently Assistant Professor at Hawaii University)

Other Participating Researchers: L. J. Donner and V. Ramaswamy (GFDL/Princeton), Y. Ming (NCAR), C. Seman (GFDL), C. Andronache (Boston College), P. J. DeMott (Colorado State University), S. S. Lee (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 andRespond (50%)

NOAA’s Goal #3: Serve Society’s Needs for Weather and Water Information (50%)

Objectives: Develop tools to represent the aerosol effects on ice-clouds in global models, and to advance the understanding of such effects.

Methods and Results/Accomplishments:

The following projects occurred in 2006, while Phillips was at Princeton University. Firstly, the relative roles of physical mechanisms for nucleation of cloud-droplets and crystals were studied in a mesoscale cloud ensemble. This was done by applying a double-moment bulk microphysics scheme constructed by Phillips et al. (2007a). The scheme predicts the supersaturation that determines nucleation processes within clouds. It was found that for sufficiently rapid (> 1-2 m/s) and deep updrafts, homogeneous freezing of cloud-droplets occurred, dominating the crystal numbers. Homogeneous aerosol freezing prevailed only in regions of weak ascent (< 1 m/s) with high supersaturations (Figure 1). The scheme has recently been applied to study aerosol impacts on precipitation (Lee et al. 2007). Secondly, a paper comparing 2D and 3D clouds was finished (Phillips and Donner 2007). Updrafts were found to be stronger in 3D, and there were related sensitivities of the microphysical and radiative properties of the cloud ensemble. Thirdly, a double-moment version of a deep convection parameterization (Donner 1993) for a global model was constructed, following Phillips et al. (2007a). Its inclusion in a global model affected predicted patterns of precipitation. Fourthly, the design of a scheme to parameterize heterogeneous nucleation of ice was started. The scheme includes dependencies on multiple chemical species of aerosol and is based on field observations of IN activity (Phillips et al. 2007b). Following extensive validation, it is currently being implemented in cloud models with spectral (Phillips et al. 2005) and double-moment bulk (Phillips et al. 2007a) microphysics to simulate a case from NASA’s Tropical Cloud Systems and Processes (TCSP) field experiment. The aim is to assess how nucleation (e.g. by desert dust) modifies the microphysical properties of storm-clouds.

References:


**Publications:**


![Figure 1: Frequency of supersaturation as a function of vertical velocity in a simulation of deep convection in the tropical West Pacific region (from Phillips et al. 2007a).](image)
**Progress Report:** Impacts of carbonaceous aerosols on climate: Examination of the sensitivity of simulated regional climates to absorbing and scattering aerosols

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

**Other Participating Researchers:** V. Ramaswamy-advisor (GFDL/Princeton), Paul Ginoux (GFDL), Hiram Levy II (GFDL/Princeton), Lynn M. Russell (Scripps Institution of Oceanography), 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 climate effects of black and organic carbonaceous aerosols (BC and OC) from anthropogenic and biomass burning sources. To understand the sensitivity of aerosol direct radiative forcing and simulated regional climate response to changes in aerosol extinction optical depth and aerosol absorption optical depth in the GFDL AM2 GCM with prescribed sea surface temperatures.

**Methods and Results/Accomplishments:**

Using a thermodynamic equilibrium hygroscopic growth model coupled to a Mie scattering model, Randles has investigated the climate effects of internal mixtures of organic carbon (OC) and sea salt. The sensitivity of aerosol optical properties and radiative forcing to internally mixing sea salt and organic carbon aerosols is investigated. Increased organic mass content (1) decreases aerosol hygroscopic growth and (2) decreases aerosol scattering consistent with observations. Increased OC mass content also decreases clear-sky shortwave radiative cooling over the oceans relative to pure sea salt aerosols, with the magnitude of the change sensitive to the amount of absorption assumed for the organic carbon fraction. This work was published in Randles et. al. [2004].

Guided by the available observations, numerical experiments are designed for the GFDL AM2 global climate model (GCM) with prescribed sea surface temperatures to test the sensitivity of aerosol direct radiative forcing and climate response to potential changes in aerosol amount (extinction optical depth; $\tau_e$) and aerosol absorption (absorption optical depth; $\tau_a$) that have occurred over India and China over the past half century. This work aims to augment the studies of Menon et. al [2002], Chung and Ramanathan [2002], and Ramanathan et. al. [2005]. Aerosol optical properties and the resulting direct radiative forcing are compared to available observations. The response of the model to lower $\tau_e$ is usually statistically insignificant. At higher $\tau_e$, increased $\tau_a$ contributes to enhanced shortwave atmospheric heating and an enhanced monsoonal circulation that increases precipitation, precipitable water, and low cloud amount over India. In contrast, decreasing $\tau_a$ spins down the hydrological cycle and decelerates the monsoon; also dimming at the surface is reduced because cloud amount decreases, counteracting the surface solar flux reduction due to high $\tau_e$. Precipitation changes over southeastern and northeastern China are qualitatively consistent with observations when some aerosol absorption is present. A manuscript for this work has been prepared for submission to the Journal of Geophysical Research [Randles and Ramaswamy, in preparation for JGR].

Randles is also looking at the effects of biomass burning OC and BC over southern Africa. The GFDL GCM is being used to investigate climate forcing and response to realistic biomass burning from satellite observations of the spatial distributions of aerosol 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 [Haywood et. al., 2003a; Haywood et. al., 2003b; Kiel and Haywood, 2003]. Measurements of aerosol extinction optical thickness ($\tau_e$) and single scattering albedo ($\omega_o$) from the EP-TOMS satellite [Torres et. al., 2005] are incorporated into the GCM. The observationally based $\tau_e$ associated with biomass burning improves the agreement between observed and modeled surface temperature and precipitation rate. Increased $\tau_e$ and increased $\tau_a$ produce a monsoonal circulation that drives increased upward motion and precipitation in the main biomass burning region, while decreased $\tau_a$ weakens this circulation and decreases precipitation.

References:


Randles and Ramaswamy (2007), Absorbing aerosol over Asia: A Geophysical Fluid Dynamics Laboratory general circulation model sensitivity study of model response to aerosol optical depth and aerosol absorption, manuscript in preparation for the Journal of Geophysical Research.


Publications:

Randles and Ramaswamy (2007), Absorbing aerosol over Asia: A Geophysical Fluid Dynamics Laboratory general circulation model sensitivity study of model response to aerosol optical depth and aerosol absorption, manuscript in preparation for the Journal of Geophysical Research.
Progress Report: Numerical Study of a Dry Hurricane

Principal Investigator: Agnieszka Smith-Mrowiec (Princeton graduate student)

Other Participating Researchers: Stephen Garner - advisor (GFDL/Princeton), O. Pauluis (NYU)

Theme #1: Earth Systems Studies/Climate Research

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

Objectives: To gain better understanding of hurricane dynamics, to evaluate potential intensity theory for dry hurricanes, to compare results with simulations including moisture.

Methods and Results/Accomplishments:
Here we present the development and analysis of a dry hurricane-like vortex. We argue that it is possible to have a hurricane spin up in an environment without any or very little moisture. A dry thermodynamics provides a simplified system for studying the dynamical properties of hurricanes. Dry hurricane dynamics may also be related to other planets, and it proves that we should expect hurricane formation in cold Earth scenarios.

The theoretical framework used here is based on axisymmetric hurricane intensity theory of Emanuel 1986. This model assumes slantwise neutrality, which implies that above the boundary layer, potential temperature is constant along angular momentum lines. The assumption of gradient wind and hydrostatic balance enables simple analytical relationships between entropy, angular momentum and the tangential wind or central pressure derivation. Emanuel 1986 does not introduce moisture explicitly, but includes its effects in the moist entropy. We demonstrate that the same theoretical considerations are valid for dry thermodynamic system. The maintenance of the tropical storm depends on the energy flux between the ocean and the atmosphere. In a moist environment this energy flux is a combination of latent and sensible heat fluxes. In the dry case only sensible heat flux is present. Compensation for the absence of that latent energy source is possible through enhancement of sensible heat flux.

A dry version of Emanuel’s maximum intensity theory is then used for analyzing the numerical simulations. In this investigation an axisymmetric, nonhydrostatic version of the ZetaC model, with the GFDL radiation package on a 10 degrees domain has been used to simulate a hurricane-like circulation. The horizontal resolution of the model is 1 km so convection is fully resolved. Simulations were run for about 25 days, producing a steady state. In the series of experiments performed, surface temperature, tropopause temperature, latitude (Coriolis parameter), domain size, resolution, surface heat flux and other parameters were varied.

It is demonstrated that the maximum intensity theory can be studied within a simpler, dry system without moist processes. In the resulting simulations a maximum tangential wind is stronger than the theoretical one by about 10%. It is suggested here, that this is a result of the strong ageostrophic circulation contribution. There needs to be additional explanation for what factors control the entropy and angular momentum distribution, and surface fluxes may not be sufficient. The analysis of the radius of maximum wind (RMW) dependence on the model's input parameters was also performed in order to attempt an explanation of what controls the RMW. Finally comparison of the dry and moist hurricane simulations was done which allowed us to isolate the contribution of moist processes on hurricane dynamics.

References:
Progress Report: Potential Predictability Of The Sst Anomalies In The Indian Ocean

Principal Investigator: Qian Song (Princeton Associate Research Scholar)

Other Participating Researchers: Gabriel Vecchi (GFDL) Tony Rosati (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: Explore the predictability of the SST anomalies associated with the Indian Ocean Dipole in the GFDL coupled climate model

Methods and Results/Accomplishments:
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.

References:

Publications:
Progress Report: Large Scale Atmospheric Circulation and Climate Variability, and Convection Parameterization

Principal Investigator: Geoffrey Vallis (Princeton Senior Research Scientist/Professor)

Other Participating Researchers: Edwin Gerber (Columbia), I. Held (GFDL/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: Understand the nature of the large-scale extra tropical patterns of variability in the atmosphere

Methods and Results/Accomplishments:

We have investigated the nature of the North Atlantic Oscillation and the so-called annular modes of variability using idealized atmospheric general circulation models. We find that the fundamental basis for these patterns of variability lies in the troposphere, and that neither the ocean nor the stratosphere is necessary for their presences. More specifically, we have shown that the structure of the empirical orthogonal functions (EOFs) of the NAO and annular modes follows, at least in part, from the structure of the baroclinic zone. Given a single baroclinic zone, and concomitantly a single eddy-driven jet, the meridional structure of the EOFs follows from the nature of the jet variability, and if the jet variability is constrained to conserve zonal momentum then the observed structure of the EOF can be explained with a simple model. In the zonal direction, if the baroclinic zone is statistically uniform then so is the first EOF, even though there may be little correlation of any dynamical fields in that direction. If the baroclinic activity is zonally concentrated, then so is the first EOF. Thus, at the simplest order of description, the NAO is a consequence of the presence of an Atlantic storm track; the strong statement of this would be that the NAO is the variability of the Atlantic storm track. The positive phase of the NAO corresponds to eddy momentum fluxes (themselves a consequence of wave breaking) that push the eddy-driven jet polewards, separating it distinctly from the subtropical jet. The negative phase of the NAO is characterized by an equatorial shift and, sometimes, a weakening of the eddy fluxes and no separation between sub-tropical and eddy-driven jets. Variations in the zonal index (a measure of the zonally averaged zonal flow) also occur as a consequence of such activity, although the changes occurring are not necessarily synchronous at different longitudes, and the presence of annular modes (i.e., the associated patterns of variability) does not necessarily indicate zonally symmetric dynamics.

