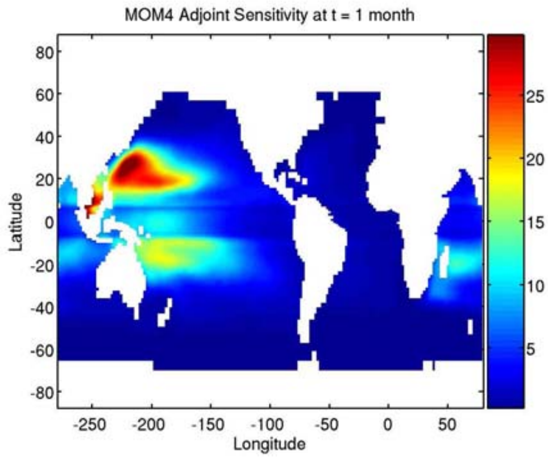
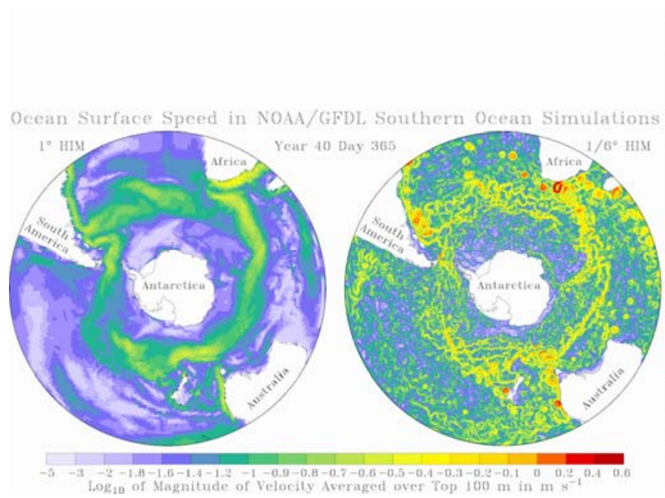


Annual Progress Report
July 1, 2004 – June 30, 2005
Cooperative Institute for Climate Science
at Princeton University



CICS

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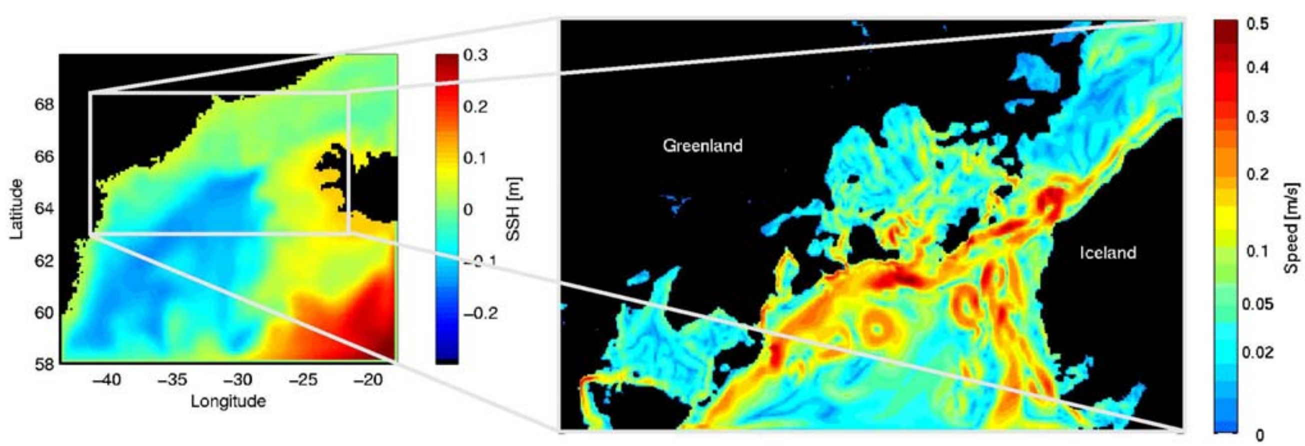

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Cooperative Institute for Climate Science
Princeton University

Annual Report of Research Progress under Cooperative Agreement NA17RJ2612
During July 1, 2004 – June 30, 2005

Jorge L. Sarmiento, Director

Introduction

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

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

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

Research Themes Overview

CICS has four research themes all focused around the development and application of earth system models for understanding and predicting climate.

(1) **Earth System Studies/Climate Research.** Earth System modeling at GFDL and in CICS is now emerging from an intense period of model development during which we have produced fundamentally new atmospheric, oceanic and land models, coupled models, chemistry-radiative forcing models, cloud resolving models with new microphysics, and a non-hydrostatic limited area model. Although these models are already producing useful products, new and more sophisticated tools will 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 investigations of the dynamical processes that give rise to climate variability on interannual to multi-decadal timescales.

CICS is also pursuing new 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 naturally 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 changes in the radiatively-active short-lived species and their climate forcing, clouds and the hydrologic cycle, soil moisture, interdecadal oceanic variability, and the glacial-interglacial cycles of the Pleistocene. These all represent distinct challenges that must ultimately be addressed simultaneously by a successful Earth System model, and the research presented below describes some of the efforts along these lines.

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

Finally, CICS also sponsors a limited number of symposia and workshops that explore the relationship among natural science, social science, economics and policy options for dealing with climate change.

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

The new dynamic land model that has been developed simulates carbon, but still lacks nitrogen or phosphorus dynamics that are likely to limit the growth of the land carbon sink caused by CO_2 fertilization. CICS is developing a global model for nitrogen and phosphorus in natural and agricultural ecosystems. In addition to improving predictions of the future land sink, this model will predict nutrient inputs into coastal waters. CICS is also performing a series of modeling experiments to investigate the causes of the current terrestrial sink (e.g., CO_2 fertilization vs. land use) and the large interannual variability in its size.

The development of a new fully predictive ocean biogeochemistry model of carbon, nitrogen and phosphorus, is nearing completion in a close collaboration between CICS and GFDL. The model includes critical processes such as iron limitation and the formation of organic matter in the surface of the ocean and its export to the abyss. CICS is performing a series of modeling experiments to examine variability of air-sea CO_2 fluxes on seasonal, interannual, and decadal time scales and its response to global warming, and study the impact of global warming on marine biology.

CICS is also building a data inversion capability for our models of the carbon cycle that integrates data from flask stations, tall towers, eddy correlation towers, shipboard ocean transects, and forest inventories, in order to provide ongoing estimates of the air-sea and land-atmosphere CO_2 fluxes particularly over North America.

(3) **Coastal Processes.** The coastal oceans are being severely impacted by human activities and climate change, and these impacts will grow with time. Traditionally, the main models used for climate prediction at GFDL have not included processes like tides and bottom boundary layers that play a dominant role in the dynamics of the coastal zone, nor have they had the lateral resolution to fully represent physical, geochemical and biological processes on the narrow continental shelves. CICS has recently initiated a collaborative project with Rutgers University that will enable the development of tools that link coastal models to global climate models. These linked models will be used to provide the best scientific information possible to decision makers, resource managers, and other users of climate information. To address the specific research questions, the project will use a multi-disciplinary approach including analyses of *in situ* and remotely obtained data sets, circulation modeling, biogeochemical models with explicit carbon chemistry, and data assimilation techniques using dynamical and/or biological models.

(4) **Paleoclimate.** The most valuable observational constraints that we have to test our understanding of the response of the Earth System to changes in forcing come from the geological and ice core record. GFDL has a long history of important contributions to our understanding of climate change through the application of climate models. In recent years, Princeton University has attracted several new faculty with active research programs in the

empirical and theoretical analyses of paleoclimate. CICS is supporting research on critical issues that Princeton has particular expertise in that are likely to be of importance in determining future climate response. These include the changing response of the climate to solar insolation forcing, the influence of tropical ocean-atmosphere states on climate, and the influence of freshwater fluxes and temperature changes on ocean circulation.

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

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

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

Structure of the Joint Institute

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

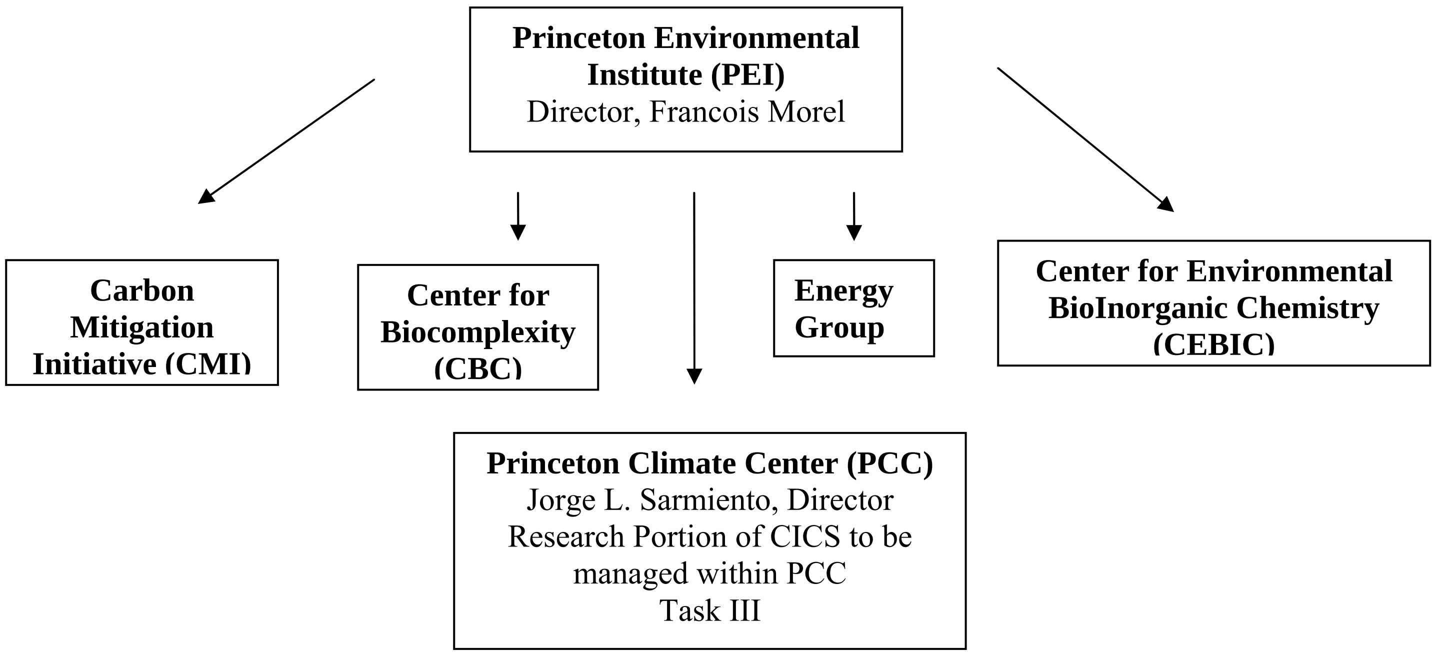
I. Administrative Activities including outreach efforts, are carried out jointly by the AOS Program and Princeton Environmental Institute (PEI).

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

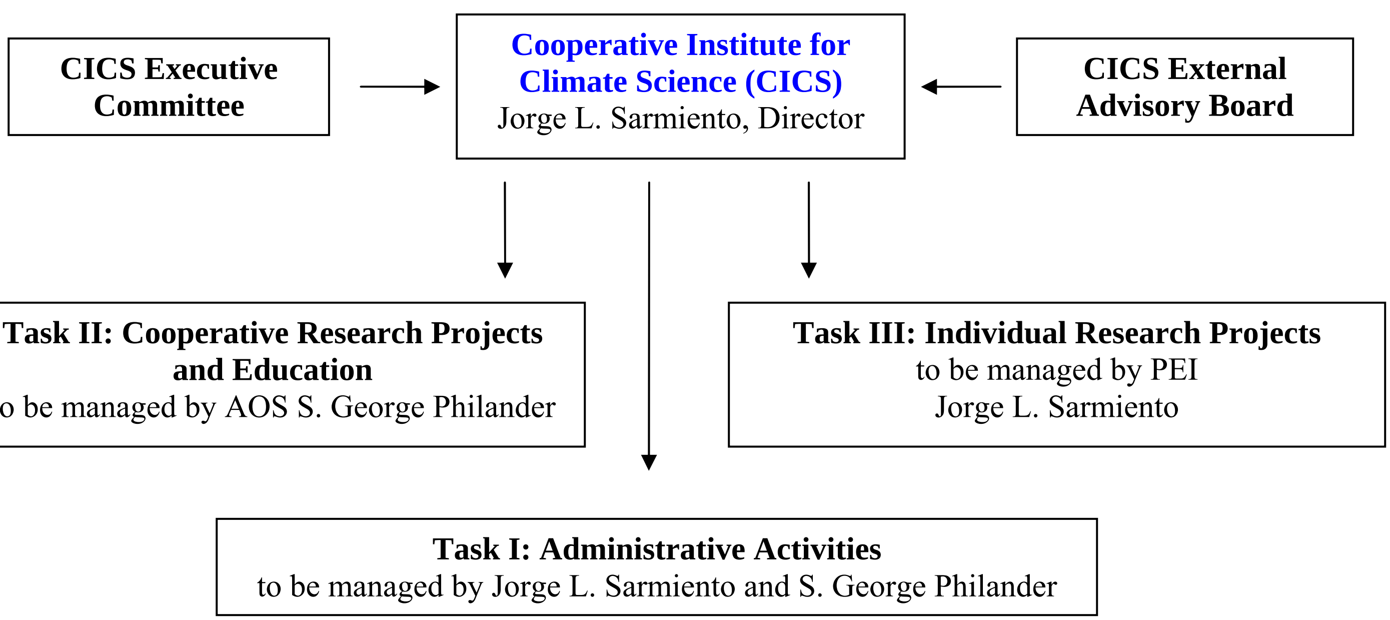
III. Principal Investigator led research projects supported by grants from NOAA that comply with the themes of CICS. These all occur within the newly formed Princeton Climate Center (PCC) of the Princeton Environmental Institute (PEI) and may also include subcontracts to research groups at other institutions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

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

Princeton Environmental Institute Structure



Cooperative Institute for Climate Science Structure



CICS Committees and Members

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

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

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

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

Research Highlights

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

Earth System Studies/Climate Research

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

Land Dynamics and Hydrology

Land dynamics and hydrology is playing an increasingly important role in climate simulations and projections, and this is reflected in the range and depth of the activities funded through CICS. In particular, the physical and biological components of the land model in GFDL's climate modeling system have been largely developed through CICS. One major, long term objective of this research is to develop and improve the land-surface parameterizations in the model, and this activity continues through the continued support of postdoctoral fellows and junior scientists who are physically located at GFDL. In addition to this activity, CICS also funds Eric Wood with support for a postdoc, for more basic research in understanding the predictability and variability of hydrologic variables on seasonal-to-interannual timescales. As well as its basic importance, this study will hopefully lead to very practical improvements in forecast skill on these timescales. In a related effort, Professor Ignacio Rodriguez-Iturbe is funded to develop a theoretical framework for modeling the space-time variability of soil moisture. Again this is basic research with a practical pay-off: an understanding of such processes is necessary if we are to properly measure soil moisture content by sparse sampling. Finally, on the more applied side, a postdoc is helping to develop a real-time stream flow information system, which will not only provide stream flow information but also help tune the newly developed land models.