In other work we have investigated rescaling the equations of motion in order to make the scale of convection larger and possibly resolvable by an atmospheric general circulation model. This approach would be an alternative to convective parameterizations.

Publications:


Progress Report: Parameterizing Mesoscale Eddies in the Ocean.

Principal Investigator: Geoffrey Vallis (Princeton Senior Research Scientist/ Professor)

Other Participating Researchers: Rongrong Zhao (Former Princeton Research Associate)

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: Understand the nature of the large-scale ocean circulation, in particular the role of mesoscale eddies

Methods and Results/Accomplishments:
We have investigated a parameterization scheme for mesoscale eddies based on a residual, or transformed Eulerian mean, formulation of the equations of motion in which the eddies are parameterized by a large vertical viscosity in the momentum equations, with no parameterization appearing in the tracer (e.g., temperature or salinity) evolution equations.

The residual scheme is compared both to a conventional parameterization that uses a skew diffusion (or equivalently advection by a skew velocity), and to eddy-permitting calculations. Although in principle equivalent to certain forms of skew flux schemes, the residual formulation is found to have certain advantages over the conventional scheme, in particular near the upper boundary where conventional schemes are sensitive to the choice of tapering, but the residual scheme less so. The residual scheme also enables the horizontal viscosity --- which is mainly applied to maintain model stability --- to be reduced. Finally, the residual scheme is somewhat easier to implement, especially in simulations with multiple tracers, and the tracer transport is easier to interpret. On the other hand, the residual scheme gives, at least formally, a transformed velocity, not the Eulerian velocity. To summarize, the scheme provides a viable alternative to the popular Gent-McWilliams scheme.

Publications:
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), M. Daniel Schwarzkopf (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 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:

Our previous work emphasized the management of ozone air quality by reducing methane emissions, analyzing methane reductions from point of view of both atmospheric science and quantitative policy analysis (West et al., 2006). During the past year, we published an analysis of 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., 2007).

In extending this work, Dr. West contributed to a modeling study of the effect of methane on tropospheric ozone, in which MOZART-2 was used in fully-transient 30-year simulations. This research shows that neither the ozone air quality benefits nor the climate benefits depend on the location of methane emission changes. We further show that tropospheric ozone responds linearly to changes in methane emissions, over a wide range of emissions, and that most of the ozone produced from methane oxidation is within the lower troposphere. Finally, we show that simulations conducted at future steady-state conditions can be used to approximate the long-term changes in a transient simulation with emissions of many precursors changing (Fiore et al., submitted). Dr. West is now preparing a complementary article to this work that presents the future methane simulations used, and which analyzes the global benefits of avoided human mortalities under these scenarios and compares these with the projected costs of emission control (West et al., in preparation).

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., V. Naik, L. W. Horowitz, and D. L. Mauzerall (in preparation) Ozone long-range transport: effect of NOx emission controls from world regions.
Progress Report: Seasonal Predictability and Seasonal Hydrologic Prediction over the U.S

Principal Investigator: Eric F. Wood (Princeton Professor)

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

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:
1) To develop a multiple-model framework for seasonal hydrological predictions.
2) To develop methodology that support ensemble hydrologic prediction.
3) To develop strategy to evaluate and validate ensemble hydrologic predictions.
4) To demonstrate realtime drought monitoring and drought prediction capability

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
− Develop realtime US drought recovery prediction capability

A Bayesian merging procedure was developed in 2005-2006 and was implemented in the seasonal hydrologic prediction system that is currently used in realtime over the entire U.S. We have identified streamflow points over the eastern U.S. to produce realtime streamflow predictions. A realtime U.S drought monitoring capability was developed to provide weekly updates on the drought conditions over the continental U.S. Associated with the drought monitoring activity is the development of realtime drought prediction system. Figure 1 shows our most recent drought monitoring compared with the official U.S. drought monitor, and Figure 2 shows the predictions of 2007 U.S. droughts over the West and the Southeast. Our predictions successfully capture the evolution of the droughts over these regions several months in advance. More information about this work and available products can be found at http://hydrology.princeton.edu/forecast. This web has been visited over 40000 times since it was up online and over 16000 times last year.
Figure 1: Realtime drought monitoring over the U.S. compared with the official U.S. Drought monitor.

Drought Monitoring and Prediction During 2007

Figure 2: Drought monitoring and forecast over the West and the Southeast U.S. during 2007.

Publications:


Eric F. Wood and Lifeng Luo (2007), Improving precipitation generation for seasonal hydrologic prediction. The 3rd workshop of HEPEX.
Progress Report: Research on the Atlantic Thermohaline Circulation and Its Interaction with El Nino

Principal Investigator: Jianjun Yin (Princeton Research Associate)

Other Participating Researchers: Ronald Stouffer (GFDL), Keith Dixon (GFDL), Stephen Griffies (GFDL), 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 investigate the interaction between the Atlantic Thermohaline Circulation (THC) and the Pacific El Nino; To study the impact of the variations and changes in the THC on El Nino events; To better understand the predictability of ENSO and the THC.

Methods and Results/Accomplishments:
Yin has participated in an internationally collaborative research on the impact of a shutdown of the THC on El Nino. The results have been described in an in-press paper of Journal of Climate. In addition, Yin has performed a hosing-dehosing experiment with CM2.1, in which the external freshwater addition into the high latitudes of the North Atlantic alternates between 0.05 Sv and -0.05 Sv. The purpose was to amplify the modeled multi-decadal variations of the THC and better trace the signal propagation from the Atlantic to Pacific. If any phase relation can be established between the two significant systems, it would have important implication for climate predictability. The data analysis of the experiment is under way.

Publications:

Progress Report: Implement, Develop and Evaluate Moist Physics Parameterizations for a Hierarchy of GFDL Atmospheric Models

Principal Investigator: Ming Zhao (Princeton Associate Research Scholar)

Other Participating Researchers: Isaac Held and Leo Donner (GFDL/Princeton), 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 incorporate, develop and evaluate moist physics parameterization schemes for use in a hierarchy of GFDL atmospheric models ranging from highly idealized to comprehensive GCM at different horizontal and vertical resolutions. To support these models being used by the GFDL community for investigating climate variability, climate prediction, climate sensitivity, and atmospheric circulation.

Methods and Results/Accomplishments:

In the past year, Zhao has been working with Isaac Held, Leo Donner and the GFDL GAMDT on incorporating the University of Washington shallow cumulus (UW-ShCu) scheme (Bretherton et al. 2004) into AM3 and on the unification of UW-ShCu with Donner deep convection (Donner 1993) by creating a unified plume module for both shallow and deep convection schemes. The UW-ShCu code was restructured and modernized and connections to the boundary layer and stratiform cloud schemes have been suitably modified. The method of temperature iteration was changed to ensure the accuracy of the iteration. Multiple choices of plume microphysics have been implemented, including a simple auto-conversion as function of temperature, a smooth precipitation with an assumed PDF of in-cloud condensate, auto-conversion based on explicit droplet number and also the Donner microphysics. Multiple choices for cloud-base mass flux closures were also implemented. Plume cloud droplet nucleation to aerosol, plume transport of droplet number and aerosol, and plume wet-deposition are also included. On the deep convection side, Zhao have made available a unified/simplified version of the Donner deep convection scheme, which utilizes the unified plume model and performs plume calculations on the host model grid instead of the default high resolution cloud model grid. For the current AM3 configuration, the unified/simplified Donner deep convection scheme saves approximately 35% total computation time for the full AMIP integration. The incorporation of the UW-ShCu and the unified/simplified Donner deep convection scheme improves the global cloud simulation and the implied ocean heat transport compared to the earlier configuration of AM3. The improvement for other simulated fields is also systematic and it has therefore been proposed as the current candidate configuration for AM3. On-going effort is now focusing on testing and unifying the shallow and deep convective closure, which a primary target to improve the Amazon precipitation simulation.

In the past year, Zhao continued to work with Isaac Held on the understanding of GFDL column physics and their interactions in a simplified dynamical framework (Cartesian geometry, doubly periodic boundary condition, horizontally homogeneous sea surface temperature, see Held et al 2007). He has examined rotating radiative-convective equilibria simulations using the GFDL AM2 physics at resolutions of 220, 110, and 55 km, in a large (20000x20000 km) domain with fixed SST and uniform Coriolis parameter. The large domain allows a number of tropical storms to exist simultaneously. Once equilibrium is attained, storms often persist for hundreds of days. The number of storms decreases as SST increase, while the average intensity increases. As the
background rotation is decreased, the number of storms also decreases. At these resolutions and with this parameterization of convection, a dense collection of tropical storms is always the end-state of moist convection in the cases examined. We propose these horizontally homogeneous rotating radiative-convective equilibria at GCM resolutions as a useful framework for studying the tropical storm-like vortices produced by global models. These simulations raise a number of theoretical issues related to the factors that determine storm size and intensity and the effects of global warming on these storm characteristics.

During the past year, Zhao also participated in the NSF funded project entitled “Tropical-extratropical interactions in a hierarchy of atmospheric models” by providing diagnostic and code support. Zhao has partially implemented the SPEEDY radiation code in the FMS for potential use in this project.

References:


Publications:


Progress Reports:

Biogeochemistry
Progress Report:   A Direct Carbon Budgeting Approach to Infer Carbon Sources and Sinks

Principal Investigator: Cyril Crevoisier (Princeton Associate Research Scholar)

Other Participating Researchers: Colm Sweeney (NOAA/GMD), Manuel Gloor (University of Leeds), Jorge Sarmiento (Princeotn), 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\(^{-1}\). 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), by the NOAA/GMD/ESRL team. 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 [Crevoisier et al., 2006].

The DCBA method has been used to analyze the strengths and weaknesses of the network, leading to the implementation on a new station at Berms (Saskatchewan, Canada) to complement the network in a region that was poorly sampled by the existing network.

More recently, in collaboration with NOAA/GMD/ESRL, we have started to exploit the first years of data. The observations have provided valuable information about CO\(_2\) surface fluxes and transport over the North American continent. Importantly, the measurements have suggested a moderate carbon sink in North America of -0.51±0.31 GtC.yr\(^{-1}\) [Crevoisier et al., in prep.]. The sinks are mainly distributed in three regions: mid-west states, which are characterized by an extensive agriculture; South-East regions where most of the deciduous forests are located; and the South of the boreal region. The implication of this result on the global carbon budget is now under study.