Ocean Dynamics and Modeling

Although the poleward atmospheric transport of heat is almost double that of the ocean, the ocean plays the key role in determining the nature of climate variability on timescales from the interannual to the millennial. Furthermore, the ocean 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, appropriately for such an important activity, a number of postdocs and students are studying varying aspects of the circulation, and CICS now funds some more senior researchers: in particular it enabled the hiring of S. Legg from WHOI and A. Adcroft from MIT. One new activity in which CICS is participating is the so-called

‘Climate Process Teams’ (CPTs) These activities are jointly funded by NOAA and NSF, and specifically call for an interaction between government laboratories and universities. CICS is involved in two oceanographic CPTs, one 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 (such as the GIN Sea) into the general circulation, and thus potentially greatly impact the general circulation. The second CPT seeks to understand how mesoscale eddies interact with the oceanic mixed layer, and to parameterize this interaction in climate models. It is, of course, the surface of the ocean that interacts with the atmosphere. Current activities in this area include the development of new parameterizations of entrainment in overflows and for eddy–mixed-layer interactions, and setting up and using eddy-resolving numerical models to provide a ‘ground truth’ for parameterizations.

Work is also underway on a variety of other fascinating topics, from the development of new theories of aspects of the general circulation of the ocean (such as MODE water), through studies of the annual cycle of the tropical Pacific and Indian Ocean variability, to the construction of the next generation of ocean models at GFDL and to the development of data assimilation schemes for these models. These are all described in more detail in the individual reports.

Large-Scale Atmospheric Dynamics

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

A number of students, then, are focusing their work on fundamental aspects of the large-scale circulation. For example, one student is trying to understand why the westerly winds move poleward if surface friction is reduced. Although it may seem an arcane topic, its dynamics are undoubtedly linked to the very important topic of why the westerly winds seem to change latitude in simulations of global warming. By posing a related problem in a simpler context, we can hope to understand better the real-world but terribly complex problem of the changing winds in a warmer world. In a related area, another student is trying to understand the underlying mechanisms that give rise to the North Atlantic Oscillation and the related phenomenon of ‘annular modes’. And finally, in an ambitious effort, a recently graduated student has constructed and used an idealized moist general circulation model; understanding the effects of moisture is one of the biggest challenges in understanding the general circulation, and is the region of the biggest disconnect between comprehensive modeling and conceptual understanding.

Clouds and Moist Convection

As well as its effects of moisture on the large-scale circulation moisture (by way of condensation are release of latent heat), 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 activities range from trying to understand cloud microphysical properties better, to trying to better parameterize the macroscopic effects of convection. Regarding the former, one of our postdocs is working on nucleation processes in cloud ensembles with the goal of developing a more sophisticated and more accurate treatment of cloud microphysics for use in new deep convection and large-scale cloud parameterization schemes. At a more macroscopic level, another postdoc has been developing single-column models; these are models that contain all the parameterizations of a GCM, and that can be forced with observations to simulate actual events, and herby provide a real-world test of the parameterizations. Finally, and linking with the activities in large-scale dynamics, CICS is involved in simulations with three-dimensional cloud resolving models. Here, one goal is to compare very high-resolution models with lower resolution, parameterized models to understand better the influence of convection on the large-scale circulation.

Atmospheric Chemistry and Radiative Forcing

The atmosphere is ultimately forced by radiation from the sun, and so it is crucial to accurately calculate that radiative forcing. Aspects of this forcing are well understood; for example, highly accurate calculations are available for clear sky absorption if the atmospheric composition is given. However, other aspects are less clear, even aside from clouds effects. The prediction and effects of aerosols remain a significant source of uncertainty in modeling efforts. Research continues both in understanding the effects of aerosols on the radiation budget, and in understanding the factors that determine the global distribution of aerosols. One student focused her studies on better understanding black carbon aerosols and its global impact, using a global chemistry model. A visiting scientist, supported by CICS, studied the effect of tropospheric aerosols on South Asia, especially on the monsoon. And, moving away from aerosols, a CICS postdoc working with GFDL scientists has been engaged in modeling the effects of methane emissions on radiative forcing and on tropospheric ozone levels.

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 from these back on to climate. Biogeochemistry research in CICS has three components: (1) development of land ecosystem and biogeochemistry models and implementation of these in coupled climate models; (2) development of ocean carbon sink/ecosystem models and implementation of these in coupled climate models; and (3) inverse modeling and data assimilation of atmospheric, oceanic, and terrestrial carbon observations with the goal of determining the large scale distribution of carbon sources and sinks around the world, and of contributing to the ongoing national effort to determine the spatial and temporal distribution of the North American carbon sink.

Land Ecosystem and Biogeochemistry Modeling

A dynamic land model has been implemented by Pacala's group in collaboration with GFDL. An important aspect of this model is that it allows the vegetation to change and to track dynamics of carbon in vegetation and soil pools. Grasslands, for example can become forested as climate and land use patterns change, or the reverse can occur. The model is able to simulate water and energy exchange between the land and atmosphere in a way that is consistent with the vegetative dynamics. It has now been run with prescribed climate for the period from 1700 to the present and in coupled simulations with the GFDL atmospheric and mixed layer climate models. The results of the prescribed climate simulation are currently being evaluated to examine the interactions and feedbacks between climate and carbon sources and sinks over the 20^{th} century. The coupled simulations are also being used to examine historic as well as possible future land climate feedbacks. The land model has been integrated into the fully coupled GFDL Earth System Model (ESM). Additional work has included the influence of soil moisture treatment on the quality of seasonal forecasts.

In addition to the development of a dynamic land model, Hurtt of the University of New Hampshire has been funded by CICS to address the issue of human land use and its impact on the physical properties, biogeochemical cycles and hydrology of the land. Hurtt has developed a new synthesis model of global land-use which has been combined with historical records in order to produce global gridded estimates of land-use changes for the period 1700-2000. An analysis of these maps is proceeding. In addition, progress is being made on developing and analyzing a model for fire dynamics and suppression, which plays a major role in determining land-atmosphere fluxes of CO_2. A parallel effort by Crevoisier, in Sarmiento's group, is developing a fire model based on empirical analyses of how ignition frequency is related to air temperature, air humidity, rainfall, distance to human habitation, and previous fire history.

The land model currently does not simulate the cycling of nitrogen or phosphate. Understanding the cycling of nutrients like nitrogen in natural and managed ecosystems is vital 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. The Hedin and Oppenheimer group has developed a strategy for adding nitrogen cycling to the land model. The initial model will have three soil organic matter pools, two with short turnover times (months to a few years) that consist of high nitrogen easily decomposable plant material and the second of which has low nitrogen structural material; and a third pool composed by humic material with a decay time scale of decades. In addition, a layered version of the model is being considered that would be analogous to the vertical soil water distribution models.

Ocean Carbon Sink and Ecosystem Modeling

The CICS ocean carbon modeling group led by Sarmiento has made progress in three areas in collaboration with GFDL scientists and with joint support received from CICS as well as other sources: the development and improvement of models of ocean carbon chemistry and biology, the application of ocean carbon models to estimate the carbon sink and to examine ocean carbon sequestration strategies, and the application of the models to study the potential impact of climate change on ocean biology.

As regards model development, a new ocean carbon model has been implemented in the GFDL Earth System Model and two efforts are underway to develop alternative models based in one case on observations of dissolved nutrient, carbon, silicic acid, and alkalinity in the ocean to infer the production of organic matter, opal, and $CaCO_3$; and in the other on distributions of chlorophyll and carbon biomass inferred from satellite color observations to determine the biome structure of the ocean and how this is related to physical processes. In addition, through the use of observations of chlorofluorocarbons and radiocarbon, the ocean carbon modeling group has been evaluating the how well ocean circulation models simulate processes of particular importance to ecosystem and carbon cycle dynamics in order to lay the groundwork for improving them. These studies highlight the importance of realistic levels of Southern Ocean ventilation for a realistic carbon cycle-and show that the wind field within the Southern Ocean can play an important role in setting this ventilation. Other processes that were examined over the past year include the parameterization of air-sea gas exchange and the influence of phytoplankton on the radiative balance of the surface ocean. Finally, Sarmiento's group has been contributing to the development of a flux-coupler for the GFDL Flexible Modeling System that will allow gas transfers between the land atmosphere can ocean components of the GFDL Earth System Model; and to the development of a coarse resolution earth system model, required for longer term simulations, which are particularly important for studies of ocean carbon chemistry.

Over the past year, the pre-existing Princeton/GFDL ocean carbon models have been applied to a wide range of problems, including the interactions between the biological and solubility pumps, estimates of the uptake of anthropogenic CO_2 by the oceans and an examination of carbon mitigation by deep injection of CO_2. One important analysis showed that estimates of contemporary oceanic uptake of anthropogenic carbon cluster quite tightly if models that do not fit radiocarbon and CFC observations are first eliminated. Taken together with other recent research such as the air-sea fluxes obtained by ocean inversions carried out by Sarmiento's group, there is now a convergence of oceanic uptake estimates of anthropogenic carbon around a value of 2.2 ± 0.2 Pg C yr^{-1} for the early 1990's.

Finally, the ocean carbon models have been used to examine the potential impact of ocean carbon chemistry changes and global warming on ocean biology. One study used a wide range of ocean carbon models, including Princeton/GFDL's, to demonstrate that ocean pH changes may lead to $CaCO_3$ undersaturation at the surface of the ocean, particular in the Antarctic region, much earlier than had previously been expected. Another pair of studies led by Sarmiento's group demonstrated that about three-quarters of the biological production outside of the Southern Ocean results from nutrients supplied by Subantarctic Mode Water (SAMW). The response of this water mass to climate change is thus likely to have a significant impact on global biological production, and several studies are being undertaken to better understand what controls it.

In a separate related CICS project, Key, a member of Sarmiento's group, has been involved in the compilation of ocean carbon observations to better characterize the temporal evolution of the carbon sink.

Atmosphere and Ocean Inverse Modeling and Data Assimilation

The purpose of this component of the project, which is taking place jointly between Sarmiento and Pacala's groups, is the analysis of carbon system observations to determine the spatial and temporal distribution of carbon sources and sinks. Three separate tasks have been undertaken during the past year. The first of these was the development of an ocean-atmosphere "joint inverse." This effort combined large scale atmospheric as well as oceanic observations to determine the spatial distribution of carbon sources and sinks on a continental and ocean basin scale. The oceanic observations provide extremely tight constraints on air-sea fluxes. When combined with atmospheric observational constraints, a major finding from this research is that there appears to be no need for a large CO_2 fertilization sink in the tropics to balance the deforestation source. This has significant implications for future predictions by terrestrial biosphere models, which up to now have included a major CO_2 fertilization sink.

A second task was a collaboration with GFDL to test the realism of an atmospheric high-resolution transport model to be used for inverse studies. Comparisons of simulations of SF_6, oxygen, and carbon dioxide with observations have identified some issues that are being addressed, but overall show the model to be very good. For the third task, the atmospheric high-resolution mesoscale model is presently being used to generate basis functions that will be used in inverse models to estimate monthly fluxes of CO_2, CO, and CH_4. In addition, the model is being used to examine the feasibility of doing a control volume carbon budget over North America based on the tall tower data that will soon become available across the United States. Preliminary results from this research show that the borders of the United States will be well represented by the tall tower data over most of the country except in the southwest.

Coastal Processes

This research theme has just been initiated beginning July 1, 2005 with the funding of a proposal from Professor Dale Haidvogel of the Institute of Marine and Coastal Sciences (IMCS) of Rutgers University. The overall objective of this theme is to establish a Princeton/Rutgers collaboration for the purpose of linking the advanced coastal modeling and observing capabilities at IMCS with the global climate modeling activities at Princeton/GFDL. The proposed activities combine several linked technical and science tasks.