Publications:


Crevoisier C., Sweeney C., Gloor M., Sarmiento J. L., and Tans P. P., A moderate carbon sink in North America is suggested by extensive CO\(_2\) vertical profile observations used in a direct budgeting approach, in preparation.
Figure – Annual mean of horizontal fluxes of carbon in GtC yr⁻¹ as derived from the first years of measurements of NOAA/ESRL aircraft network using the Direct Carbon Budgeting Approach. Positive fluxes show outgoing CO₂. On average, high horizontal positive fluxes are found along the East Coast. They follow the outflow of CO₂ (easterly wind) and highlight the elevated CO₂ due to fossil fuel emissions from Texas to the East Coast that accumulate in this eastern corridor.
Progress Report: Disturbance of Vegetation by Fire: Inclusion of Fire Models in Climate Models

Principal Investigator: Cyril Crevoisier (Princeton Associate Research Scholar)

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:

Development of predictive fire models is needed to understand fire effects on ecosystem dynamics, air quality and climate feedbacks. The current generation of dynamic vegetation models (DGVM) uses simple fire models to represent the impact of fires on vegetation mortality and the flux of carbon from the terrestrial biosphere to the atmosphere, which are typically evaluated on an annual time scale. In order to investigate the impacts of fires on atmospheric chemistry and physics, fires and associated emissions need to be evaluated on a monthly or even daily time with improved spatial accuracy, particularly in boreal regions where the current global fire models under-predict fire occurrence and distribution.

As part of this effort, a fire model, the Potential Burned Area (PBA) model, relying on in-situ and remote sensing observations, has been designed for boreal regions [Crevoisier et al., 2007]. The PBA model estimates monthly burned area from four climate (precipitation, temperature, soil water content and relative humidity) and one human-related (road density) predictors for boreal forest. The burned area model is a function of current climatic conditions and is thus responsive to climate change. Model parameters are estimated using a Markov Chain Monte Carlo method applied to on ground observations from the Canadian Large Fire Data Base.

The model has been validated against large sets of in-situ observations for Canada and Alaska (see Figure) and of burned area estimates from remote sensing observation for Siberia. Provided realistic climate predictors, the model successfully reproduces the spatio-temporal evolution of burned area in the boreal forest, including seasonality and interannual variability. The predicted burned area is in the range of various current estimations, which makes it suitable to study quantitatively the evolution of fire with climate. The fire model is currently being implemented in the GFDL DGVM LM3V.

References:

Figure – Evaluation of our PBA model in Alaska. *Top:* Annual burned area as estimated by the PBA model (full line) and as observed in-situ (dashed line). The model, built on Canadian observations, is able to capture the good interannual variability in Alaska. *Bottom:* Burned area expressed as a fraction of a grid-cell as observed in-situ (left) and as estimated by the PBA model (right).
Progress Report: Disturbance of Vegetation by Fire: Direct Observation of Fire Emissions in the Tropics from Space

Principal Investigator: Cyril Crevoisier (Princeton Associate Research Scholar)

Other Participating Researchers: Alain Chédin (LMD/IPSL), Elena Shevliakova (Princeton).

Theme #2: Biogeochemistry

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

Objectives: Understanding carbon emissions from fire in the tropics.

Methods and Results/Accomplishments:

Recently, CO₂ observations from space have become available from space-borne infrared sounders, which provide information on tropospheric variations of these trace gases, including plumes due to biomass burning emissions. In particular, monthly mean mid-tropospheric CO₂ columns over the tropics have been retrieved from evening and morning observations of TOVS instruments flying onboard NOAA polar satellites [Chédin et al., 2003] and AIRS instrument flying onboard the Aqua platform [Crevoisier et al., in prep.]. We have shown that the difference between these two columns, hereby called Daily Tropospheric Excess (DTE), exhibits spatio-temporal patterns in very good agreement with fire patterns over most of the tropical regions affected by fires [Chédin et al., 2007]. This strong correlation found between DTE and fire emissions is related to the strong diurnal cycle affecting fires observed in various regions [Giglio, 2007]. The DTE variability has been related to the El Niño Southern Oscillation (ENSO). Therefore, for the first time, a proxy for CO₂ fire emission in the tropics is directly available from space observations.

We are using the DTE of CO₂ derived from TOVS observations (1987-2005) to study the spatio-temporal variability of fire emission in the tropical region. In particular, the DTE signal is compared with in-situ measurements of CO₂ made at the surface to study the global variability of carbon emission from biomass burning. DTE is also used in conjunction with climate, ecological and human data to derive the main drivers of fire emissions in the tropics. This is the first step towards the modeling of fire emission in the tropics and the inclusion of the derived fire model into the dynamic vegetation model LM3V of GFDL.

References:


Crevoisier C. et al., Four years of CO₂ observation in the mid-to-upper troposphere from AIRS/AMSU system flying onboard NASA/Aqua, in preparation for JGR, 2007.

Figure – Slope (ppmv.mm⁻¹) between annual Diurnal Tropospheric Excess of CO₂ derived from TOVS observations and annual precipitation. Red indicates that an increase in precipitation will lead to an increase in DTE and thus emissions from fire. Those regions are mostly covered by xeric vegetation, which are characterized by low productivity. On the contrary, most of the blue regions are covered by mesic vegetation, for which fire emission is limited by periods when fuels are dry enough to permit ignition.
**Progress Report:** Evaluation of Ecosystem Carbon Dynamics in North America Using Hourly to Decadal Data on Local to Regional Scales

**Principal Investigator:** Cyril Crevoisier (Princeton Associate Research Scholar)

**Other Participating Researchers:** Sergey Malyshev (Princeton), Drew Purves (Microsoft Research), Elena Shevliakova (Princeton), Stephen Pacala (Princeton).

**Theme #2:** Biogeochemistry

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

**Objectives:** Understanding how adaptation and acclimation within ecosystems might affect the future of carbon sources and sinks

**Methods and Results/Accomplishments:**

There are major uncertainties in the causes and magnitudes of ecosystem CO₂ fluxes, and hence ecosystem carbon storage, in North America. Because of the complexity, and varied spatiotemporal scales, of the key processes, detailed process-based models are needed to understand and predict carbon fluxes and storage. It is crucial that these models are constrained properly, calling for an integrated modeling-data approach utilizing data at a wide variety of scales.

We combine two different data sources (eddy flux, forest inventories) to estimate biophysical parameters, with an emphasis on respiration parameters, for the state-of-the-art dynamic vegetation model LM3V of GFDL. Eddy flux data provide information on terrestrial carbon fluxes at short (hourly to seasonal) time-scales, whereas the USDA forest inventories (FIA) measure land carbon over decades to a century, including physiological and ecological changes within ecosystems, which is needed to accurately simulate ecosystem carbon dynamics in the context of climate change. These data thus mutually constrain model parameters, accounting correctly for the varied spatiotemporal scales of the processes, and leading to a new understanding of how adaptation and acclimation within ecosystems might affect the future of carbon sources and sinks.

FIA allow ecosystem fluxes to be decomposed into the growth and mortality of individual trees, residing in different forest communities, and thus provide a constraint on growth and mortality parameters of LM3V. Eight sites have been selected to perform the optimization, by finding all FIA with soil water holding capacity within 0.6 standard deviations of the soil depth of Harvard Forest (NHF) and by retaining the grid-cells with the largest number of individual plots. The sites are located along the East Coast, from North (Site A) to South (site G). Growth and mortality differ at all this site and reflects the North-to-South temperature gradient as shown on the following figure, which highlights the link between climate and long-term evolution of the carbon pool. One of the eight sites is the Harvard Forest (NHA) site, on which an eddy flux tower provides measurements that are used to optimize the short-term evolution of the carbon pool.

The Bayesian framework used to perform the optimization and which comprises LM3V and an MCMC scheme has been designed and is being implemented into the FMS system of GFDL.
Figure. The Figure was generated by extracting all available biomass/age data from the FIA data from each of 3 sites (Site A, Harvard Forest and Site F) and fitting a 3rd-degree polynomial to these data (thick line). The magnitude and nature of the long-term evolution of the carbon pool differs sharply from one region to another within the eastern US (note the North-South gradient).
Progress Report: Multi-Species Atmospheric Inversions for Fluxes of CO₂, CO, And CH₄

Principal Investigator: Sara Mikaloff Fletcher, (Princeton Associate Research Scholar)

Other Participating Researchers: Cyril Crevoisier (Princeton), Jorge Sarmiento (Princeton), Andy Jacobson (NOAA-ESRL)

Theme #2: Biogeochemistry

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

Objectives: The hypothesis that increased atmospheric CO₂ leads to increased uptake of atmospheric CO₂ by the terrestrial biosphere, i.e. CO₂ fertilization, is included in many model simulations of future climate change, including those made for the recently released International Panel on Climate Change (IPCC) report. However, recent studies based on observed atmospheric and oceanic tracer concentrations and transport models (Jacobson 2007a,b) have found an unexpectedly large terrestrial source in the tropics, which is inconsistent with a large carbon fertilization sink. The net tropical flux can be considered as the sum of emissions from tropical land use change, primarily through biomass burning, and uptake from CO₂ fertilization. Therefore, this large net source suggests that either the CO₂ fertilization sink is a relatively small effect or that CO₂ emissions from land use change must be substantially higher than most satellite-based estimates. The aim of this study is to produce high quality flux maps of CO₂ and test the hypothesis that the CO₂ fertilization sink is small relative to the global carbon budget using observations of the three major carbon-related species in the atmosphere: CO₂, CO, and CH₄.

Methods and Results/Accomplishments:
In the past year, we finalized publications on time independent air sea fluxes estimated from ocean interior data and models (Mikaloff Fletcher et al., 2007) and their implications for terrestrial fluxes when combined with analogous atmospheric data and models (Jacobson et al., 2007a,b). In addition, we employed forward simulations using the MOZART atmospheric transport model to examine whether the large tropical and southern hemisphere land fluxes estimated in Jacobson et al. (2007a,b) are consistent with atmospheric observations of the 13C/12C isotopic ratio in CO₂ from the NOAA-ESRL flask network. Since the terrestrial biosphere discriminates against 13C while the ocean has relatively little effect on the 13C/12C ratio, this serves as an independent test of the flux estimates.

Furthermore, we are in the process of developing an inversion to estimate time varying fluxes of CO₂, CO, and CH₄ simultaneously. Fluxes of tracers to the atmosphere are often estimated with atmospheric tracer inversions, which combine in situ observations of atmospheric tracer concentrations and simulations from atmospheric tracer transport models to estimate regional surface fluxes to the atmosphere. In the tropics, where few in situ observations are available, the atmospheric inversions are highly data-limited (e.g. Gurney et al.). Furthermore, atmospheric inversions provide limited insight into the source processes responsible for these fluxes to the atmosphere. By inverting simultaneously for CO₂, CO, and CH₄, we hope to improve the flux estimates, transports, and partition between spatially overlapping source processes such as terrestrial uptake and biomass burning. This will allow us to test the hypothesis that there is not a substantial carbon fertilization sink.

As a first step, we are currently adapting the Carbon Tracker data assimilation and inversion developed at NOAA-ESRL (Peters et al., 2007) to the MOZART atmospheric transport and chemistry model. This will provide us with an excellent framework for the multi-species
inversion and also provide a second model to the Carbon Tracker community for intercomparison.