On the technical side, IMCS will:

- evaluate the sensitivity of a state-of-the-art regional/coastal model of the U.S. East Coast to the dynamical formulation of its open boundary conditions, and the manner in which boundary data from the exterior climate model are sampled and preprocessed;
- determine and improve the predictive skill of the coastal model by assimilating satellite and other *in situ* data within the regional model domain, and explore the extent to which this could supplant accurate open boundary data; and
- quantify model fidelity by comparison to data acquired with coastal ocean observing systems on the Northeast North American shelves.

The resulting validated multi-scale climate model will be used to conduct climate impact studies of relevance to Princeton/Rutgers investigators as well as to NOAA, *e.g.*,

- retrospective simulations of biogeochemical processes and ecosystem variability in the Western North Atlantic over the past three decades, and
- simulations of coastal impacts accompanying future climate and land use changes scenarios.

Lastly, as resources permit, the generalized coupling techniques developed here will be applied to additional coastal regions with unique dynamical character and/or ecological importance, *e.g.*, the Coastal Gulf of Alaska, the Southern Ocean, the European shelves, *etc.*

To meet these goals ICMS will rely heavily on the unique combinations of talents represented among the IMCS PI's on this proposal. These capabilities include a state-of-the-art, end-to-end modeling system for the coastal zone, a world class observing network in the Middle Atlantic Bight, and expertise in the simulation and understanding of coastal ocean (physical and biogeochemical) processes.

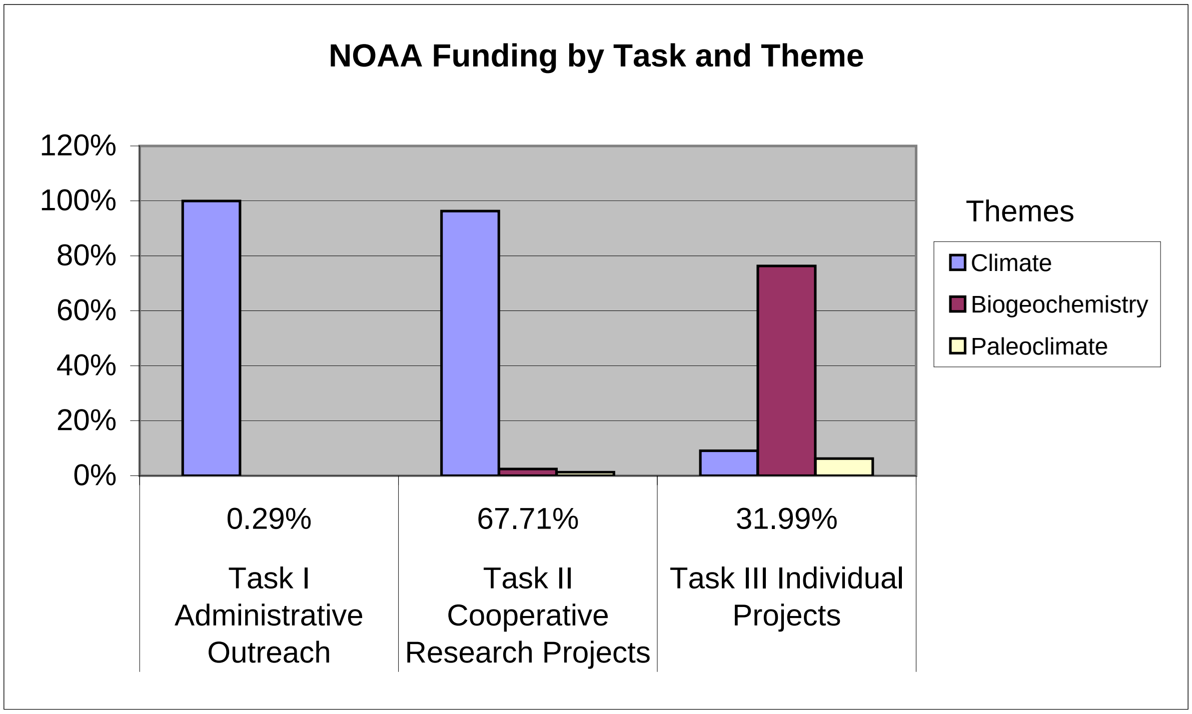
Lastly, IMCS will build upon its current vigorous outreach program to ensure that NOAA decision makers and resource managers have timely access to the results of these studies.

Paleoclimate

The response of the high latitude ocean has been hypothesized to play a critical role in climate both through its impact on heat transport, for instance, in the case of North Atlantic Deep Water formation and its tendency to warm Northern Europe; and on atmospheric carbon dioxide, for instance, in the case of the Southern Ocean, which is a recognized leak in the ocean's natural mechanism for sequestering carbon in the deep ocean. Numerical modeling conducted as part of CICS has expanded our understanding in both of these areas. Model simulations of a freshwater-induced weakening of the North Atlantic overturning circulation indicate that this regionally forced change would have rapid and far-field climate impacts. The atmosphere and ocean together orchestrate coherent changes in the Indian and Asian monsoons, African precipitation, South American precipitation, and the tropical Pacific, all in excellent agreement with paleoclimate records. These results are complemented by other simulations by CICS Fellow Sigman and his group, which show that global changes in climate have different impacts on deep circulation in each of the major ocean polar regions, with these differences relating in a simple way to the boundary conditions of each region. Again, there is a remarkable correspondence with paleoclimate observations, suggesting a partial explanation for the observation of lower atmospheric CO_2 levels during recent ice ages.

Today, sea surface temperatures in the eastern equatorial Pacific are as high as those in the west only at the peaks of intense, brief El Niño episodes such as the one of 1997. What factors could have caused the indefinite persistence of such conditions, in effect a perennial El Niño, up to 3 million years ago? A workshop on that period, the Pliocene, hosted by CICS and organized by CICS Fellow Philander, addressed this question and is motivating ongoing theoretical studies with a variety of climate models. Tentative results by Philander's group identify a decrease in oceanic heat loss in high latitudes, because of a warmer atmosphere and a freshening of surface waters, as a major contributor to perennial El Niño conditions.

NOAA Funding Table



Progress Reports:

Earth System Studies/Climate Research

Progress Report: **Hybrid Ocean Model Development**

Principal Investigator: Alistair Adcroft (Princeton Research Oceanographer)

Other Participating Researchers: Robert Hallberg, Stephen Griffies, V. Balaji, Zhi Liang, Alex Pletzer, and Peter Phillips (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 develop the foundations of the next generation of ocean models

Methods and Results/Accomplishments:

Adcroft has been planning, designing and implementing the development of a new ocean model that will both encompass all the capabilities of the three existing in-house ocean models (MOM4, HIM and MITgcm) and also extend the capabilities by adopting i) a generalized approach in the vertical axis of the model and ii) a hybrid algorithm that can solve different equations of motion applicable at different scales in the ocean.

Working towards a hybrid ocean model has involved re-thinking of the formulation of ocean models in general and led us to some new insights into how to build better ocean models (some of the consequences are published in Adcroft and Hallberg, 2006) . We now know how to build a single model in a generalized vertical framework (combining the ALE method and the traditional fixed grid approach) that can solve the hydrostatic compressible equations (non-Boussinesq) and the incompressible non-hydrostatic equations. This means the model will be suitable for a both very small-scale process studies and hi-resolution global climate simulations.

In preparation for the implementation of the new model, Adcroft has been involved in several infrastructure projects: i) Kernalization, ii) GRIDspec and iii) Mosaics. Kernalization involves the layering of model software such that the "work" routines are self-contained, portable and efficient: this helps facilitate inter-operability of packages between models. GRIDspec is a new concept for describing "conventional" grids and has been proposed as a standard and is meeting wide acceptance. Mosaics builds on GRIDspec and allows the construction of arbitrarily general grids including unstructured tiles and nested grids. This last project is a pre-requisite before any new code can be written since it provides a new concept of "symmetric" arrays.

The design and implementation of the new model involves the writing of six extensive documents (white papers) describing i) the model formulation, ii) the code design, iii) the model structure, iv) variable and unit conventions, v) documentation and code development methodology and vi) evaluation strategy. Adcroft and Hallberg are currently preparing these documents that will then be sent out to the community for comment and review.

Publications:

A. Adcroft and R. Hallberg, 2006: On methods for solving the oceanic equations of motion in generalized vertical coordinates. Ocean Modelling, 11 (1-2), 224-233.

A. Adcroft, C. Hill, J.-M. Campin, J. Marshall and P. Heimbach, 2004: Overview of the Formulation and Numerics of the MIT GCM, Proceedings of the ECMWF Seminar Series on Numerical Methods, Recent developments in numerical methods for atmosphere and ocean modeling. 139-149.

J.C. Marshall, A.J. Adcroft, J.-M. Campin and C. Hill, 2004: Atmosphere-Ocean Modeling exploiting fluid isomorphisms, Monthly Weather Review, 132 (12), 2882-2894.

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

Principal Investigator: V. Balaji (Princeton Professional Technical Staff)

Other Participating Researchers: Alistair Adcroft (Princeton), John Dunne (GFDL), Isaac Held (GFDL), Robert Numrich (University of Minnesota), Max Suarez (NASA/GSFC).

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: Development of the Flexible Modeling System (FMS)

Methods and Results/Accomplishments:

The Flexible Modeling System (FMS) is a software framework that underpins the models run by GFDL, Princeton and CICS scientists. FMS provides standard and simple methods to build algorithms on parallel architectures, and to couple models of different components of the climate system into a comprehensive Earth system model.

FMS provides the basis for our publicly released models such as the AM2 atmospheric model and the community ocean model MOM4. It is the basis of the CM2.0 and CM2.1 coupled climate models used by GFDL and Princeton scientists for research, as well as in integrated assessments such as the 2007 round of the Inter-governmental Panel on Climate Change (IPCC). Recent developments in FMS to meet CICS goals include extensions to the coupling superstructure in FMS, to model the carbon cycle. This involves the development of accurate, conservative methods to exchange uxes between carbon reservoirs in several media (ocean and land ecosystems, and the atmosphere) while maintaining a constant global inventory. Other recent research activities include the development of a generalized formalism for expressing data dependencies on shared and distributed memory, and for coupling across ensembles of coupled models for data assimilation. CICS has been awarded a grant of 700,000 CPU hours on NASA's 40-tera op Columbia machine for the ensemble lter study, with myself as PI.

FMS serves as a design prototype for community-wide frameworks under development: the Earth System Modeling Framework (ESMF) and the Program for Integrated Earth System Modeling (PRISM). As Head of the Modeling Systems Group, I am responsible for the design and development of FMS, as well as serving as Technical Lead on ESMF, and on the Scienti c Steering Committee of PRISM. I was also responsible for organizing the PRISM-ESMF workshop in Princeton in September 2004, and the Workshop on Large-Scale Modeling of the Indian Ocean in Bangalore in October 2004.

References:

http://www.gfdl.noaa.gov/~fms"The FMS Manual, a design, implementation and use guide to the Flexible Modeling System."

Publications:

Balaji, V., and Robert W. Numrich, 2005: A uniform memory model for distributed data objects on parallel architectures. ECMWF Computing Workshop 2005 Proceedings, World Scienti c Press, in press.

Zhang, S., M. J. Harrison, A. Wittenberg, A. Rosati, J. L. Anderson and V. Balaji, 2005: Tropical Paci c Ocean Data Assimilation Using a Parallelized Ensemble Filter with a Stochastic Hybrid Coupled GCM. *Mon. Wea. Rev.*, in press.

Delworth et al 2005: GFDL's CM2 global coupled climate models, Part 1. Formulation and simulation characteristics. Submitted to J. Clim., in press.

Gnanadesikan et al 2005: GFDL's CM2 global coupled climate models, Part 2. The baseline ocean simulation. Submitted to *J. Clim.*, in press.

Progress Report: **Diagnosis of Tropical Atlantic Climate in CM2**

Principal Investigator: Marcelo Barreiro (Princeton Research Associate)

Other Participating Researchers: GFDL Coupled Model Development Team

Theme #1: Earth System Studies/Climate Research.

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

Objectives: Evaluate the performance of the GFDL's coupled model (CM2) in the tropical Atlantic.

Methods and Results/Accomplishments:

Marcelo Barreiro formed part of a community effort to evaluate the new GFDL's coupled model performance. He focused on the tropical Atlantic and analyzed the simulated mean state, climatological cycle and interannual variability, and also performed a comparison with observational data.

Publications:

A. Ganadesikan et al., 2005: GFDL's CM2 global coupled climate models-Part 2: The baseline ocean simulation. *Submitted to J. Climate*.

Project Report: **Professional Development Summer Institute in Weather and Climate**

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

Other Participating Researchers: 17 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: To train the next generations to deal with the increasing complexity of understanding and predicting climate, CICS collaborated with a Princeton University professional development institute for New Jersey teachers, known as QUEST. QUEST is a long-standing summer program led by Princeton University's Teacher Preparation Program. The two-week Weather and Climate unit, July 11-22, 2005, was for teachers in third through sixth grades and 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 the Geophysical Fluid Dynamics Laboratory (GFDL), and is currently a middle school science teacher in Princeton.

Methods and Results/Accomplishments:

The unit began with experiments and measurements involving pressure, temperature and humidity. A variety of activities were used to develop understanding of how energy from the sun is distributed over the earth, the seasons, the ways in which heat is transferred, and the basis and importance of the greenhouse effect. Many of those ideas were then brought together through the demonstration of the principles of cloud formation and the conditions that produce wind. Experiments demonstrating the Coriolis effect served as a basis to understand global circulation of the atmosphere and the generation of tropical cyclones. Hands on activities were used to develop explanations for lightning and tornadoes. Dr. R. Wetherald, a guest speaker from GFDL, further drew on the topics studied to discuss research and modeling concerning causes and consequences of global warming.