References:


Publications:


**Progress Report:** Development of a New Global Terrestrial Carbon-Nitrogen Model

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

**Other Participating Researchers:** Stefan Gerber (Princeton), Jack Brookshire (Princeton), Elena Shevliakova (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 (20%)

**NOAA’s Goal #2:** Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond (80%)

**Objectives:**
1. To add nitrogen dynamics to the existing Geophysical Fluid Dynamic Laboratory land model LM3V, a dynamic vegetation model that is part of the NOAA/GFDL fully coupled earth system model; 2. To develop a flexible and intellectually novel modeling platform capable of addressing fundamental questions about how nutrients in terrestrial ecosystems influence biosphere-climate dynamics; 3. To model and understand natural and human impacts on the transport and cycling of nitrogen at a global scale – a central issue for the management of nutrients, land use, and pollution at regional to global scales.

**Methods and Results/Accomplishments:**

Our goal is to add nitrogen dynamics to the existing Geophysical Fluid Dynamic Laboratory land model LM3V, a dynamic vegetation model that is part of the NOAA/GFDL fully coupled earth system model. We hired Stefan Gerber to work with the Hedin and Oppenheimer laboratory groups, and in collaboration with Steve Pacala’s group, Lena Shevliakova and NOAA/GFDL scientists. We have also partially supported Jack Brookshire who has assisted Stefan with parameterization of the model against empirical datasets on the global N cycle.

We have made excellent progress over the past year. The model kernel is now fully developed, and Stefan is finishing a first manuscript that describes this kernel, discusses the essential challenges to representing nitrogen in coupled land-atmosphere models, and applies the new model to both global and local scenarios of nitrogen and carbon coupling. The model dramatically improves upon all previous state-of-the-art dynamic vegetation models. It captures processes not previously treated by any model, yet that are essential for resolving critical feedbacks between terrestrial ecosystems, climate and land use change. In addition, the model dynamically resolves key aspects of the nitrogen cycle and it’s feedbacks to carbon and climate. This represents an important step forward as models thus far have relied upon “static” approaches using prescribed data fields. Such “static” treatment is perceived as a major impediment for resolving key nutrient-climate feedbacks (e.g., Friendlingstein et al. 2006; Torn and Harte 2006).

Our model is designed as a flexible platform that can be applied to questions of vegetation-climate dynamics as well as questions of land-use and nitrogen transport in rivers that feed into coastal regions. Models used in assessing climatic feedbacks for different IPCC CO2 emission scenarios currently do not explicitly treat terrestrial carbon- and nitrogen interactions, nor the potential for nitrogen limitation. In addition, human nitrogen pollution has the potential to cascade into river and coastal systems threatening the nutrient balance of estuarine ecosystems.

The new model captures the following essential features: feedback between carbon and nitrogen on the plant level; belowground processes that determine soil organic and inorganic nitrogen transformations; feedbacks between nitrogen and recalcitrant litter and soil organic matter; hydrological losses of dissolved inorganic and dissolved organic nitrogen (DON) to groundwater and rivers; integration of predictive equations for biological nitrogen fixation.
At present, the model is able to reproduce broad scale patterns of vegetation and soil nitrogen, as well as stream water concentrations of dissolved forms of nitrogen (Fig. 1). Simulations show that productivity and carbon balances strongly depend on external nitrogen supplies at scales of centuries or millennia, and as a function of annual temperature and rainfall. A major finding is that the balance between nitrogen inputs via biological fixation vs. nitrogen losses by fire/DON is the essential determinant of the degree to which nitrogen can limit productivity after a disturbance event. Further simulations show that ecosystem nitrogen losses can exceed non-fixation inputs, acting to force severe N limitation or to establish a niche for biological nitrogen fixation as a compensatory mechanism (see Figure 1). These initial results also point to the urgent need to incorporate a mechanistic treatment of biological nitrogen fixation; we are currently working on this.

Jack Brookshire has assisted in amassing and synthesizing global data sets of N pools and losses across primary humid forests worldwide. This information is critical for equation formulation and parameterization of the N component of the new model. We have now synthesized hydrologic N loss data for over 270 unpolluted primary humid forests worldwide, including plant-available soils N pools. Brookshire and Gerber have worked together to incorporate routines for ecosystem level dissolved organic N (DON) losses and inputs via biological N fixation (BNF) into the N module of LM3V. These fluxes are critical to modeling C-N interaction globally as losses of plant-unavailable DON can sustain N limitation.
Figure 1:

Figure: Nitrogen deficit, nitrogen limitation and biological nitrogen fixation as compensatory mechanisms. Top: Nitrogen requirements for plants to maintain unrestricted growth at the model’s steady state. Middle: Simulated nitrogen fixation at steady state after establishing nitrogen fixation in the model. Bottom: Reconstruction of natural nitrogen fixation (Cleveland et al., 1999).
References:

Publications:
**Progress Report: Modeling Land-Use Dynamics In The Earth System**

**Principal Investigator:** George Hurtt, (UNH Associate 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:**

For 2006-2007, we proposed to further develop and refine land-use products, parameterizations, and submodels to advance ability of Princeton/GFDL models to simulate the biophysical (e.g. albedo etc..) and biogeochemical (C, N, H2O) effects of historical land use/land management activities on the Earth system. Specific proposed activities included: (i) continued work related to the atm-land-river-coastal zone nitrogen experiment (December 2005 Video Conference) deliverables related to this team (land use effects), (ii) submodels and parameterizations that account for different agricultural systems, crop-types, management practices, and the horizontal transfers of C and N over time, and (iii) studies of the long term global effects of shifting cultivation and logging, and the secondary lands these activities create, on the global carbon/climate system.

During the past year, we made substantial progress on all of these activities.

(i) In 2006-2007, we provided global gridded estimates of: global land-use activates, major pre-industrial and contemporary N loading terms, point source and non-point source N loadings to river systems, and global gridded estimates of major crop types -- all consistent with the global land-use information developed by this team and already incorporated in LM3V. We also continued work with the GFDL, Princeton, and Vörösmarty et al. (UNH) teams on the key steps of integration needed for the global simulations of the impacts of these activities on coastal systems.

(ii) In 2006-2007, we worked on completing maps of global crop management activities that are important for both biophysical and biogeochemical applications. These maps include identification of single-, double-, and triple-cropping rotations, based on new maps from the HYDE group at RIVM in the Netherlands (HYDE 3) and our own work in South, Southeast, and East Asia. We also developed consistent maps of fertilizer inputs by cropping system based on FAO data. These data are being used in: (1) a new global simulation of the process-based agro-ecosystem biogeochemistry model DNDC (e.g., Li 1996) to generate estimates of crop yield, trace gas fluxes (CO2, CH4, NO, N2O, NH3) and nitrate leaching at 5' resolution, and (2) in generalizations of more aggregated cropping systems (e.g. C3 annual, C3 perennial, C4 annual, N fixers) for inclusion in future versions of both GLM and LM. In addition, we 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). We also joined a
national study to assess the potential for abrupt emissions of methane from terrestrial ecosystems in the future (Brooks et al. 2007-In prep.), and completed a publication on the effects of human fire suppression activities on patterns of fire (Girod et al. 2007). Recently, we began work on calculating the impacts of horizontal transfers of agricultural and wood harvest products on the spatial/temporal pattern of air-land fluxes using output from the LM3V model. These efforts all contribute to our overall objectives by providing important new inputs, algorithms, and reference datasets needed for model estimates of the effects of land-use in the Earth system.

(iii) In 2006-2007, we upgraded our Global Land-Use Model (GLM) from version 3.2 to 3.3, correcting an error in the parameterization of wood harvesting. We also produced a new regional version of GLM-compatible land-use history products for the coterminous U.S. based on Hurtt et al. 2002. We worked with Elena Shevliakova and Sergey Malyshev to fully integrate the resulting products into the Princeton/GFDL land model LM3V. These land-use history products are essential and distinguishing drivers for the LM3V model, and provide the basis for a new paper in preparation describing the effects of land-use history on the carbon balance of the planet (Shevliakova et al. 2007-In prep.). During the past year, we made all GLM version 3.2 and 3.3 products available to the public on the EOS-Webster Digital Library of Earth Science Data (http://eos-webster.sr.unh.edu/data_guides/glm_dg.jsp). In 2006-2007, we completed a detailed study of the effects of land-use history on Eastern US forests (Albani et al. 2006), and joined a new international global land-use model intercomparison project (Akinori et al. 2007-In prep.). We also participated in an IPCC Working Group meeting at the Aspen Global Change Institute to develop a new plan for the next generation of climate change projection modeling experiments (Meehl et al. 2007). This plan specifically anticipates the role and importance of land-use activities in the Earth system. In 2007, we were solicited for participation in a key upcoming IPCC future-scenario development workshop in the Netherlands. Stemming from these activities, we developed a preliminary algorithm to construct globally gridded land-use scenarios of the future that are consistent with historical reconstructions (smoothly transition from) and are based on the IPCC future scenarios. The further development and implementation of this work will be essential to running Princeton/GFDL models, and other next generation models of land and Earth system, into the future.

Publications:
Akinori et al. 2007-In prep. Historical emissions from land use change (MATCH Paper #4).


Shevliakova et al. 2007-In prep. Carbon Cycling under 300 years of Land-use Changes in the Dynamic Land Model LM3V.


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

Other Participating Researchers: Chris Sabine and Richard Feely(NOAA-PMEL), Rik Wanninkhof and T.-H. Peng (NOAA AOML); Frank Millero (Miami), Andrew Dickson (UCLA)

Theme #2: Biogeochemistry

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

Objectives: Monitor the oceanic inventory of anthropogenic carbon dioxide

Methods and Results/Accomplishments:
Significant progress has been made during the past year on the construction of a new data base which will be used for the study of the distribution and time rate of change of inorganic carbon in the ocean. In large part the mechanics of constructing this data base are very similar to those used for GLODAPv1.1. The primary difference is that the new collection is based largely on cruise results generated by the European ocean carbon community. These data have not previously been available for use by U.S. scientists. Also significant is the fact that the vast majority of these new data are from the northern North Atlantic. Coverage of that area in GLODAPv1.1 was sparse to none. Prior to this year, this collaboration was limited to Princeton with the European CARBOOCEAN project combined with the continuing Princeton participation with the U.S. CLIVAR carbon science team. This past summer, however, a meeting was held in Iceland and the full U.S. team formally joined the analysis effort.

Data Collection and Synthesis:
European Data
The new data base will be called CARINA and has as it's original core cruise data from a failed European project by the same name. The original collection consisted of data from approximately 30 cruises. Other than amassing the files on a single computer, no quality control or synthesis had occurred and the data records were largely too poor to be of any real value. The original CARINA collection was transferred to CDIAC for archiving and subsequently to Princeton for synthesis. The initial synthesis phase has consisted of primary quality control and collection of metadata. During the first two years of this effort Key attended all the CARBOOCEAN meetings (participation funded by CARBOOCEAN) and developed a close collaboration with the European community. This interaction combined with the initial data synthesis directly resulted in a significant increase in the data collection from 30 to 80 cruises (by mid summer 2006). In many cases the data from the new cruises is significantly better than the original collection. Primary QC of all measured parameters from these 80 cruises and metadata collection has been largely completed. The task continues because previously unknown (yet relevant) data are continually being "discovered" for existing cruises and new cruises are still being added.