During the second week the drawing of isotherms on maps of monthly average temperature was used to develop ideas of climate vs. weather and relate the patterns to principles developed in the first week. Weather conditions and patterns were further explored through drawing isotherms and plotting fronts, examining a variety of maps available on the internet, and learning the meaning of forecast terminology. More quantitative experiments were done with the distribution of light energy over the earth and with different ways to measure and express humidity. These were related to models of weather and climate. Dr. Robert Wanton, a guest speaker from the Mount Holly Forecast Office of the National Weather Service provided further insight into data collection and forecasting. The formation of snow crystals and light and color in the atmosphere were also explored.

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

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

Principal Investigator: Gang Chen (Princeton graduate student)

Other Participating Researchers: Isaac Held (Advisor), Pablo Zurita, Isidoro Orlanski, Walter Robinson (UIUC), Edwin Gerber

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 mid-latitude jet shift with surface friction, and its implication to the climate change.

Methods and Results/Accomplishments:

The jet shift has been seen in the observation and simulated by a number of general circulation models (GCMs) in response to the global warming. This current work aims to understand the dynamics of jet shift in the simple case of surface friction, and hope to isolate various factors determining the jet position in the global warming simulations in the future.

We employ the GFDL dynamical core forced by Held-Suarez forcing in FMS. The jet displaces poleward as surface drag is reduced. This shift is primarily controlled by the drag on zonal mean flow rather than the drag on eddies. More detailed investigation indicates that barotropic flow and the phase speed of large scale waves play important roles in the jet shift. Similarly, reducing gravity wave drag can cause the poleward jet shift.

The nature of jet shift involves the internal variability of zonal wind, which is statistically regarded as annular modes. We are currently exploring the jet shift as well as annular modes quantitatively with a shallow water model with stochastic stirrings.

Publications:

G. Chen and I. M. Held, in preparation: Sensitivity of the jet latitude to surface friction.

Progress Report: **The Effect of Moisture on the General Circulation of the Atmosphere**

Principal Investigator: Dargan Frierson (Princeton graduate student)

Other Participating Researchers: Isaac Held (Princeton Advisor), Pablo Zurita-Gotor, Steve Garner, and Ming Zhou (GFDL), Olivier Pauluis and Andy Majda (NYU), Geoff Vallis and Sarah Kang (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 effect of moisture on the general circulation of the atmosphere to improve our understanding of the climate and future climate change.

Methods and Results/Accomplishments:

Frierson has developed a simplified moist general circulation model and has used this to study a wide array of problems involving the effect of moisture on the general circulation of the atmosphere. The model has been constructed using the GFDL Flexible Modeling System as a basis, with various idealized physical parameterizations that are suitable for the complexity of the model. For instance, the boundary conditions of the model are an aquaplanet slab mixed layer ocean, and the radiative transfer scheme is gray radiation, so water vapor, clouds, and other constituents have no effect on radiative transfer. This model provides a useful framework to isolate the dynamical effect of water vapor in isolation from radiative feedbacks. Additionally we can vary the water content over orders of magnitude without the model blowing up due to overpowering radiative feedbacks.

With increased temperatures, the water vapor content of the atmosphere is expected to increase significantly. Frierson has used the simplified moist general circulation model to study the effect of this increase on both the extratropical and tropical general circulation of the atmosphere. First, in terms of extratropical dynamics, we have studied the effect of moisture on the determination of static stability, eddy scales, energy fluxes, and jet latitude in midlatitudes. The study of Frierson, Held, and Zurita-Gotor (2005) has demonstrated that moisture plays a fundamental role in the determination of the extratropical static stability. Moist convection in the warm cores of baroclinic eddies causes the static stability to increase significantly as the moisture content of the atmosphere increases. Despite increases in the Rossby radius, the eddy scales of the model change little with moisture. We additionally show that moist static energy fluxes vary little with moisture: there is a large compensation of the increase in moisture fluxes with decreases in the dry static energy flux. We interpret this behavior with energy balance models, including a model with the property of exact compensation as moisture content increases.

In terms of tropical dynamics, Frierson has developed a simplified Betts-Miller convection scheme to study the effect of convection on tropical dynamics. A key result from this work is that the ability to build up and rapidly release convective available potential energy is a key classification of convection schemes. In collaboration with Zhou and Held, Frierson is studying the effect of moisture on the Walker circulation, using this model and more sophisticated GCM's. In collaboration with Garner, Held, Pauluis, and Vallis, Frierson is using the simplified physics package developed for the model above within a nonhydrostatic model to evaluate the usefulness of a mathematical scheme that allows deep convection to be better resolved with current computing power. In collaboration with Held and Kang, Frierson is studying the effect of a land surface on precipitation distributions.

Publications:

Accepted for publication in Journal of the Atmospheric Sciences, pending minor revisions:
D. M. W. Frierson, I. M. Held, and P. Zurita-Gotor, A Gray-Radiation Aquaplanet Moist General Circulation Model. Part 1: Static Stability and Eddy Scales.

Progress Report: **A Study of Oceanic Meridional Overturning Circulation (MOC) Through a Hierarchy of Idealized Models**

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

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

Theme #1: Earth System Studies/Climate Research

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

Objectives: Understanding the dynamics and variability of oceanic MOC, and its role in global climate

Methods and Results/Accomplishments:

Motivation for this study stems from the fact that oceanic meridional heat and freshwater transport together with atmospheric counterpart play a crucial role in determining the Earth's climate. Hence, understanding the dynamics of oceanic meridional overturning circulation (MOC) and its transport capabilities, including the partition between shallow and deep overturning, pose itself as critical point for predicting distribution of possible outcomes of present climate change, as well as explaining rich climate history as revealed in paleorecords.

At the core of our methods is the use of the Modular Ocean Model version 4.0c (MOM4). Specifically, at this point we use idealized single-basin configuration (with and without the Southern Ocean channel) with annually averaged surface forcing. The focus is on the sensitivity of the MOC to (1) surface buoyancy forcing at high latitudes, (2) magnitude of the vertical mixing in ocean and (3) surface wind intensity over the Southern Ocean and equatorial region. One specific result is that introduction of the channel yields substantial interhemispheric asymmetry even when all surface forcing fields are equatorially symmetrical. In a number of experiments bottom water in the whole basin originates from the surface south of the channel, which confirms that deep overturning circulation can be strongly influenced by surface wind stress at critical regions. This appears to be independent of vanishing limit of diapycnal mixing.

Future research will test robustness of these results using a surface forcing with seasonal cycle, and also using the Hallberg Isopycnal Model (HIM). Our ultimate goal is to confirm or correct results and conclusions from the ocean only study by coupling the ocean model to a hierarchy of simplified atmospheric models, perhaps first an energy moisture balance model.

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

Principal Investigator: Edwin Gerber (Princeton graduate student)

Other Participating Researchers: Geoffrey Vallis (Princeton Advisor), Benjamin Cash (COLA), Gang Chen, Dargan Frierson (Princeton), Isaac Held (GFDL), Paul Kushner(GFDL, now at University of Toronto), Thomas Reichler (Princeton, now at University of Utah)

Theme #1: Earth System Studies/Climate Research

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

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

Methods and Results/Accomplishments:

Gerber has developed a hierarchy of models to explore the statistical and dynamical features of the North Atlantic Oscillation and annular modes, the primary modes of intra- to inter-seasonal variability in the extratropical atmosphere. His work with a stochastically forced barotropic model and an analytic stochastic model have contributed to the understanding of the spatial and basic temporal structure of the annular modes. Building on this work, Gerber has engaged in a study with a dry GCM with idealized forcing to better explain (1) the persistence of the NAO and annular modes and (2) the dynamics that lead to zonally localized patterns of variability like the NAO. The dry GCM produces a fairly realistic climate controlled by a few well defined parameters, providing an ideal context for studying the dependence of low frequency variability on thermal forcing and frictional damping.

To address goal (1), Gerber has performed a parameter sweep with the GCM to determine the key parameters that control the persistence of the variability. He has found that variability is highly nonlinear with respect to the forcing and damping time scales. With weaker forcing, the variability extends to long time scales, suggesting that a feedback between the eddies and mean flow may be present, where with strong forcing, the flow becomes eddy dominated and the time scales of variability approaches the timescale of eddy activity. He has also found that the variability of the model is sometimes sensitive to model resolution, particularly in the stratosphere, and that these sensitivities can be reduced with a gravity wave drag parameterization.

To address the second question, Gerber has performed a series of the experiments with the GCM to study the effect of a zonally localized storm track on the low frequency variability. The addition of topography and perturbations to the model's thermal forcing, as to approximate the effect of land-sea contrast, were used to vary the baroclinicity of the model as a function of longitude and create a localized region of increased synoptic (time scales of 2-10 days) variability. As suggested by earlier work with the barotropic model, the low frequency (10-100 day) variability also localized; a dipole pattern similar to the NAO appeared just downstream of the storm track. Analysis of the eddy dynamics allowed him to explain the position of the low frequency pattern in relation to the high frequency variability in terms of the baroclinic eddy life cycle. The low frequency variability is controlled by the eddy momentum fluxes, which are largest when the eddies are decaying in the exit region of the storm track.

Publications:

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

E. P. Gerber and G. K. Vallis, 2005: A Stochastic Model for the Spatial Structure of Annular Patterns of Variability and the North Atlantic Oscillation, Journal of Climate, 18, 2102-2118

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

Principal Investigator: Thomas Haine (John Hopkins University Faculty)

Other Participating Researchers: Steve Griffies (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: Development of Ocean Circulation Model of the Denmark Straits

Methods and Results/Accomplishments:

1. The PI has developed a 1/30o (4km), 60-level circulation model (MITgcm) of the Denmark Straits and tested its performance against several in-situ and remotely-sensed data sources. These include hydrographic measurements, current measurements, floating ice data, and satellite climatologies of surface ocean conditions. Although the O(10km) scale circulation looks realistic, the model representation of surface jets (especially on the East Greenland shelf), and in the Denmark Strait Overflow is not ideal (the jets are too weak and diffuse and the entrainment is excessive). At least some of these problems are due to errors in the model initial and boundary conditions and our results are similar to those of *Käse* and *Oschlies* [2000] for idealized dam-break experiments (they used the sigma-coordinate SPEM model at similar resolution and claim good agreement with in-situ data).
2. The PI has developed a $1/60^{o}$ (2km), 97-level circulation model of the Denmark Straits and tested its performance against data sources as mentioned above (see Figure 1, right). At this resolution the jet structures and entrainment south of Denmark Strait look realistic. It seems likely that this model could accurately reproduce real measurements given appropriate initial and boundary conditions (in other words, the model bias is low compared to the errors inherent in the sparse observations). Preliminary estimates of the cross-shelf fluxes of mass, heat, and freshwater have been made. The synoptic atmospheric forcing is very important in controlling the fluxes and causes substantial short-term variability. The model East Greenland Coastal Current carries a large fraction of the total freshwater on the East Greenland continental shelf, mainly in the upper 30m. Some of these results are used in the ASOF report of *Haine* [2004].
3. The PI has written and submitted a manuscript on the prospects of 4DVAR data assimilation at $1/12^{o}$ (9km) resolution in the Denmark Straits and Irminger Sea (Lea et al. [2005] - see above for details). This effort was partly supported from other sources.
4. The PI has visited GFDL on several occasions and participated in the CLIVAR GCM modeling workshop at GFDL and the Gravity Current Entrainment CPT workshop in November 2004.

These results contribute to the ability of GFDL to understand climate variability and develop state-of-the-art ocean circulation models.

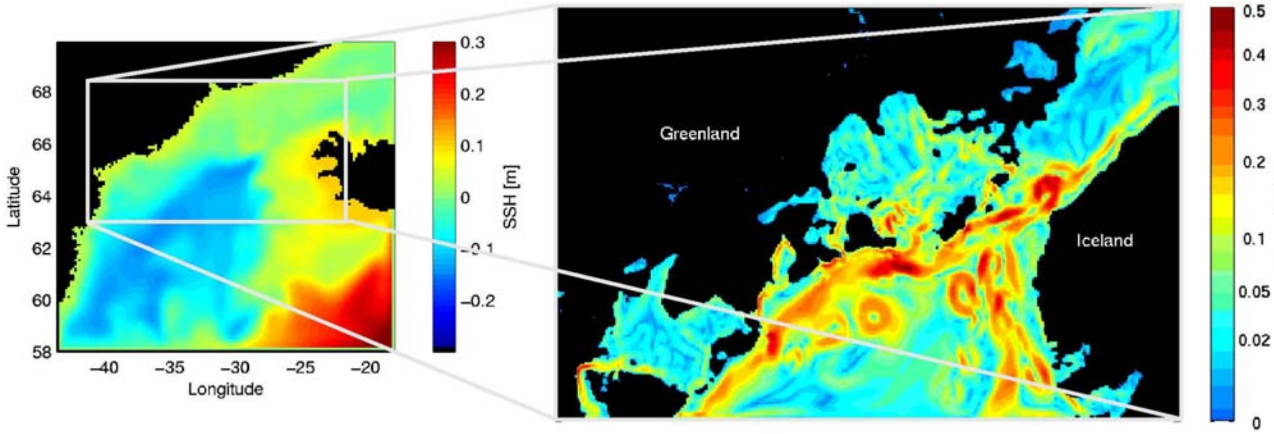


Figure 1: Results from the Johns Hopkins University Irminger Sea/Denmark Strait model. Left: 1/12^o (9km), 30-level sea-surface height, and Right: 1/60^o (2km), 97-level current speed at 330 m. Results are shown for (nominally) August 1999. Both models are forced with the NCEP/NCAR reanalysis atmospheric state at daily (left) or six-hourly (right) periods. Initial conditions are taken from the 1/4^o global assimilation of Fox and Haines [Fox and Haines, 2000; Fox et al., 2000]. Open boundary conditions are set by the same product and are updated every 5 days for the 1/12^o model. The 1/60^o open boundary conditions can be taken from the 1/12^o model so that the very high resolution Denmark Strait simulation is nested in the larger domain as shown schematically in the figure. A 1/12^o, 7-level configuration (same domain as left) and a 1/30^o, 60-level configuration (same domain as right) exist and may also be used in this project.