The data base expansion from 30 to 80 cruises had already exceeded plans for this phase of the U.S synthesis, however, as a result of the Iceland meeting this summer and the direct involvement of other U.S. Science Team members (USSTM), the data base effort has again expanded significantly. At that meeting a number of key decisions were made, some of which are integral to the U.S. efforts. These are outlined below:
1. The analysis effort for the data was broken into three regional projects: a. Nordic Seas and Arctic Ocean, b. North Atlantic and Southern Ocean. Additional regional efforts were discussed, but these regions will have little or no European participation (presumably U.S. plus Japanese and Australian scientists). At least one USSTM will be active in each of these efforts and, because of the data connection, Key will participate in each of them.

2. U.S. CLIVAR data will be used to help quality control the European data although these data may not be included in the actual CARINA collection.

3. All historical data which will be included in the collection should be delivered to Princeton by the end of 2006.

4. After initial QC of the new cruises is completed, regional subsets of the total data collection will be compiled at Princeton and delivered to each of the synthesis teams.

5. Those teams will carry out secondary QC for their respective data sets in a manner similar to that developed during the production of GLODAPv1.1.

6. Once secondary QC is complete, scientific analysis will begin. Specific science topics were outlined at the meeting. Not surprisingly, the range of these topics is virtually identical to those of USSTM, but with more emphasis on change than the original U.S. effort. The additional focus on change will largely fall to USSTM because of experience, the ongoing CLIVAR program and the fact that we have been actively working on these topics for over two years.

A cruise summary table is included there which lists the cruises already in the CARINA collection. There are at least 8 additional Arctic Ocean cruises, an entire Icelandic time series and a number of Southern Ocean cruises which are "in hand" or expected prior to the end of this year which are not listed. Also not listed in this table are the Japanese and U.S. CLIVAR cruises which have already been fully processed and are available. The cruises already listed in the table represent significantly more carbon data than was included in GLODAPv1.1 for the entire Atlantic Ocean.

U.S. Data

With the exception of changing ship schedules, CLIVAR data collection and processing has been fairly routine. With a couple of notable exceptions, all of the CLIVAR carbon data have been submitted to both WHPO and CDIAC well ahead of the minimum time requirement of this program. The new U.S. data (and the Japanese CLIVAR data) have been been remarkably high quality. The combination of initial high data quality with the fact that USSTM now have extensive experience working together has made primary and secondary QC of these data almost routine. Over determination of the carbon system on all U.S. CLIVAR cruises has been extremely beneficial both for technical issues and scientific reasons.

We encountered one major data quality issue during the past year. The problem derived from the very early data release policy adopted by CLIVAR combined with a lack of communication between two major data centers. The end result was that NODC imported (from WHPO) and distributed raw shipboard carbon data from one cruise. The problem was discovered by A. Kozyr (CDIAC) and steps have been taken to assure that this does not happen again. Both the data generators and the agencies were upset by this mistake, but it is worth note that even the raw data were comparable in quality to what was considered "best" quality when the GLODAP work began. The mistake was only discovered when NODC released a new collection so that can't be undone, however, future releases by NODC will contain the final data for this cruise.

Advanced Data Synthesis

During the initial GLODAP synthesis the steady state assumption (in one form or another) was core to many of the analyses. Subsequent analysis by this team and many others has demonstrated that our assumptions were reasonable under the conditions we had. Paramount among these was the simple fact that the time separation between WOCE and previous measurement programs was 15-25 years. Over that sort of time span changes due to the invasion of anthropogenic carbon effectively masked any changes due to biology of physics. CLIVAR is
repeating WOCE lines with a time separation of about 10 years. Over this sort of time frame the signal to noise ratio is much smaller and we are now strongly focused on change rather than simply asking distribution and inventory questions. In a word, the scientific analysis is significantly more difficult than anyone imagined.

We initially hoped that a reasonable estimate of the change in anthropogenic carbon could be obtained simply by measuring along the same sections as WOCE then using either simple MLR or subtraction to find the decadal change. Either of these techniques do show the absolute change in inorganic carbon, however a significant fraction of that change is due to processes other than simple invasion of the anthropogenic signal. Probably the two most important factors which were not initially considered are gyre wobble and changes in oxygen ventilation. Both issues were initially noted by S. Emerson (U. Washington). Subsequently, USSTM plus many others have tried to address these complicating factors. Among USSTM this work has primarily been done by Feely, Sabine and Wanninkhof who have developed various new analysis techniques including oxygen corrections and MLR variants (e.g. double MRL). Success with these has been mixed - what works in one region may not work elsewhere and the technique application can be extremely sensitive to details. Very active independent efforts continue on this problem. Some of these new methods are quite labor intensive. At Princeton progress has been made to at least semi-automate some of these procedures. Such development is beneficial and required due to a simple lack of manpower and support as well as the desire to remove human bias from the procedure - that is, to make the calculation more objective. One example of this concerns the "oxygen correction procedure" in which the absolute change in TCO₂ along a section is compensated for the accompanying change in oxygen. Scientifically, the new procedure is identical to that originally developed by Wanninkhof and others, however, it can now be done quickly and routinely. Application of this procedure is outlined and illustrated here for the P16N section north of Hawaii which was occupied during both WOCE and CLIVAR.

Procedural Outline:
1. Create an objectively gridded section in density space for the upper water column for AOU and for TCO₂ for both occupations. All four sections have identical grid resolution and the same degree of data smoothing.
2. Subtract the former occupation from the new for both properties to get the change spatial distribution over the time interval. In this example the comparison was restricted to the zone between high gradient regions bordering at the north and south to simplify interpretation (Fig A and B).
3. Calculate the mean change and standard error for each density horizon for both properties. These averages can be plotted against density level to create an average change profile for each parameter (Fig. C & D) or against each other to study the relationship between the two parameters (Fig. E). Both the AOU and TCO₂ in this example show the greatest change (increase) well below the surface (potential density ~26.5). The AOU profile additionally shows minor near surface change which is not mirrored in the TCO₂ profile. To put it mildly, the TCO₂ change depth distribution is radically different than what we would have expected after the first phase of the GLODAP work. Our naive expectation would have been to find the greatest change at the surface and decreasing change with depth.
4. Correct the TCO₂ change for changes in oxygen. When this procedure was developed it was hoped that this adjustment would provide a reliable estimate of the change in anthropogenic carbon over the time interval with biological influences removed. The resulting profile (Fig F) certainly looks more like what we expected a priori, but the decreasing trend in near surface waters is still unexpected. Current speculation is that the oxygen "correction" is simply too large in near surface waters. If correct this would in turn imply a significantly variable stoichiometric C:O ratio with depth. This is certainly possible, but there are alternate explanations.
Other techniques have similar problems. The bottom line at this point is that we simply do not understand or haven't yet accounted for all the important processes. Significantly more research is needed in this area.

Other Collaborations:

Key worked with D. Waugh using what is known as the TTD (transit time distribution) method to derive an alternate estimation of the distribution and inventory of anthropogenic CO₂ based on GLODAPv1.1. This method is radically different from that used by the USSTM. The study strongly supported the GLODAP inventory estimate (within quoted errors), but indicated some differences in the depth distribution for certain ocean regions. This work is now published.

Key worked with C. Goyet and F. Touratier (France) to test another alternate method for estimating anthropogenic CO₂ called TROCA. TROCA was developed by Goyet and is a variant of the Gruber method used by GLODAP. A number of papers have been published in which TROCA is compared to GLODAP at the regional scale (all European). The primary benefit of TROCA is that it, unlike the Gruber method, is extremely easy to apply. Mapping and integration at Princeton, however, very clearly demonstrated that this method has major flaws. Goyet and Touratier are now trying to modify TROCA accordingly.

Funded separately, but very closely related to this project, Key collaborated with C. Sweeney and others to re-estimate the air-sea CO₂ gas exchange rate relationship. Previous estimates had been based largely on W. Broecker's bomb-radiocarbon inventory and the accuracy of that inventory has long been questioned. The new estimate is based on the WOCE radiocarbon data set combined with numerical model analysis. Results from this work will find obvious application in our CO₂ studies. Results from this work are in press.

Key has been working with K. Rodgers at Princeton to investigate both natural and anthropogenic CO₂ change in the upper ocean. This is essentially a model-data comparison and because of the close collaboration will allow model modification on a timely scale and in reverse will help understand the changes we are seeing with the CLIVAR data. We are hopeful that this work will also provide guidance in planning future sampling scenarios designed to monitor the accumulation of anthropogenic CO₂ in the ocean. We also hope that this work will provide significant insight on error estimates for our current work.

Publications:


**Progress Report:** Lm3 Code Integration And Infrastructure Design

**Principal Investigator:** Sergey Malyshev and Elena Shevliakova (Princeton Associate Research Scholars)

**Other Participating Researchers:** P. C. D. Milly (USGS), Kirsten Findell (GFDL), Krista Dunne (USGS)

**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:** To design and implement an advanced land surface and dynamic vegetation model to enhance the ability to simulate Earth climate system, including hydrological and carbon cycle.

**Methods and Results/Accomplishments:**
Sergey Malyshev, in collaboration with Chris Milly, Elena Shevliakova, and Kirsten Findell has implemented an initial release of the next version of the land model LM3. The model is a descendent of the two models extensively used in previous research at GFDL, LM2 (Milly and Shmakin, 2002, Delworth et al., 2006) and LM3V (Shevliakova et al., 2007, Malyshev et al., 2007), and combines major features of both, but also adds features that aren’t present in either of the ancestors.

Compared to LM2, one of the characteristic features of LM3 is a mechanistic model of stomatal conductance and photosynthesis that introduces realistic stomatal control on transpiration and carbon uptake by the vegetation, similar to LM3V. The model includes comprehensive representation of vegetation and canopy air physics, including exchanges of water and energy between ground surface, canopy, canopy air, and atmosphere.

One of the important features of LM3 that distinguishes it from its ancestors LM2 and LM3V is the capability to represent the vertically-resolved hydrological processes within soil and snow pack, including the vertical transport of liquid water and phase changes.

LM3 include representation of surface heterogeneity that goes beyond the capabilities of the previous models. While it uses traditional tile-based approach to the sub-grid-cell variability of surface properties, the number of tiles per grid cell is not limited by model design, nor severe model performance considerations. Moreover, it is possible for different kinds of tiles to have totally different surface parameterizations and sub-models associated with them, opening a possibility to implement comprehensive representation of special kinds of surfaces, such as, for example, lakes.

LM3 includes new comprehensive high-resolution model of river transport of water, heat, and other substances.