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

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Zhang, J., and D. Rothrock (2000), Modeling Arctic sea ice with an efficient plastic solution, *J. Geophys. Res., 105*, 3325-3338.

Progress Report: **The Annual Cycle of Temperatures and Winds in the Eastern Tropical Pacific**

Principal Investigator: Arno Hammann (Princeton graduate student)

Other Participating Researchers: George Philander (Princeton Advisor), Anand Gnanadesikan (GFDL)

Theme #1: Earth System Studies/Climate Research

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

Objectives: To understand the dynamics and thermodynamics of the annual cycle (of ocean temperatures, currents, and winds) in the tropical Pacific.

Methods and Results/Accomplishments:

The investigation has been based on analyses of observational data and model runs from GFDL's coupled climate model (CM2.1). It has shown that oceanic advection plays the most important role in the larger-scale heat budget of the annual cycle in the eastern Pacific Ocean. However, air-sea heat fluxes, and in particular latent heat, are instrumental in driving the dynamics of the annual cycle. Since latent heat fluxes also are an important component in the mean heat budget, nonlinearities in the evaporation function could theoretically lead to interactions between the annual cycle and mean state. However, such nonlinearities were shown to be negligible, which lends support to well-known theoretical frameworks which consider mean state and annual variability independently.

The findings also corroborate the idea that an asymmetric mean state is necessary for the excitation of an annual cycle at the Equator by antisymmetric solar forcing. A new finding from the CM2.1 modeling results is that the excitation of the annual cycle depends on subtle atmospheric effects connected to the moisture content of the air.

Progress Report: **Application of Satellite Observed Thermal IR Radiances in Validating GCMs**

Principal Investigator: Xianglei Huang (Princeton Research Associate)

Other Participating Researchers: Host: V. Ramaswamy (GFDL). Collaborators: Daniel Schwarzkopf (GFDL), Brian J. Soden (Univ. of Miami), James G. Anderson, Brian Farrell (Harvard University), Yuk L. Yung (Caltech).

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 variability of the thermal IR radiances and explore efficient ways to use such observations to evaluate the performance of the new GFDL AGCM, AM2.

Methods and Results/Accomplishments:

Huang studies the temporal and spatial variability seen from outgoing thermal IR radiances and then examines how good such variability could be represented in current GCMs. With a careful treatment of the sampling disparity between GCM and satellite observations, Huang has applied the "model-to-satellite" approach to evaluate model performance with respect to satellite observations of IR radiances. This approach computes synthetic IR spectra and narrowband radiances based on GCM outputs and then directly compares these synthetic quantities with observed ones. This approach is affordable with today's computational power and effectively avoids the uncertainty resulted from ill-posed nature of IR retrieval. Three subtasks haven bee carried out in the last year:

(1) **Quantify the source of errors in AM2 simulated tropical clear-sky OLR**: we quantify the source of errors in AM2 simulated clear-sky OLR by comparing synthetic IR spectra from AM2 simulation to IRIS spectra. We conclude that the sampling disparity does not account for the majority of the bias. The negative bias mainly comes from H_2O bands and could be explained by a too humid layer around 6-9 km in the model. Meantime, our results imply that the boundary layer in the model might be too dry. These facts together suggest that the negative bias in the simulated clear-sky OLR can be attributed to the large-scale water vapor transport. We also found that AM2 simulated clear-sky OLR has ~1 Wm^{-2} positive bias originated from the stratosphere and this positive bias should exist in total-sky OLR as well.

(2) **Interannual co-variability seen from comparisons among HIRS, AM2 and reanalysis**: We first homogenized 20-year record of HIRS radiance measurements at several channels then they are used to evaluate the fidelity of the interannual co-variability of tropical humidity and temperature in reanalyses and AM2 simulations. Large inconsistencies between the NCEP and ECMWF reanalyses are found as are disagreements between the reanalyses and AM2 model simulations. The largest discrepancies occur in the middle and upper troposphere where NCEP and ECMWF tropical-mean relative humidity anomalies are found to be negatively correlated. When compared to HIRS observations, the radiance anomalies simulated from AM2 model output are shown to agree well with those observed by HIRS. These results support the validity of the strong coupling between temperature and humidity variations simulated in the GFDL AM2 and highlight the need to improve the representation of interannual variations of humidity in reanalyses.

(3) **Temporal and spatial variability of observed and simulated IR spectra**: 10-month IRIS spectra are use to examine the temporal variability of outgoing IR spectra over tropical Pacific. It turns out that, for three GCMs we examined (AM2, NCAR CAM2, UCLA AGCM), they are all different from the observation in very different ways (figure 1). Most of these discrepancies would be attributed to simulation of clouds, especially the intraseasonal variation of clouds. 16-day high quality AIRS spectra

are used to examine the spatial variability of outgoing IR spectra. AM2 has fairly good agreements with AIRS in terms of both the tropical and stratospheric spatial variability reflected in the spectra, partly due to the spectral-dependent parameterization of cloud longwave radiative effect (figure 2).

Besides these activities, Huang has been a collaborator in two projects lead by J. Anderson and B. Farrell exploring the linear stochastic representation of variability seen in infrared spectra and co-authored three papers, ranging from the fast radiative transfer, variability in earth upper troposphere, to the interaction between zonal flow and moist convections in Jovian atmosphere.

Publications:

Huang, X.L., and Y. L. Yung (2005), Spatial and spectral variability of the outgoing thermal IR spectra from AIRS: A case study of July 2003, *Journal of Geophysical Research - Atmospheres*, 110, D12102, doi:10.1029/2004JD005530.

Huang, X.L., B.J. Soden, and D.L. Jackson, Interannual co-variability of tropical temperature and humidity: a comparison of model, reanalysis data and satellite observation, accepted by *Geophysical Research Letters*.

Huang, X.L., V. Ramaswamy and M. D. Schwarzkopf, Quantify the source of errors in AM2 simulated tropical clear-sky OLR, to be submitted to *Journal of Geophysics Research*.

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

Soden, B.J., D.L. Jackson, V. Ramaswamy, M.D. Schwazrzkopf and X.L. Huang, The radiative signature of upper tropospheric moistening, submitted to *Nature*.

Li, L., A.P. Ingersoll, X.L. Huang, Interaction of Moist Convection with Zonal Jets on Jupiter and Saturn, submitted to *Icarus.*

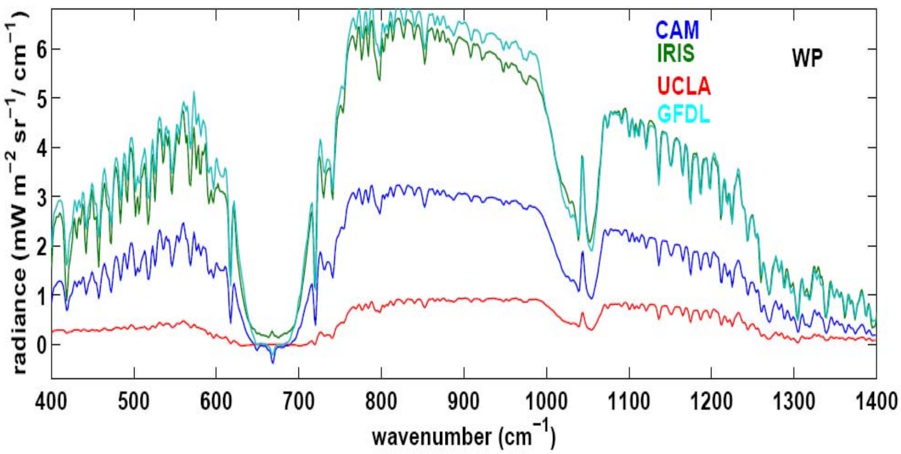


Figure 1. The first principal component (PC1) derived from temporal-spectral EOF analysis of 9-month IRIS (Infrared Interferometer Spectrometer) observations over the western Pacific from April to December 1970 (The green line). The corresponding PC1s derived from GFDL AM2 simulation over the same period is shown as the cyan line. The blue and red curves are the PC1s from NCAR CAM2 and UCLA GCM simulations, respectively. All simulation are forced with the observed SST over April to December 1970.

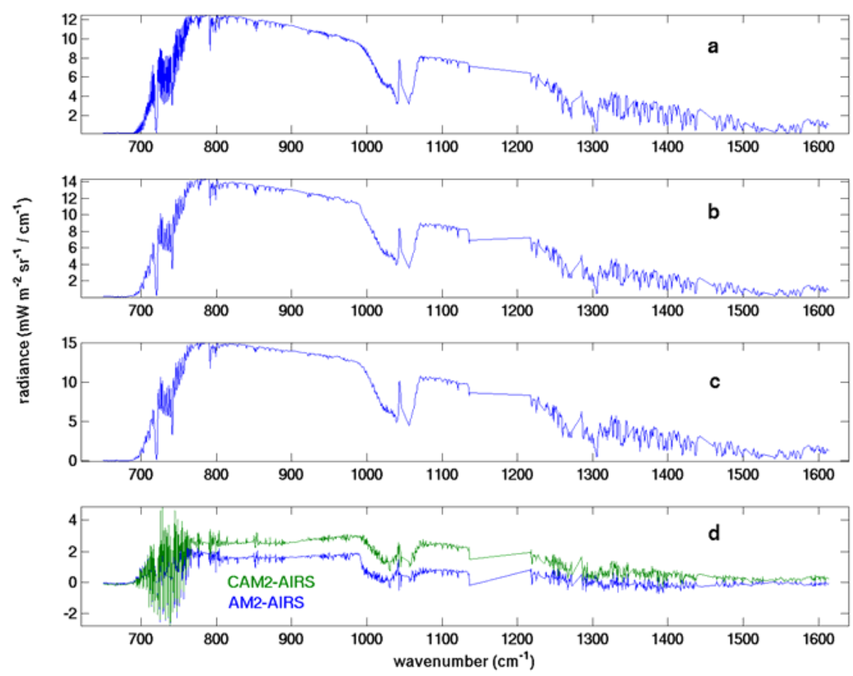


Figure 2. (a) The first principal component (PC1) derived from spatial-spectral EOF analysis of 16-day AIRS (Atmospheric Infrared Sounder) spectra over the tropical/subtropical oceans (30°S-30°N) from July1-16, 2003. (b) Same as (a) except that it is based on GFDL AM2 simulation forced with observed SST over the same period. (c) Same as (b) except it is from NCAR CAM2 simulation. (d). The difference between AM2 PC1 and AIRS PC1 (the blue line) and the difference between CAM2 PC1 and AIRS PC1 (the green line).

Progress Report: **Sensitivity of Clear-sky Outgoing Longwave Radiation (OLR) to Atmospheric Temperature and Water Vapor**

Principal Investigator: Yi Huang (Princeton graduate student)

Other Participating Researchers: Advisor: V. Ramaswamy(GFDL), Brian Soden(U. Miami)

Theme #1: Earth System Studies/Climate Research

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

Objectives: To understand how OLR spectrally depends on the vertical distribution of temperature and water vapor.

Methods and Results/Accomplishments:

Under clear-sky condition, atmospheric temperature and water vapor (wv) are two major factors that affect the Outgoing Longwave Radiation. The spectral dependence of OLR on the vertical profiles of the two factors is essential to our understanding of climate change. Here, with GFDL's Line-by-line radiative transfer model as well as the longwave band approximation applied in its climate modeling system, FMS, we examined the radiative adjoints of temperature and wv under the conditions of three typical atmospheres, tropical, mid-latitude summer and mid-latitude winter. Some of the results are interesting. For example, if keeping relative humidity constant, the OLR variation induced by temperature change exceeds that induced by the consequent change of wv. The comparison between adjoint curves showed that different formulations of wv continuum absorption applied in the RT models, as well as the band approximation, does not significantly change the results in terms of clear-sky OLR. Also the adjoints were applied in analyzing the individual contributions to OLR change simulated by climate model.

Publications:

A paper with the same topic is being written and to be submitted soon.

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

Principal Investigator: Laura Jackson (Princeton Research Associate)

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

Theme #1: Earth System Studies/Climate Research

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

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

Methods and Results/Accomplishments:

This past year, Dr. Jackson has been working on (1) documenting the sensitivity of overflows to the range of parameters of our existing shear-mixing scheme, (2) developing an entrainment and shear-driven diapycnal mixing parameterization that can be used in both isopycnal- and geopotential-coordinate models, and (3) implementing this new parameterization for use in our climate models. The work in documenting the sensitivities identifies the critical shear Richardson number as being of primary importance for determining the final properties of many plumes with oceanographically relevant parameters. This insight will help guide our efforts in developing improved parameterizations. The work on a new diapycnal mixing parameterization stems from a clear demonstration from Large Eddy Simulations by our CPT partners of significant deficiencies of the existing parameterizations. This new parameterization will describe vertically non-local quasi-equilibrium shear-driven turbulent mixing, and will be calibrated with large eddy simulations from both GFDL and U. Miami. It will be substantially simpler (and more appropriate for climate studies) than existing fully three-dimensional non-equilibrium two-equation turbulence models. If successful, it will replace both the interior shear-mixing part of KPP (Large et al., 1994) and the Hallberg (2000) shear mixing parameterization.

In the coming year, we anticipate that Dr. Jackson's work on shear mixing will lead to full parameterizations that can be tested in our climate models. In addition, she will be a part of the effort at GFDL to implement and evaluate the eddy-driven mixed layer restratification parameterizations now under development by our CPT partners at MIT.

References:

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

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

Publications:

A pair of papers on our new parameterization and its numerical implementation are being prepared.

Progress Report: **Diurnal Cycle of Summertime Precipitation over North America as simulated by the GFDL AGCM**

Principal Investigator: Xian-an Jiang (Princeton Research Associate)

Other Participating Researchers: Ngar-Cheung Lau, Isaac M. Held, Jeffrey Ploshay (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: This study aims to explore physical mechanisms responsible for the summertime precipitation regime over the North American Continent, and to assess the fidelity of GFDL AGCM simulation of the observed features. The final goal of this study is to improve the GFDL AGCM performance in simulating summertime climate over the North America region.

Methods and Results/Accomplishments:

As one of the key components of the summertime climate system over North America, the nocturnal Great Plains low-level jet (GPLLJ) simulated by the GFDL AGCM have been analyzed. Results show that the most important observed features of the GPLLJ are well simulated by the AGCM, including the diurnal phase, amplitude and location. Hence, based on the AGCM output, physical mechanisms for the formation of this nocturnal low-level jet are re-evaluated in the context of two main existing theories, i.e., the alternate heating and cooling of the slopes of the Rockies (Holton 1967) and the inertial oscillation due to frictional decoupling (Blackadar 1957). Results indicate that the observed phase and amplitude of the GPLLJ are largely ascribed to the combination of these two mechanisms. While both of the mechanisms contribute to the amplitude of the GPLLJ, the diurnal peak of the low-level jet resulting from either Holton's or Blackadar's mechanism alone tends to display an unrealistic meridional phase shift. It is also found that terrain induced meridional pressure gradient distribution could be important in determining the location of the GPLLJ center.

Although the AGCM can well simulate the GPLLJ and other large scale dynamical circulation over North America, the simulation of the diurnal cycle of precipitation over this region is still a great challenge. Particularly, over the Great Plains, the model simulated precipitation signal is much weaker than the observed. This signal exhibits a late afternoon maximum instead of a midnight peak as in the observations. Our preliminary analyses indicate that the land surface in the AGCM is too dry and too hot as compared to the observations. The poor simulation of the eastward propagating mesoscale systems east of the Rockies is another notable deficiency of the AGCM. The causes of these AGCM errors are complex, and could involve the formulation of land model, cumulus parameterization and planetary boundary layer schemes, as well as the horizontal resolution of the AGCM. We are currently diagnosing the observed data in order to identify the key factors responsible for the precipitation regime in the observed atmosphere. We are also performing detailed comparison between the AGCM simulation and its observed counterpart, so as to obtain some clues for improving the model physics.

References:

Blackadar, A. K., 1957: Boundary layer wind maxima and their significance for the growth of nocturnal inversions. *Bull. Amer. Meteor. Soc.*, **38**, 283-290

Holton, J. R.,1967: The diurnal boundary layer wind oscillation above sloping terrain. *Tellus*, **19**,199-205.

Publications:

Xian-an Jiang, Ngar-Cheung Lau, Isaac. M. Held: AGCM simulated Great Plains Low-level Jet and its mechanisms. In preparation.

Progress Report: **Dynamics of Rainbelt Movement**

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

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

Theme #1: Earth System Studies/Climate Research

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

Objectives: To understand what determines the boundary of rainbelt to investigate the Sahel drought.

Methods and Results/Accomplishments:

During the first semester, Kang took several classes that are required for the general exam in next year. In numerical methods class, Kang has done a research about how moisture is advected differently when different advection schemes are applied using shallow water model. Kang was able to capture several realistic characteristics from this simple model.

In the second semester, Kang investigated the influence of aerosol on precipitation over Sahel. To make a link between aerosol and precipitation, Kang has worked on how aerosol affects the shortwave flux at the surface and how it changes the sea surface temperature over North Atlantic Ocean and Indian Ocean.

Throughout the year, Kang has developed an interest in African climate change. The African Sahel experienced a prolonged dry episode in the latter decades of the 20th century. It's surprising that every model produces different trend for the next century. Especially, Japanese model says it'll get moistened and GFDL model says it'll become drier catastrophically. To understand what is going on over Sahel, Kang decided to use an intermediate complexity moist general circulation model to study what determines the extent of precipitation movement, the position of ITCZ and the boundary of rainbelt.

Kang started working with a simplified moist GCM. Several experiments, like putting an idealized rectangular continent and inputting seasonal variation by modifying solar flux as a function of time have been done recently.

Progress Report: **Observing Network Design for Improved Prediction of Geophysical Fluid Flows**

Principal Investigator: Shree P. Khare (Princeton graduate student, now a postdoctoral fellow at the National Center for Atmospheric Research)

Other Participating Researchers: Geoffrey Vallis (Princeton Advisor), Jeffrey L. Anderson (NCAR), Jim Hansen (MIT)

Theme #1: Earth System Studies/Climate Research

NOAA's Goal #3: Serve society's needs for weather and water information

Objectives: Develop theories and implement algorithms for designing optimal networks of observations in both space and time for improved prediction of geophysical fluid flows.

Methods and Results/Accomplishments:

Khare has investigated theories and algorithms for designing optimal networks of observations for improved prediction of geophysical fluid flows. The first problem investigated is the so-called adaptive observations problem. For the adaptive observations problem the goal is to identify optimal configurations of observational networks at times in the future to improve predictions of some atmospheric/oceanic quantity of interest at times even farther into the future. The classic example of adaptive observations are airplanes flying over the pacific dropping observing instruments over poorly observed baroclinically unstable features. Adaptive observation algorithms help decide where to direct those airplanes. Khare has developed a Bayesian framework for formulating solutions to the adaptive observations problem. Under some circumstances, the Bayesian framework is equivalent to the ETKF adaptive observations technique used operationally at NCEP. Khare has performed a theoretical/numerical investigation of such algorithms in a low-order atmospheric like prediction model. One of the key conclusions of this work is that sampling errors play a crucial role in implementing ETKF type algorithms. This work has been written up in Khare and Anderson (2005).

Khare has developed and tested a methodology for designing fixed networks of observations. The methodology, called the retrospective design algorithm (RDA), uses ensemble forecasts generated from an ensemble data assimilation system to decide the impact of various configurations of fixed observational networks. The key advantage of the RDA over traditional observing system simulation experiments is computational cost. Application of the RDA to large atmospheric/oceanic design problems of interest is not strongly limited by computational expense. The underlying reason is that the RDA does not require repeated integration of the prediction model equations in assessing the benefit of various configurations of fixed observational networks. The RDA has been tested by making direct comparisons to observing system simulation experiments. Experiments in a simulated global atmospheric prediction system were used in this investigation. The key result is that the RDA is able to mimic information derived from doing observing system simulation experiments at a much reduced computational cost. Khare's work on both adaptive and fixed observational network design is described in a PhD thesis completed in November, 2004.

Publications:

S.P. Khare and J. L. Anderson, 2005: An examination of ensemble filter based adaptive observation algorithms, accepted in Tellus A.

S. P. Khare, 2004: Observing network design for improved prediction of geophysical fluid flows – analysis of ensemble methods, PhD thesis, Princeton University.

Progress Report: **Evaluation of GFDL SCM Cloud Fields with Those from the Ground-based Remote Sensing at SGP**

Principal Investigator: Byung-Gon Kim (Princeton Research Associate, now at Kangnung National University, Korea)

Other Participating Researchers: Stephen Klein (GFDL, now at Atmospheric Science Division, Lawrence Livermore National Laboratory),Gerald Mace and Sally Benson (University of Utah)

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

Meanwhile, the various kinds of these approaches to obtain cloud fraction in the model still have the limitations, which accordingly result in the consequent errors in the model radiative fluxes. Because of the different schemes to estimate the cloud fraction by the model and also observation artifacts, the prudent comparisons should be made in order to reach the right answer. This study demonstrates the more revised approaches of comparisons to improve the evaluation of cloud fraction.

In this project, the whole year 2000 of measurements over the ARM Southern Great Plain (SGP) site are used to evaluate treatment of clouds in the single cloud model which uses the same parameterization as are in the GFDL climate model.

Methods and Results/Accomplishments:

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

To do this, a relatively inexpensive and computationally efficient model-evaluation method is the use of so-called single column model (SCM), which contains all of the physical parameterizations of the GCM and can be forced with observations. In terms of the observation, a technique to derive cloud faction as a function of height using ground-based radar and lidar is applied to the SCM evaluation. The full-year measurements of 2000 over the SGP site are used to evaluate treatment of clouds in the single column model which uses the same parameterization as are in the GFDL climate model (GFDL Global Atmospheric Model Development Team, 2004). To reduce comparison issues of single point and represent the temporal scale more comparable to the size of the SCM domain, the observations and the SCM outputs are averaged in time to 3 hr.

The preliminary results demonstrate that the model cloud fractions correspond well with radar observations, however model clouds persist slightly longer than observations. Comparison of SCM total cloud to that of the observation indicates binary representation of total cloud fraction relative to partial cloud fraction of the observation. Figure 1 demonstrates the detailed evaluation of the SCM using the cloud properties obtained from the radar. In general, there seems to be some discrepancy in the lower cloud boundary; most of the observed cloud base touches the ground, which differs from that of SCM. Especially on 2 March when the distinctive frontal cloud system passed over the SGP site, SCM apparently overpredicts the upper-layer cloud occurrence. Additionally SCM predicts the persistent cloud relative to the observation on 8 March when a clear period was observed. Besides, if the cloud field is not counted as cloud when the SCM LWC is less than 10 mg m^{-3} and IWC less than 1 mg m^{-3}, for which no cloud should be present especially in the upper layer, the model agreement would significantly improve.

In addition, several comparisons demonstrate the considerable potential of active instruments for validating the representation of clouds in models. Excluding times when either the SCM precipitation or the observed precipitation is greater than 0.5 mm hr^{-1} appears to significantly improve the agreement of SCM cloud fractions with observations. Furthermore, the contribution from the SCM precipitation area by snow and rain should be considered because the radar cannot distinguish precipitating snowflakes and raindrop from nonprecipitating clouds.

References:

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

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

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

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

Tiedtke, M., Representation of clouds in large-scale models, *Mon. Wea. Rev.,* 121, 3040-3061, 1993.

Zhang, M.H., J.L. Lin, R.T. Cederwall, J.J. Yio, and S.C. Xie, Objective analysis of ARM IOP data: Method and sensitivity, *Mon. Wea. Rev.,*129,295-311, 2000.

Presentations:

One poster presentation by Byung-Gon Kim was submitted to the Atmospheric Radiation Measurement Science Team Meeting, Daytona Beach, FL in March 2005. He could not attend the meeting because he had to return to his country for the new teaching position at the university.

Kim, B.G., S.A. Klein, G. Mace, and S., Benson, 2005: Evaluation of GFDL SCM Cloud Fraction and Surface Radiation Fields with Those from the Ground-based Remote Sensing at SGP, In *Proceedings of the 15th Atmospheric Radiation Measurement Science Team Meeting*, Department of Energy, Daytona Beach, FL.

Publications:

With regard to the previous work for cloud variability, the following paper has been published through the constructive revisions;

Kim, B.G., S.A., Klein, and J.R. Norris, 2004: Variability of continental liquid-water cloud and its parameterization using ARM data. J. Geophys. Res. 110(D15)S08, doi10.1029/2004JD005122.

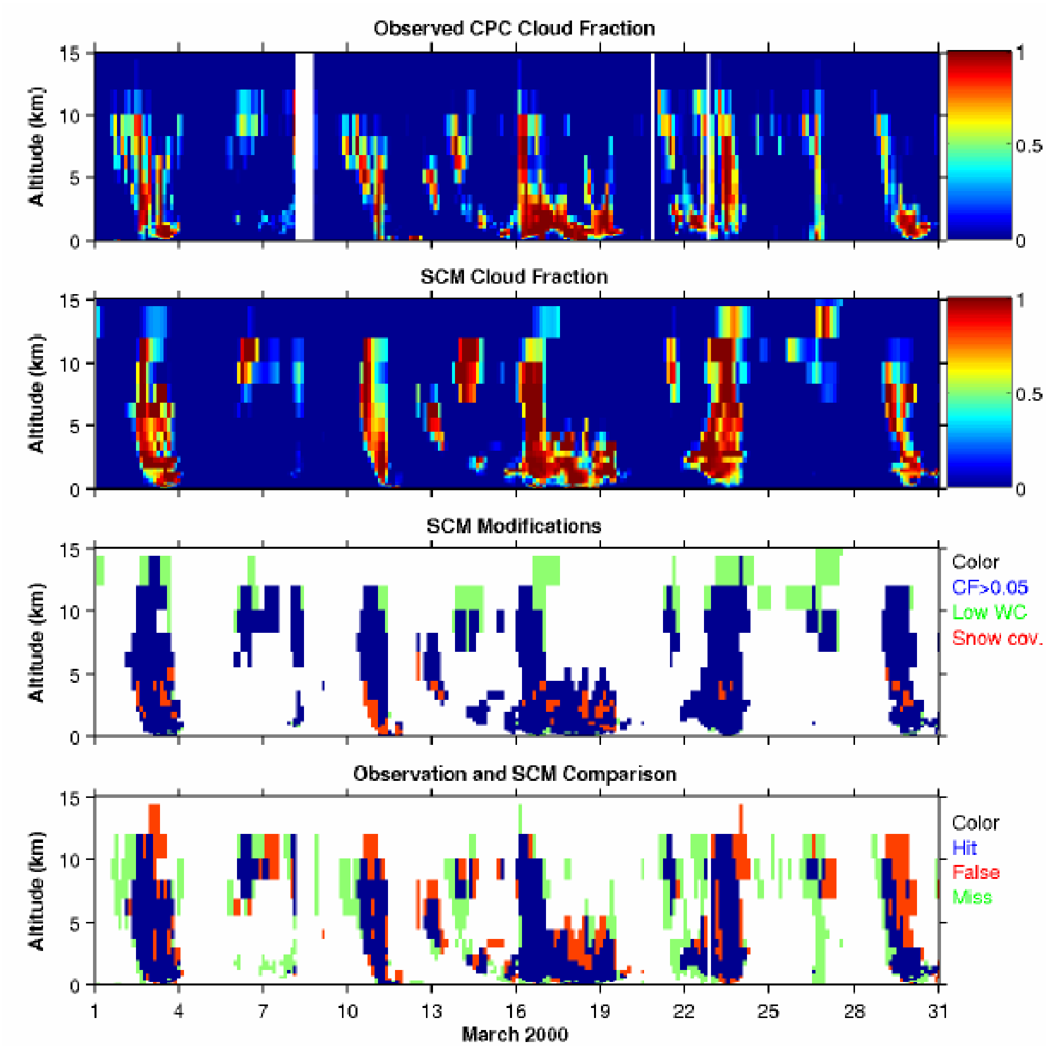


Figure 1. The evaluation of SCM cloud fractions with the observed cloud properties (1st panel indicates the observation and 2nd panel indicates the SCM output.). The 3rd panel shows the agreement of cloud fraction between the model and the observation in which the blue color means both cloud fractions larger than 0.05, green denotes the cloud fraction but with lower water content, and red denotes the snow coverage by precipitation. The bottom panel demonstrates the skill score such as blue, red, and cyan colors indicate hit, false, and miss, respectively.