LM3 has been used in a number of numerical experiments designed to demonstrate the model performance and sensitivity to parameters. In particular, a coupled land/atmosphere run has been performed with AM2p14 version of the atmospheric model (Anderson et al., 2004, Delworth et al., 2006) and LM3p2 version of the land model. The parameters of the vegetation cover in this run were specified based on a previous run of LM3V. This simulation demonstrated that the performance of the new model is close to the performance of the LM2 in the same setup, even though very little to none tuning has been done with LM3, as opposed to highly-tuned LM2. One of the encouraging features demonstrated by the LM3/AM2p14 is the reduction of the low summer-time precipitation bias over the South-Eastern US, shown in Figure 1. This bias is well-known to be present in the LM2/AM2p14 and in
virtually all previous versions of the GFDL atmospheric model, and proved to be hard to address; in light of that the result obtained in LM3 simulation is very promising.

LM3 has also been run coupled to the latest version of the GFDL atmospheric model, AM3. In fact, there has been a number of runs with different land model parameters, aimed to demonstrate the sensitivity of AM3/LM3 to gross changes in land properties. The AM3 model is still pretty much work in progress, and therefore such sensitivity runs are essential to address emerging problems in simulated climate. Sergey Malyshev in particular, and Land Model Development Team in general, continue to collaborate closely and actively with GFDL’s Atmospheric Model Development Team to address the issues that become apparent in the results of the AM3 simulations.

Sergey Malyshev and Elena Shevliakova continue to work on implementing the vegetation dynamics in the framework of LM3.

**Figure 1.** Summer-time precipitation field simulated by LM2/AM2p14 (left) and LM3/AM2p14 (right). Upper panel: simulated precipitation field; middle panel: observed precipitation according to CMAP data set (Xie and Arkin, 1997); lower panel: difference between simulated and observed precipitation fields. Note a reduction of low precipitation bias over the Southern US in the LM3 simulation.
References:


**Progress Report:** Analysis of the coupling between LM3V and the GFDL atmospheric model

**Principal Investigator:** Sergey Malyshev and Elena Shevliakova (Princeton Associate Research Scholars)

**Other Participating Researchers:** Steve W. Pacala (Princeton), P. C. D. Milly (USGS), Lori Sentman (GFDL/RSIS), Krista Dunne (USGS)

**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:** To enhance understanding of the vegetation/atmospheric feedbacks in the coupled land/atmosphere climate system, and investigate the influence of land surface scheme on simulated climate.

**Methods and Results/Accomplishments:**

LM3V simulates a number of land surface properties that traditionally have been prescribed in the land surface schemes, including the widely used in GFDL LM2 (Milly and Shmakin, 2002, Delworth et al., 2006). Among the simulated properties that potentially affect the state of the atmosphere are albedo of vegetated surfaces, surface roughness length, and vegetation stomatal conductance (a major controlling parameter for transpiration), just to name a few. On the other hand, the state of the atmosphere in turn influences the short-term (e.g. stomatal conductance) and the long-term (e.g. vegetation height, roughness length) properties of the vegetation. This project aims to examine the feedbacks between the vegetation simulated by LM3V and the GFDL atmospheric model (Anderson et al., 2004, Delworth et al., 2006) on the time scales from sub-diurnal to decadal.

To spin-up the vegetation state to an approximate equilibrium with the climate that the atmospheric model produces, we recorded high-frequency surface forcing fields through a 50-year LM2/AM2p14 run and used this dataset to repeatedly drive the stand-alone land model, for the total simulation length of about 350 years. After that, the coupled LM3V/AM2p14 model was started from the obtained land surface initial condition, and ran for a total of 100 years. We used the Hurrell and Trenberth, 1999 sea surface temperature dataset as a boundary condition all of the above simulations, repeating it as necessary.

The simulated vegetation characteristics are, on the whole, quite realistic, with the exception of several regional features. As an example, Figure 1 shows biomass and net primary production, as simulated by LM3V/AM2p14. In addition, Figure 2 shows the distribution of leaf area index (the total area of leaves per unit area of land) in January and July. As apparent from those pictures, the model tends to simulate somewhat smaller extent, biomass, and leaf area index of the Amazon tropical forest compared to the observations. The reason for this is a well-known dry bias of AM2 in this region.

The response of the atmosphere to the change of the land surface scheme is mostly confined to the near-surface levels: there is very little difference in the atmospheric circulation and temperatures between the two experiments. The surface climate is, on the contrary, sensitive to the surface scheme. Figure 3 shows the difference in seasonal climatology of near-surface temperature and precipitation between LM3V/AM2p14 and LM2/AM2p14 simulations. We hypothesize that perceptible further decline in tropical precipitation (and associated increase of temperature) can be associated with positive vegetation-climate feedbacks; the changes in high
and mid-latitudes are most likely due to differences in surface properties of prognostic vegetation model.

Our results emphasize the importance of biophysical feedbacks in the coupled atmosphere/biosphere model and highlight the biases of the component models that show up prominently in the coupled simulation. The results of this research are being prepared for publication (Malyshev et al., 2007)

**Figure 2.** Some biological parameters simulated by LM3/AM2p14. (a) Total biomass, kg C/m²; (b) Net primary production, kg C/(m² year)

**Figure 3.** Leaf area index (area of leaves per unit land area) simulated by LM3/AM2p14, January (left) and July (right).
Figure 4. Difference in simulated near-surface (2m) temperature (left) and precipitation (right) between LM3/AM2 and LM2/AM2. Upper panel is average over December, January and February (DJF); lower panel is average over June, July, and August (JJA). Areas where the differences between models are not statistically significant with 95% confidence are grayed out.

References:


Publications:
**Progress Report:** Detection of Anthropogenic Changes in Oceanic Dissolved Inorganic Carbon (DIC) Using Models and Observations

**Principal Investigator:** Keith Rodgers (Princeton Associate Research Scholar)

**Other Participating Researchers:** Jorge Sarmiento (Princeton), Anand Gnanadesikan (GFDL), Robert Key (Princeton), Rik Wanninkhof (NOAA-PMEL), John Dunne (GFDL)

**Theme #2:** Biogeochemistry

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

**Objectives:** Significant NOAA resources are currently being devoted to measuring changes in ocean carbon uptake through the CLIVAR CO₂ Repeat Hydrography program, with the goal of detecting interdecadal trends in the ocean storage of CO₂. However, initial analysis of the observations (Sabine et al., 2006) indicate that while changes are occurring, they do not resemble the smooth large-scale fields predicted by models that assume steady ocean circulation. Rather, they are characterized by patchy structures that reflect natural variability. Thus there is a need to develop detection methods which can separate the anthropogenic signal from the large background variability.

**Methods and Results/Accomplishments:**

The first step of this work has focused on an analysis of three models of ocean biogeochemistry (IPSL, MPI, FRCGC) which have been forced with NCEP reanalysis fluxes over 1948-2002 (Rodgers et al., 2007). These models suggest that a significant part of the natural variability in oceanic DIC may be due to interannual variability in the position of fronts separating gyres. These mechanisms identified in the model experiments are currently being evaluated in high resolution repeat measurements from the tropical Indian Ocean and the North Atlantic. These data analyses lend support to the results from the models, suggesting that natural variability is indeed strongly impacted by time-varying fronts. Currently this work is focusing on analyses of the version of the coupled ocean/atmosphere model at GFDL (CM2.1) which includes the GFDL ocean biogeochemistry model (TOPAZ).

**References:**


**Publications:**

Progress Report:  A Wintertime Uptake Window for Anthropogenic CO₂ in the North Pacific

Principal Investigator:  Keith Rodgers (Princeton Associate Research Scholar)

Other Participating Researchers:  Jorge Sarmiento (Princeton), Olivier AUmont (IRD, France), Cyril Crevoisier (Princeton), Clement de Boyer Montegut (FRCGC, Japan), and Nicolas Metzl (LOCEAN, France)

Theme #2:  Biogeochemistry

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

Objectives:  The goal of this modeling study is to identify the pathways and timescales relevant to the uptake of anthropogenic CO₂ over the North Pacific.

Methods and Results/Accomplishments:
  The model used for this study was ORCA2-PISCES, and it was forced with NCEP reanalysis fluxes over 1948-2003.  The model reveals that there are two principal regions of uptake of anthropogenic CO₂ over the North Pacific, the first in the Kuroshio Extension region near 40°N in the western Pacific, and the second along a band between 10°N-20°N between 120°W and 180°E.  For both of these regions, the dominant timescale of variability is seasonal, with maximum uptake occurring during winter and uptake being close to zero or slightly negative during summer when integrated over the basin.

Publications:
**Progress Report:** A Potential Role for Tectonic Changes in the Indonesian Throughflow Region for the Sudden Stratification of the North Pacific at 2.7 Mya.

**Principal Investigator:** Keith Rodgers (Princeton Associate Research Scholar)

**Other Participating Researchers:** Jorge Sarmiento (Princeton), Anand Gnanadesikan (GFDL/Princeton), Jennifer Simeon (Princeton), Eric Galbraith (Princeton)

**Theme #2:** Biogeochemistry

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

**Objectives:** The goal of this study is to test the idea that the abrupt increase in stratification inferred from pale proxies in the subpolar North Pacific 2.7 Mya (Haug et al., 1999) and the corresponding decrease in surface nutrients were triggered nonlocally by tectonic changes in the Indonesian Throughflow region. Specifically, our intention is to test the idea that the northward crossing of the equator by Halmahera/New Guinea in the western Equatorial Pacific between 3-5 Mya led to large-scale changes in the circulation of the Pacific basin, and subsequently to changes in the density structure of the North Pacific.

**Methods and Results/Accomplishments:** The model used for this study is the coarse resolution version of GFDL’s CM2P1 (CP2P1c), which consists of the MOM4 ocean model coupled to the AM2 atmospheric model. There are two model simulations currently being conducted as part of this study. The first uses modern boundary conditions in the Indonesian regions, while for the perturbation simulation Halmahera and New Guinea have been removed and replaced by ocean with 1km depth everywhere north of 3S. The model results indicate a relatively strong response in the stratification of the subpolar North Pacific over the first 160 years of model integration, lending support to the idea that a closing of the ITF opening has allowed (via planetary wave dynamics) for a dramatically increased role of the Southern Ocean in exerting a non-local control on the mean stratification and nutrient cycling over the subpolar North Pacific.

**References:**

**Publications:**
Rodgers, K.B., J.L. Sarmiento, A. Gnanadesikan, J. Simeon, and E. Galbraith (2007), A potential role for tectonic changes in the Indonesian Throughflow region for the sudden stratification of the subpolar North Pacific at 2.7 Mya, in preparation for Paleoceanography.
Progress Report: Decadal Variations in Equatorial Pacific Ecosystems and Ferrocline/Pycnocline Decoupling

Principal Investigator: Keith Rodgers (Princeton Associate Research Scholar)

Other Participating Researchers: Olivier Aumont (IRD, France), Christophe Menkes (IRD, France), Thomas Gorgues (U. Washington)

Theme #2: Biogeochemistry

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

Objectives: An ocean model has been used to investigate the dynamical mechanisms which may underlay decadal variability in ecosystems for the Equatorial Pacific.