Progress Report: **The Dependence of Aerosol Effects on Clouds and Precipitation on Cloud-System Organization, Shear and Stability**

Principal Investigator: Seoung Soo Lee (Princeton graduate student) GFDL Advisor: Leo Donner

Other Participating Researchers: Charles Seman and Vaughan Phillips (GFDL)

Theme #1: Earth System Studies/Climate Research

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

Objectives: Precipitation suppression due to an increase of cloud condensation nuclei (CCN) number concentration in stratiform cloud is well known. It is not certain whether the suppression applies for deep convection; a recent research by Khain et al. [2003] suggested an increase of precipitation due to increase of CCN number concentration in the case of deep convection. Lee and Donner [2005] found this was because of strong dynamic interaction in deep convection. The more cloud liquid, due to delayed autoconversion, provides more abundant source of evaporation, leading to more active downdraft, convergence-and-divergence field, more condensation, more intense collection processes among precipitable hydrometeors and cloud liquid and more precipitation at high CCN subsequently. It indicates aerosol effect on cloud and precipitation depends on the intensity of the dynamic interaction. Evaporation of cloud liquid, determining the intensity of the dynamic interaction primarily, is controlled by wind shear modulating the entrainment of dry air into cloud and transportation of cloud liquid into undersaturated area and the active convergence-and-divergence field, directly linked to the more condensation, is not conspicuous in cloud, embedded in the environment of low Convective Available Potential Energy (CAPE). Therefore, aerosol effect on cloud and precipitation can be different, given the environmental condition, represented by CAPE. Four different environmental conditions are imposed on a pair of numerical experiments, composed of high and low CCN cases, to investigate the dependence of aerosol effect on cloud on the environmental condition.

Methods and Results/Accomplishments:

To investigate the sensitivity of aerosol effect on cloud to environmental condition, four pairs of numerical experiments were carried out, with the four different environmental conditions, using Cloud-System Resolving model. The four conditions are as follows:

1) high CAPE
2) moderate CAPE
3) low CAPE
4) very low CAPE

The collection processes among snow, graupel, rain and cloud liquid were more intense in the 500 case. But the difference in their intensity narrowed down as the environmental condition changed from the high CAPE case to very low CAPE and the sign of difference was reversed in the very low CAPE, indicating their compensating ability for the deficit in autoconversion at high CCN got weaker and finally vanished. This is because the supply of cloud liquid, the primary source of the collection processes, by condensation and the difference in the supply between the 50 and 500 cases got smaller, because of more decrease in condensation in the 500 case, resulting in less cloud liquid and smaller difference in it between the cases as we move from the high CAPE to very low CAPE case. The more decrease in the condensation in the 500 case resulted from the more rapidly weakening updraft in the 500 case, making the difference in the updraft smaller. The more and stronger updraft in the 500 case is closely linked to the dynamic interaction to result in the stronger convergence-and-divergence field at the initial stage of each convection. As the condition changed from the high CAPE to very low CAPE, the dynamic interaction weakened and the difference in the intensity of convergence-and-divergence field became inconspicuous, making the difference in the subsequent feedback between updraft and condensation smaller.

In the environment of high CAPE, cumulonimbus-type clouds are dominant, making the intensive dynamic interactions. The intensity of the interaction was much stronger in the 500 case because of more active transportation of cloud liquid to undersaturated areas to lead to more evaporation. The more and stronger downdrafts induced by the stronger evaporation could reach the surface, after fully developed, to cause intensive convergence-and-divergence activity, and subsequent condensation. But the active transportation of cloud liquid and more evaporation in the 500 case attenuated in the environment of low CAPE, where cumuli dominated, and the very low CAPE case, where low-level cumuli and stratocumuli dominated. And it was hard for downdrafts to be intensified fully before reaching the surface due to the reduced cloud depth. The cumulus, low-level cumulus and stratocumulus are not dynamically active cloud types and the more cloud liquid in the 500 case was not transported as actively as in the high and moderate CAPE cases, leading to lessened difference in condensation and collection processes. The weakened collection processes among precipitable hydrometeors and cloud liquid at high CCN could not catch up with the deficit in autoconversion to lead to less precipitation at high CCN.

The aerosol effect on cloud varies with environmental condition, determining the dynamic activity of clouds primarily. The strong dynamic activity creates a favorable condition for aerosol to have a strong impact on cloud dynamics to compensate for the deficit in autoconversion. But the intensity of aerosol effect on cloud dynamics is not significant under the weak dynamic activity, created under low CAPE, so that autoconversion dominates over the dynamic compensation to result in less precipitation at high CCN.

References:

Khain, A., D. Rosenfeld, and A. Pokrovsky, Simulations of aerosol effects on convective clouds developed under continental and maritime conditions, *Geophysical Research Abstracts*, 5, 03180, European Geophysical Society, 2003.

Lee, S. S., L. J. Donner, Impact of aerosols on deep convection. *Submitted to J. Geophys. Res.,* 2005.

Progress Report: **Ocean Tidal Mixing**

Principal Investigator: Sonya Legg (Princeton Research Oceanographer)

Other Participating Researchers: Karin Huijts (summer student fellow at Woods Hole, now graduate student in Netherlands)

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 and mixing over topography and incorporate this understanding into mixing parameterizations in GFDL climate models.

Methods and Results/Accomplishments:

Legg has carried out a series of simulations of tidal flow over isolated topography using the nonhydrostatic MITgcm. and examined (a) the rate of energy conversion from barotroic tide to baroclinic mode; (b) the ratio of this energy dissipated locally versus propagated away as internal tides; (c) the net mixing effected locally. The dependence of these processes on the tidal flow amplitude and topography slope and height has been examined. This work aims to refine models of tidal mixing (e.g. Simmons et al, 2003) which currently assume a fixed fraction of the baroclinic tidal energy is dissipated locally. Undergraduate student Karin Huijts (Woods Hole summer student fellow, 2002) assisted in the development of some of the diagnostic tools.

Publications:

S. Legg and K.M.H.Huijts, Preliminary simulations of internal waves and mixing generated by finite amplitude tidal flow over isolated topography. Accepted for publication in Deep Sea Research, pending minor revisions.

Progress Report: **Dense Overflows**

Principal Investigator: Sonya Legg (Princeton Research Oceanographer)

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

Theme #1: Earth System Studies/Climate Research

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

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

Methods and Results/Accomplishments:

Coordinated with the efforts of the gravity current entrainment climate process team, Legg has been examining the ability of z-coordinate models to represent dense overflows at both coarse and high resolutions. Using the MIT model in idealized domains the sensitivity of simulated dense overflows to model parameters such as resolution, viscosity, advection scheme and eddy parameterization (e.g. Gent-McWilliams) has been examined. A principal result is that the use of the Gent-McWilliams eddy parameterization does not eliminate spurious mixing at coarse resolutions. This mixing is generated by the convective adjustment scheme, and an approach being pursued is the replacement of parcel mixing by "parcel swapping" when convective adjustment is used near topography. Legg is also supervising the work of Ulrike Riemenschneider at Woods Hole, examining the ability of z-coordinate models such as the MITgcm to simulate the Faroe Bank Channel overflow, as a complement to the more idealized studies mentioned above. Finally Legg is working with Jackson and Hallberg to provide direct numerical simulations of shear-driven turbulence intended to calibrate and test a new parameterization of shear driven mixing such as in overflows.

Publications:

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

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

Principal Investigator: Lifeng Luo (Princeton Research Associate) and Stepen Déry (Princeton Research Scientist, now at University of Northern British Columbia)

Other Participating Researchers: Eric F. Wood and Sergey Malyshev (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, and
NOAA's Goal #3: Serve Society's Needs for Weather and Water Information

Objectives: This project has two foci: (1) To understand the predictability of hydrologic variables in the seasonal-to-interannual timescales and to improve the predictive skill to its potential with new forecast methods. Support for this element has come through NOAA/OGP and is also related to NOAA/OGP funding for seasonal hydrological forecasting in the eastern U.S. This work is not being reported on here. And, (2) To better understand the variability of high latitude terrestrial hydrological processes and how their variability may influence climate teleconnections throughout the Arctic climate system. The majority of support for this activity is through NSF, but some CICS funding has supported Arctic predictability studies and is being reported below.

Methods and Results/Accomplishments:

For the first foci (Luo, lead researcher), improving the predictability of hydrologic variables in the seasonal-to-interannual timescales, the execution of the project consists of three steps. The first step is to design and run experiments with the GFDL climate model. The experiments were designed to investigate the variability and predictability of the global hydrological cycle at seasonal-to-interannual timescales. The focus of the study is on precipitation. The experiments also address the question of how different components of the earth climate system, namely, ocean, land and atmosphere contribute to such predictability if it exists. The experiments consist of a series of model integrations with the GFDL climate model, where different combinations of ways to treat land and ocean as boundary conditions are used. These ways include interactive land, climatological land and ocean where the climatologies of sea surface temperature and soil moisture are prescribed, interannually-varying land and ocean where realistic time series of soil moisture and SST are prescribed. Multiple member ensemble is generated for each type of integrations. These experiments were carried out last year with AM2p11 version of the climate model. The second step is to analyze the output from the experiments, and try to compare with the results from other similar studies that took place at other institutes. The GFDL model shows precipitation predictability over the tropical regions that are mainly the contribution of SST. The ocean signal dominates over the tropical and subtropical regions. Over the mid-latitude, predictability does not exist over many land area with exceptions over the central North America. Land plays a certain role providing such predictability over the semi-arid regions. The analysis shows that the behavior of the GFDL climate model is quite similar to that of the NSIPP model, the results from which were published at *J. Climate* a few years ago by Koster et al.. Although our study has not shown any new or surprising results other than what has been found in Koster et al (2000), it consolidates the finding of their studies and indicates that such findings are likely to be model independent, and are features one shall see in the real world.

The third step, that is we are currently working on, is to create new methods that can help improve seasonal forecast skill. This work is exploratory but promising. As our previous results show that prescribed land surface condition is able to guide the atmospheric evolution to with certain degree of coherence, which produces a smaller spread among ensemble members, it is our hypothesis that the forecast skill can be increased if we can provide such information in advance during the forecast period. We are currently analyzing model output from step one to test our hypothesis.

Under the second foci (Déry, lead researcher), the past year the work has explored several aspects of the global land surface water budget, with a focus on northern Canada. The relevant topics of research include: 1) river discharge in northern Canada, including Hudson Bay; 2) the connectivity and predictability of Canadian snow mass and river discharge, and 3) the covariability of twentieth century land surface air temperature and precipitation. The following paragraphs summarize the work conducted and main findings for each of the three main topics of research.

1) River discharge in northern Canada: We expanded the work of Déry et al. (2005a) and Déry and Wood (2004) by investigating freshwater discharge to high-latitude oceans in 64 Canadian rivers. The mean annual discharge rate attains 1252 $km^3 yr^{-1}$ for an area of $5.6 \times 10^6 km^2$, equating to a sink of 225 $mm yr^{-1}$ in the surface water budget of northern Canada (excluding the Arctic Archipelago where insufficient data exist). Application of the Mann-Kendall test to the data reveals a 10% decrease (-125 $km^3 yr^{-1}$ or -22 $mm yr^{-1}$) in the total annual river discharge to the Arctic and North Atlantic Oceans from 1964 to 2003. This trend in river runoff is consistent with a 21 $mm yr^{-1}$ decline in observed precipitation over northern Canada between 1964 and 2000. We find evidence of statistically-significant links between the Arctic Oscillation, El Nino/Southern Oscillation, and the Pacific Decadal Oscillation to the total annual freshwater discharge in northern Canada's rivers at interannual-to-decadal timescales. The paper describing these results (Déry and Wood 2005a) was selected as an AGU journal highlight on 9 June 2005.