Methods and Results/Accomplishments:

The model analyzed is the ORCA2-PISCES circulation/biogeochemistry model of the global ocean, and it has been forced with both NCEP and ECMWF reanalysis fluxes over the period 1958-2001. The main finding is that a decrease in amplitude of the surface windstress in the mid-to-late 1970s leads to a decrease in Fe and Chl concentrations in the upwelling regions of the Eastern Equatorial Pacific after 1976/77. These changes find expression predominantly during the upwelling season (the seasonal maximum for Fe and Chl concentrations), when surface Fe and Chl concentrations tend to be significantly higher pre-1976/77 than post-1976/77. The changes in Chl concentrations need to be understood as modulations of the amplitude of the seasonal cycle, rather than as a "biological regime shift" (Chavez, 2003). In contrast to what was found for Fe and Chl, for NO3 the decadal changes in surface concentrations in the upwelling region about 1976/77 can be described as a shift in the mean state.

References:


Publications:

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), Ron Stouffer (GFDL), Andrew Wittenberg (GFDL), Michael Winton (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. A second implementation of the coupler, in the Nalanda release of FMS, includes the ability to pass 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: updated 2006].

A need for a coarse resolution coupled climate model has been clearly identified due to limitations in computing resources as well as the need for climate simulations on the timescale of decades to millennia. A coarse coupled model based on CM2.1, dubbed CM2.1C, has been developed. It is composed of the AM2 Finite-Volume Core on a nominal 3 degree grid coupled to the ocean model, MOM4, also on a nominal 3 degree grid. The coarse coupled model has the ability to support both a diagnostic and prognostic biogeochemistry model.

The coarse coupled model has computed integrations on the order of centuries. Based on a suite of diagnostics, the coarse model has been shown to be an IPCC-class model. The RMS temperature and salinity errors are within the range of IPCC class models. The interannual variability, though weak, is consistent. The North Atlantic meridional overturning is stable and reasonably robust (17 Sv). Southern Ocean mode water formation is present. The remaining tuning of the model is to improve the weak deep ocean ventilation in the Southern Ocean. Pending further fidelity assessments, the coarse coupled model can run up to 4.5 times faster than CM2.1 and is 5 times less expensive.
Figure: Temperature (°C) and salinity (psu) root-mean-square errors for the surface and the 0 to 1500 m average. In each panel, the coarse model statistics are shown at the top. The coarse model simulation called, CM2.1C, is the model run with the CM2.1 namelist settings. This initial run exhibited problems with sea surface temperatures. The simulation, CM2.1_1860_a500, is coarse model after the atmosphere radiation tuning. This simulation shows the success of the radiative tuning.
Progress Report: Ocean Biogeochemical Processes

Principal Investigator: Jorge L. Sarmiento (Princeton Faculty)

Other Participating Researchers: Danielle Bianchi, 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 CO₂ (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 are 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. Simulations were conducted in four 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 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 with a significant return pathway in the low latitudes. Two other models, Prince 2 (P2) and Prince 2A (P2A), more realistically simulate the deep ocean ventilation at high latitudes. P2 exhibits a moderate low-latitude return flow, while P2A simulates a strong high latitude return flow. The δ³He (%) in the figure below shows the mantle helium distribution in these four models.

The simulations from the Gnanadesikan et al. (2004) suite produced substantially different steady state distributions. While the difference in the magnitudes of δ³He inventories is large, the differences in the tracer distribution are more subtle, where most of the differences are localized in the Southern Ocean and in the upper water column.

Comparisons between the model simulations and the new helium data suggest that the currently accepted amount of helium injected into the ocean interior from mid-ocean ridges may be significantly overestimated. The flux estimates based on helium are also used to estimate mid-ocean ridge fluxes of other geochemical tracers; therefore this result has far-reaching implications for other areas of oceanographic research as well as our understanding of mantle geochemistry.
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 examine the role of topographic mixing in the North Pacific.

References:


Publications:


Figure: Zonal average vertical section of $\delta^3$He in the Pacific Ocean between 150°E and 100°W. Observations include tritiogenic helium in the upper water column that shows a stronger signal in the Northern Hemisphere. The models capture, to first order, the observed helium distribution, but the magnitude tends large. The model LL has the largest magnitude due to poor deep water ventilation. The models HH and P2 are perhaps closer to the magnitude of the observations, but too diffusive in the main thermocline.
Progress Report: Feedbacks between Climate Change and the 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 carbon cycle. The new global warming simulations include an ocean biogeochemistry model within the framework of the CM2 model as well as predictions of the uptake of anthropogenic CO₂ by the ocean. The ocean biogeochemistry model being used 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 are: chlorofluorocarbons (CFCs), radiocarbon and a perturbation CO₂ tracer used to estimate the oceanic uptake of anthropogenic carbon (Sarmiento et al., 1992; Siegenthaler and Joos, 1992). These simulations are based on the Memphis code release.

A series of simulations has been designed to identify the various feedbacks in the climate system. A 500-year spin-up of the IPCC historical simulation with CM2.1 has a constant1860 climate and includes the proposed biogeochemical tracers. Three additional simulations are to 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 SRESA1B scenario 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 current status of the above simulations is: the 500-year spin-up is now being integrated for 1860-2000. The IPCC historical CM2.1 ensemble simulation with the SRESA1B scenario has been completed from 1860-2000. The climate forcing simulation has successfully yielded output from the CFC and perturbation CO₂ modules. The figure shows a comparison of the model results with data for CFC-12 at 32°S over an eleven year time interval. A comparison of the 500-year spin-up, which has constant 1860 climate, and the simulation with climate forcing will allow us to determine the changes in CFC and perturbation CO₂ due to the different radiative forcing from the IPCC historical run.

References:
Figure: CFC changes along WOCE section P6. CFC observations (Uchida and Fukasawa, 2005; Bryden et al., 2005) are compared to CM2.1 modeled CFCs. The CM2.1 is able to capture salient features of the observed CFC changes. The propagation of the CFC signal into the ocean interior is present as well as the fairly constant magnitudes found in the near-surface and below 1000m.
**Progress Report:** Coupling of LM3V with the GFDL Climate and Earth System Models

**Principal Investigator:** Elena Shevliakova and Sergey Malyshch (Princeton Associate Research Scholars)

**Other Participating Researchers:** Ron Stouffer (GFDL), Mike Spelman (GFDL), Lori Sentman (GFDL)

**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:** To evaluate and improve GFDL coupled terrestrial biosphere-climate models

**Methods and Results/Accomplishments:**

Shevliakova in collaboration with Mike Spellman (GFDL), Ron Stouffer (GFDL), Sergey Malyshch (PU), and Lori Sentman carried evaluation of the GFDL coupled equilibrium climate-land model (SM2.1-LM3V) with the full range of the land-climate biophysical interactions, including dynamic vegetation. A number of experiments with different settings of land parameters were carried out to evaluate the differences of the climate from the standard SM2.1 configuration (with LM2) from the climate from the SM2.1-LM3V configuration. The experiments were configured for the 1990 conditions (e.g. CO₂ =350 ppm) and the potential vegetation (no human land-use) distribution. A number of improvements in the land radiation and biophysical parameterizations significantly reduced the annual and seasonal temperature and precipitation biases that were identified in the earlier experiments. Additionally, these tunings reduced the vegetation biomass drifts. Shevliakova introduced snow interception that improved winter albedo and temperature simulations in the Northern hemisphere high and mid latitudes. The summer biases, particularly in the mid–latitudes of the Northern hemisphere, appear to be linked to the strength of the temperature feedback on the evapo-transpiration and subsequent vegetation growth. A suite of experiments both with standalone LM3V and coupled SM2.1-LM3V was performed and analyzed to further improve summer surface climate and reduce the drifts in the vegetation.

Additionally, Shevliakova examined behavior of the coupled terrestrial and physical climate system in a series of experiments with the SM2.1-LM3V model. The experiments differ in their configuration of the land model from a model with static prescribed vegetation characteristics to a fully interactive dynamic vegetation model. Integrations were conducted for the present day and the doubling of atmospheric CO₂ concentrations, (e.g. CO₂ ={286 ppm, 350 ppm, 700 ppm}). Shevliakova compared sensitivity of the coupled land-climate system to CO₂ doubling in the integrations with different kinds of land interactions and assess the contribution of different aspects of land dynamics to overall climate sensitivity. The results of the analysis indicate a positive feedback from the changes in the state of vegetation to global climate change. Additionally, we examine the implications of the CO₂ fertilization hypothesis on the magnitude and direction of the terrestrial feedback on climate change. We find the uncertainty about the magnitude of the fertilization is the key factor determining the changes in size of various vegetation and soil carbon pools (see Figure 1).

LM3V is already coupled and fully interactive with GFDL ESM2.1 model. A multi-century simulation of ESM2.1 with LM3V model indicates that coupled climate-land system is stable. The evaluation of LM3V performance in ESM2.1 will continue in collaboration ESMDT
members. The tests to assess ESM2.1 fidelity and the strength of the climate-land carbon cycle feedbacks will continue during the next year.

The lessons learned from the SM2.1 and LM3V coupling and the analysis of their results will be described in the upcoming paper.

**Change in Vegetation Biomass, kgC/m2**

![Figure 1. Changes in vegetation carbon from the 1990s state simulated by the SM2.1-LM3V model under two different assumptions about the strength of CO₂ fertilization. Atmospheric CO₂ concentration was held constant at 700 ppm.](image)

Publications:

Progress Report: Analysis of Effects of Changes in Land-Use on the Terrestrial Carbon Dynamics in the Stand-alone LM3V Model

Principal Investigator: Elena Shevliakova and Sergey Malysh (Princeton Associate Research Scholars)

Other Participating Researchers: SW Pacala (PU), GC Hurtt (UNH), L Sentman (GFDL)

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: To evaluate spatio-temporal patterns of carbon fluxes due to land-use activities from 1700 to present.

Methods and Results/Accomplishments:

Shevliakova in collaboration with Pacala (PU), Malysh (PU) and Hurtt (UNH) performed and analyzed a set of experiments with four different scenarios of land use from 1700 to 2000. The LM3V model combines functionality of a dynamic global vegetation model and a land surface model. LM3V describes land cover at each grid cell as a combination of tiles in four land-use categories: undisturbed by human activities vegetation (i.e. “primary” or “potential”), cropland, pasture, and harvested at least once for other uses (i.e. “secondary”) (e.g. managed forests or abandoned cropland and pasture). Primary, cropland and pasture are represented each by one tile per grid cell. Secondary vegetation can be represented by more than one tile within a grid cell depending on the age of vegetation after harvesting. The number and relative area of each tile can vary in time depending on the assumptions about the land-use history. Hurtt et al. (2006) historic scenarios of land conversions are used annually to determine changes in the tiles’ sizes and carbon pools.

The first scenario (LU-H1) is based on HYDE dataset of historical land-use and land cover states (Goldewijk, 2001) and the FAO-based wood harvest reconstruction. It applied minimum transitions rule outside the tropics and non-minimum transitions (e.g. shifting cultivation) in the tropics (23N to 23S). Under non-minimum transition assumption 6.7% of cropland and pastures are abandoned and new cropland and pastures are created by conversion of natural or secondary lands. To explore implications of uncertainty in the data about the land-use states, Shevliakova conducted a second numerical experiment (LU-S1) with the land-use history scenario derived from a combination of SAGE gridded estimates of cropland for 1700-1992 (Ramankutty and Foley, 1999) and HYDE pasture estimates. In order to demonstrate significance of the secondary harvesting and shifting cultivation, the two “reduced” land-use history scenarios (LU-H2 and LU-S2) were used. These scenarios differ from the first two scenarios in two main assumptions: minimum transitions rule was applied globally and wood harvest was set to zero.

The results of this study suggest that LM3V can be used as a component of an earth system model to investigate interactions between climate, carbon cycle and effects of historic transitions between croplands, pastures, primary and secondary vegetation. Our analysis suggests a smaller terrestrial source than the bookkeeping methods’ estimates (see Figure 1). Our analyses suggests a secondary vegetation sink of 0.35 to 0.6 GtC/year and a smaller croplands and pastures sources due to deceleration of agricultural land clearing since the 1960s.
Figure 1. Net Ecosystem Exchange (Gt C/year, 17-year running mean) simulated by the LM3v model under four different scenarios of land–use change. LU-S1 – thick line, LU-H1 – thick dashed line, LU-S2 – thin line, and LU-H2 is thin dotted line. Negative values represent flux into atmosphere.

References:

Publications:
Progress Report: Development of a Freshwater Biogeochemical Model for the Princeton/GFDL Earth System Model

Principal Investigator: Charles Vörösmarty (Research Professor, University of New Hampshire)

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

Theme #2: Biogeochemistry

NOAA’s Goal #1: Protect, Restore, and Manage the Use of Coastal and Ocean Resources through Ecosystem-based Management (40%)
NOAA’s Goal #2: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond (40%)
NOAA’s Goal #3: Serve Society’s Needs for Weather and Water Information (20%)

Objectives: Development and refinement of 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 worked closely with Chris Milly and Kirsten Findell to implement aquatic biogeochemical processes into the GFDL Earth System Model. We:

1) Attempted to port both the complete GFDL GCM/ESM model as well as the River Solo version to the UNH super computer cluster. After considerable time spent on this effort, it became clear that the GFDL code is very much tied to the hardware and software infrastructure at GFDL and porting would require considerable input from GFDL personnel. Instead, in consultation with Milly and Findell, we have instituted a new mode of operation, whereby aquatic biogeochemical components will be first implemented and tested in the UNH modeling framework. As the approaches mature, necessary data sets, algorithms, and explanations will be provided to GFDL and will be coded into the latest GFDL model versions by Milly. Output from the GFDL model will then be analyzed by UNH.

2) Modeled the interactions among hydrologic variability, elevated anthropogenic N loads, and the saturation of aquatic N removal processes at the global scale using the river component of the GFDL Land Model (LM3). This effort is the first global model to explore how hydrological variability (daily time step) influences river network N removal. We compared N export fluxes using preindustrial and contemporary (1995) N loading data sets (Green et al. 2004) linked with denitrification process algorithms that show a saturating effect. Preliminary results are encouraging, showing consistency with observations in several large basins. Predicted TN exports are consistent with contemporary observations in both the highly impacted Mississippi R. basin and in the less impacted Amazon R. basin (Figure 1). Contemporary TN export concentrations are elevated over the preindustrial state in the Mississippi, but not the Amazon. This work is currently being refined, and we expect to begin working on a manuscript describing the results within the next several months. This manuscript will emphasize N removal capacity across basins as a function of river network structure and hydrologic variability across global basins, and will be valuable for assessing how nutrient fluxes are expected to change under future climate scenarios. Results of this work will be helpful to drive the ocean model being developed by John Dunne.
Figure 1. TN export fluxes observed and predicted in the preindustrial and contemporary settings for A) the Mississippi and B) the Amazon. Predicted values are for hydrologic conditions from 1986 predicted by the fully coupled GFDL atmosphere-land model assuming preindustrial and contemporary loading (two different scenarios). Observations are based on contemporary monthly averages.

3) Assisted the GFDL team to update their existing gridded river network (from our STN30p V5.12) to our most recent version (V6.01). The new network treats inland river outlets as non-flowing grid-cell, as opposed to the older network, where no-data grid cells were introduced within the continental land mass. Besides, the mentioned structural differences, STN30p V5.12 and V6.01 also differ in the flow directions along the continental shorelines, and connecting some unorganized large wetlands to the mainstream of the nearby major rivers. The handling of river networks in the GFDL model and providing updates and new higher resolution networks was identified as one of the areas where the UNH team could offer significant help.

4) We have begun to develop a carbon flux (DOC) model using a similar approach to that of nitrogen flux modeling described above. Preliminary work has centered on developing spatially distributed data sets of DOC input to aquatic systems. We tested two loading approaches. One is based on DOC vs. wetland abundance, using the wetland data set of Döll and Lehner (2004) and DOC concentration vs. wetland abundance in the literature. The second uses global soil C:N data sets in conjunction with the model of Aitkinhead and McDowell (2000). Comparison with observations suggests that both approaches have limitations, but should serve as a preliminary input data set for the development of aquatic process routines. This work is being conducted in collaboration with Elena Shevliakova.

5) One paper is currently in review at GBC that was partially funded by the CICS program (Wollheim et al. In Review). This work quantifies the relative contribution of small rivers, large rivers, lakes and reservoirs in the global N cycle under mean annual conditions and will help to inform/prioritize future aquatic biogeochemical modeling in the GFDL ESM. An additional paper was published last year (Wollheim et al. 2006) exploring the role of stream size in defining the impact of entire river network in influencing biogeochemical fluxes.

References:


Publications:


Progress Reports:

Coastal Processes
Progress Report: Ecological Forecasting in the Coastal Zone: Transitioning of the Regional Ocean Modeling System to NOAA National Ocean Service

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

Other Participating Researchers: Hernan Arango (Rutgers), Enrique Curchitser (Rutgers), Emmanuel diLorenzo (Georgia Tech), Kate Hedstrom (ARSC)

Theme #3: Coastal Processes

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

Objectives: The long-term objectives of this activity are: LT1) to develop, to evaluate, and to apply physical and ecological forecasting systems for the coastal ocean suitable for both short-term and longer-term (e.g., climate-scale) applications; and LT2) to transition these capabilities to operational use at the NOAA National Ocean Service.

Methods and Results/Accomplishments:

Funding received in year 2 of this activity was used to address objective LT2, i.e., to transition the capabilities of the ROMS system to the NOAA NOS operational setting. The initial target has been an operational forecast system for short-term (synoptic time scale) forecasts of water levels and currents in estuaries and lakes. The principal tasks include: readying of ROMS software for routine operational applications (O1), and related documentation and training (O2).

Under topic LT2, we conducted extensive training of NOAA NOS personnel, presently engaged in the transitioning of ROMS to estuaries (e.g., the Chesapeake and Delaware Bays) along the U.S. East Coast. In particular, 3-day training workshops were held at NOAA NOS headquarters in Silver Spring MD in December 2006 and April 2007. The lead personnel on this activity included Drs. Haidvogel, Arango, Curchitser, diLorenzo and Hedstrom (the latter two from Georgia Tech and the Arctic Region Supercomputing Center). A manuscript describing the ROMS model and its validation was also completed (Haidvogel et al., 2007).

Publications:

Peer Reviewed:


Ph.D. Thesis:

Non-Peer Reviewed:


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121
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, 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, who does research on ocean dynamics and paleoclimate.

Jorge L. Sarmiento, Professor of Geosciences, Director of CICS, Director of the Program in Atmospheric and Oceanic Sciences, 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.
ADMINISTRATIVE STAFF

**CICS Director**
Jorge L. Sarmiento  
Professor of Geosciences  
Director, Program in Atmospheric and Oceanic Sciences  
Princeton University  
Phone: 609-258-6585  
Fax: 609-258-2850  
jls@princeton.edu

**CICS Associate Director**
Geoffrey K. Vallis  
Senior Research Oceanographer, Atmospheric and Oceanic Sciences  
Lecturer with the rank of Professor in Geosciences and Atmospheric and Oceanic Sciences  
Phone: 609-258-6176  
Fax: 609-258-2850  
gkv@princeton.edu

**CICS Administrative and Financial Contact**
Laura Rossi  
Manager, Program in Atmospheric and Oceanic Sciences  
Princeton University  
Phone: 609-258-6376  
Fax: 609-258-2850  
lrossi@princeton.edu

**CICS Alternative Contact**
Stacey Christian  
Finance-Grants Manager, Princeton Environmental Institute  
Phone: 609-258-7448  
Fax: 609-258-1716  
smecka@princeton.edu

**CICS Administrative Assistant**
Joanne Curcio  
Administrative Assistant, CICS  
Phone: 609-258-6047  
Fax: 609-258-2850  
jcurcio@princeton.edu
Task I: Administrative Activities and Outreach Supported Personnel

<table>
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<tr>
<th>Name</th>
<th>Rank</th>
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<tbody>
<tr>
<td>Carson, Steve</td>
<td>Chemistry Teacher at Princeton Regional Schools</td>
</tr>
<tr>
<td>Curcio, Joanne</td>
<td>Administrative Assistant</td>
</tr>
<tr>
<td>Sarmiento, Jorge L.</td>
<td>CICS Director</td>
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</table>

Departures - Task II and Task III:

**Research Associates/Research Staff**
- Xianglei Huang - 8/25/06 University of Michigan, Assistant Professor
- Xianan Jiang - 10/17/06 Caltech @ JPL, Postdoctoral Scholar
- Seoung Soo Lee - 6/4/07 University of Michigan, Research Fellow
- Feng Li - 6/1/07 NASA Goddard, Assistant Research Scientist
- James West - 2/3/07 UNC, Chapel Hill, Assistant Professor
- Jianjun Yin - 10/12/06 Florida State University, Assistant Scholar Scientist
- Rong Zhang - 8/4/06 GFDL, Research Scientist
- Rongrong Zhang - 6/15/07 Goldman Sachs

**Ph.D. Defense**

*Student:* Seoung Soo Lee  
*Advisor:* Leo Donner – June 4, 2007

*Dissertation:* Aerosol Effects on Clouds and their Sensitivity to Numerical Representation of Microphysics - *University of Michigan Postdoctoral Associate*
## Task II: Cooperative Research Projects and Education Supported Personnel

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<tr>
<th>Name</th>
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<tr>
<td>Adcroft, Alistair</td>
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### Task III: Individual Projects Supported Personnel

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<td>Crevoisier, Cyril</td>
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* Ph.D. Defense – Task II: June 4, 2007  
** Student: Seoung-Soo Lee  ** Advisor: Leo J. Donner  
** Dissertation: Aerosol Effects on Clouds and Their Sensitivity to Numerical Representations of Microphysics  
** Rong Zhang, Research Scientist  
NOAA-Geophysical Fluid Dynamics Laboratory  
Start Date: August 7, 2006
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<td>Determination of Carbon Source &amp; Sink Distributions (Task III)</td>
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<td>Ocean and Atmospheric Inverse Modeling for Global Carbon Flux Determinations (OGP-Task III)</td>
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*note: some FY’07 projects were funded with unspent prior year project balances.