2) Connectivity and predictability of Canadian snow mass and river discharge: Déry et al. (2005b) explore pan-Arctic climate connectivity by examining historical time series of satellite-based measurements of Eurasian snow cover extent and of observed Canadian snow water equivalent (SWE) and freshwater discharge, with a focus on the Churchill River Basin of Labrador and the Chesterfield Inlet Basin of Nunavut. Analysis of the data reveals statistically-significant positive (negative) correlations between spring and summer Eurasian standardized snow cover extent anomalies and annual maximum monthly SWE as well as freshwater discharge in the Churchill River (Chesterfield Inlet) Basin the following year. A spatially coherent response to the forcing is observed since nineteen rivers draining more than $0.6 \times 10^6 km^2$ of northern Québec and Labrador and with a mean annual total discharge of 320 $km^3 yr^{-1}$ show statistically-significant positive correlations to the annual Eurasian standardized snow cover extent anomalies. The origin of this pan-Arctic climate connectivity is related to the persistent nature of the Eurasian snow cover extent anomalies and the associated accumulated gains or deficits in the surface radiation and water budgets that impose a memory in the climate system. The Eurasian snow cover extent anomalies provide some degree of predictability (up to one year in advance) of the surface water budget in the Churchill River and Chesterfield Inlet Basins. It further suggests that a declining trend in Eurasian snow cover extent will yield decreasing (increasing) SWE and river discharge in the Churchill River (Chesterfield Inlet) Basin in the twenty-first century.

3) Observed twentieth century land surface air temperature and precipitation covariability: Significant positive trends in surface air temperatures (SATs) and precipitation were observed over 71% and 27%, respectively, of the global land surface during the twentieth century. Although the terrestrial surface is becoming warmer and wetter, the covariability between annual SAT and precipitation is not well understood. Significant anticorrelations between annual values of SAT and precipitation exist over 24% of the global land surface. Regional-scale interannual climate variability alternates between two dominant regimes, namely relatively warm and dry or cool and wet conditions. The out-of-phase positive trends in terrestrial SATs and precipitation observed during the twentieth century provide an important climate simulation benchmark. This study (Déry and Wood 2005b) is still under review.

Publications:

Déry, S. J., and E. F. Wood, 2004: Teleconnection between the Arctic Oscillation and Hudson Bay river discharge, 31*, Geophys. Res. Lett*. L18205, doi: 10.1029/2004GL020729.

Déry, S. J., and E. F. Wood, 2005a: Decreasing river discharge in northern Canada, *Geophys. Res. Lett*., 32, L10401, doi: 10.1029/2005GL022845.

Déry, S. J., M. Stieglitz, E. C. McKenna, and E. F. Wood, 2005a: Characteristics and trends of river discharge into Hudson, James, and Ungava Bays, 1964-2000, *Journal of Climate*, 18, 2540-2557.

Déry, S. J., J. Sheffield, and E. F. Wood, 2005b: Connectivity between Eurasian snow cover extent and Canadian snow water equivalent and river discharge, *J. of Geophysical Research* (Atmospheres) (accepted pending minor revisions).

Déry, S. J., and E. F. Wood, 2005b: Observed twentieth century land surface air temperature and precipitation covariability, submitted to *Geophys. Res. Lett*.

Luo, Lifeng, S. Malyshev, C. T. Gordon, E. F. Wood: Impact of land surface condition treatments on seasonal forecast skill, in preparation for submission to *Journal of hydrometeorology*.

Presentations:

Déry, S. J., 2005: The current and future role of snow in the pan-Arctic climate, University at Albany, 29 April 2005, Albany, New York, USA.

Déry, S. J., 2005: Investigating the water budget of the Hudson Bay Basin, Center for Ocean-Land-Atmosphere (COLA) Studies, 1 March 2005, Calverton, Maryland, USA.

Déry, S. J., J. Sheffield, and E. F. Wood, 2005: Connectivity between Eurasian snow extent and Canadian snow mass and river discharge, Conference Proceedings of the 62nd Annual Eastern Snow Conference, June 2005, Waterloo, Ontario, Canada.

Déry, S. J., and E. F. Wood, 2005: Characteristics, trends, and atmospheric drivers of Canadian river discharge to high-latitude oceans, American Meteorological Society, Jan. 2005, San Diego, CA, USA.

Déry, S. J., M. Stieglitz, E. McKenna, and E. F. Wood, 2004: Recent changes and trends in freshwater discharge into Hudson, James, and Ungava Bays, American Geophysical Union, May 2004, Montreal, QC, Canada.

Project Report: **Global Warming: The Psychology of Long Term Risk Meeting**

Principal Investigator: Michael Oppenheimer (Princeton)

Other Participating Researchers: 11 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: *The first meeting was held in Princeton on November 12, 2004 to discuss the following objective:* To advance understanding of views of long term risk held by the general public and to apply that understanding to the global warming problem, with an emphasis on findings relevant to risk communication.

Methods and Results/Accomplishments:

The workshop brought together eleven experts in cognitive psychology, social psychology, economics, and public opinion and survey research to present papers on how Americans incorporate information about climate change, and how their views and attitudes compare to those held by Europeans and others. Also discussed was the question of which means of communicating information about climate change are effective and which are not. In a novel feature, the workshop also brought in four climate science experts as discussants to comment on the psychology presentations, leading to lively discussions of long term risk and risk communication. The workshop attracted an audience of about thirty participants, including philosophers, ethicists, and economists, in addition to climate scientists and ecologists. Princeton University participants came from the Departments of Ecology and Evolutionary Biology, Geosciences, and the Atmospheric and Oceanic Sciences Program and also included a half-dozen graduate students from the Science, Technology, and Environmental Policy Program. A number of participants from NOAA's Geophysical Fluid Dynamics Laboratory were also in attendance.

There is a great demand for information about climate change from scientists. Government, media, educational institutions and the general public are some of the audiences that scientists seek to satisfy. But there have been few studies of how information about climate change is absorbed and interpreted by the public, particularly with regard to how the risk of climate change is evaluated by the public. Landmark studies over the past 25 years have revolutionized understanding of the psychology of risk, yet the climate science community has thus far not incorporated these.

Publications:

Proceedings of the workshop will be published as a special issue.

Progress Report: **Development and Evaluation of a High-resolution Non-hydrostatic Model (Zetac) for Simulations of Convection**

Principal Investigator: Olivier Pauluis (Princeton Research Staff, now faculty at New York University)

Other Participating Researchers: Steve Garner, Isidoro Orlanski, Leo Donner, Vaughan Phillips, Charles Seman (GFDL), Chris Kerr (UCAR), Dargan Frierson (Princeton), and Andy Majda (NYU)

Theme #1: Earth System Studies/Climate Research

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

Objectives: Theoretical analysis of the precipitation fronts

Methods and Results/Accomplishments:
In collaboration with Dargan Frierson (Princeton University) and Andy Majda (NYU), I investigated the mathematical behavior resulting from the quasi-equilibrium assumption for convection in the context of an idealized atmospheric model. This lead to a novel theory for what we call precipitation fronts. This theory emphasize that the displacement of precipitation regions in the Earth atmosphere is similar to the propagation of a non-linear hydrodynamic shock. One paper has been published (Frierson, Majda and Pauluis 2004), a second one is being finished (Pauluis, Frierson, and Majda 2005).

Publications:

Olivier M. Pauluis Dargan M.W. Frierson, and Andrew J. Majda, 2005: Propagation, reflection, and transmission of precipitation fronts in the tropical atmosphere. *In preparation.*

Pauluis, O. 2005, and S. Garner: Sensitivity of Radiative convective equilibrium simulations to horizontal resolution. To be published in *J. Atmos. Sci*.

Dargan M.W. Frierson, Andrew J. Majda and Olivier M. Pauluis; 2004: Large Scale Dynamics of Precipitation Fronts in the Tropical Atmosphere: A Novel Relaxation Limit . *Comm. in Math. Sci*., **2**, 591-626.

Progress Report: **Cloud Microphysics and Climate Change**

Principal Investigator: Vaughan Phillips (Princeton Research Staff)

Other Participating Researchers: V. Ramaswamy, L. J. Donner, S. Garner and P. Ginoux (GFDL), Y. Ming (NCAR), S. Reddy (UCAR), A. Khain (Hebrew University)

Theme #1: Earth System Studies/Climate Research

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

Objectives: To understand nucleation processes in cloud-ensembles and to predict cloud radiative properties in a global climate model

Methods and Results/Accomplishments:

V. Phillips has finished prior projects concerning:- (1) comparison of 2D and 3D simulations with a cloud-system resolving model (CSRM) (Phillips and Donner 2005) ; (2) the study of detailed melting in cloud systems (see Khain *et al.* 2004; Phillips *et al.* 2005c) ; and (3) a modeling study of nucleation processes in a cumulonimbus updraft (Phillips *et al.* 2005a) observed in the Cirrus Regional Study of Tropical Anvils and Cirrus Layers-Florida Area Cirrus Experiment (CRYSTAL-FACE). Furthermore, V. Phillips participated in another field campaign, Tropical Cloud Systems and Processes (TCSP), in Costa Rica this summer after he wrote the scientific component of a grant proposal that won a grant from NASA earlier this year. The collaboration for TCSP includes P. Ginoux.

Over the last year, V. Phillips and Y. Ming have been developing a "double-moment" treatment of cloud microphysics for the new deep convection and large-scale cloud parametrisations of the latest version of the GFDL General Circulation Model (GCM). Such a "double-moment" representation includes prediction of particle numbers, in addition to conventional scalars of mass mixing ratio. This involves representing the natural diversity of nucleation pathways for formation of crystals and droplets.

As a test-bed for development of double-moment codes for the GCM cloud schemes, the single-moment microphysics scheme (implemented by Dr V. Phillips in the GFDL CSRM prior to 2004; see Donner and Phillips 2005) has been transformed by Dr V. Phillips into a double-moment microphysics scheme (see Phillips *et al.* 2005b). The decision for Dr V. Phillips to do this was taken by Drs L. Donner and V. Ramaswamy at a meeting in 2004. In a collaboration with Dr S. Garner, an efficient linearised supersaturation algorithm has been innovated by Dr V. Phillips this year for the new double-moment microphysics scheme of the CSRM (see Phillips *et al.* 2005b). This new linearised algorithm has inspired creation of a linearised supersaturation scheme for the deep convection scheme of the GFDL GCM.

Having created a double-moment cloud scheme for the CSRM, Dr V. Phillips has shown how the radiative properties of ice clouds are critically dependent on water-soluble aerosols known as "cloud condensation nuclei (CCN)". Phillips *et al.* (2005b) have extended very recent results, regarding the critical importance for cirrus clouds of homogeneous freezing and of entrainment of mid-tropospheric CCN into convective updrafts, from explicit microphysics simulations of individual storms (Eg. see Phillips *et al.* 2005a; see the study by Heymsfield and colleagues in 2005) to the scale of a cloud ensemble. New results described by Phillips *et al.* (2005b) for a cloud ensemble include the restriction of homogeneous freezing of droplets to updrafts > 1-2 m/s. Moreover, Dr V. Phillips has innovated a module to represent the preferential total evaporation of smaller droplets during homogeneous freezing, utilising an explicit microphysics model (see Phillips *et al.* 2005a). Further ways in which these CSRM double-moment simulations by Dr V. Phillips are informing development of the double-moment GCM cloud schemes include elimination of certain mechanisms for ice nucleation (Eg. contact nucleation) from the list of the most important ones.

A strategy proposed by Dr V. Phillips in weekly meetings of the atmospheric research group, about the necessity for ensuring that any representation of heterogeneous ice nucleation to be implemented in the GFDL GCM must be validated with aircraft observations, is generally being followed.

Publications:

J.-Y. Grandpeix, V. T. J. Phillips, and R. Tailleux "Improved mixing representation in Emanuel's scheme", *Q. J. R. Meteorol. Soc.* , **130,** pp 3207 (2004)

A. Khain, A. Pokrovsky, M. Pinsky, A. Seifert, and V. T. J. Phillips, "Simulation of effects of atmospheric aerosols on deep turbulent convective clouds by using a spectral microphysics mixed-phase cumulus cloud model. Part 1: Model description and possible applications", *J. Atmos. Sci.*, **61**(24), 2963-2982 (2004)

Y. Ming, V. Ramaswamy, L. J. Donner and V. T. J. Phillips, "A robust parametrisation of cloud droplet activation", *J. Atmos. Sci.* In press (2005)

V. T. J. Phillips, S. C. Sherwood, C. Andronache, A. Bansemer, W. C. Conant, P. J. DeMott, R. C. Flagan, A. Heymsfield, H. Jonsson, M. Poellot, T. A. Rissman, J. H. Seinfeld, T. Vanreken, V. Varutbangkul and J. C. Wilson, "Anvil glaciation in a deep cumulus updraft over Florida simulated with an Explicit Microphysics Model. I: The impact of various nucleation processes", *Q. J. R. Meteorol. Soc.*, **131,** 2019-2046 (2005a)

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

Papers for future publication:

Y. Ming, V. Ramaswamy, L. J. Donner, V. T. J. Phillips, S. A. Klein, P. A. Ginoux, and L.H. Horowitz, "Modeling the interactions between aerosols and liquid water cloud with a self-consistent cloud scheme in a general circulation model", submitted to *J. Atmos. Sci.* (2005)

V. T. J. Phillips and L. J. Donner, "Cloud microphysics, radiation and vertical velocities in two- and three-dimensional simulations of deep convection", submitted to *Q. J. R. Meteorol. Soc.* (2005)

V. T. J. Phillips, L. J. Donner and S. Garner, "Nucleation processes in deep convection simulated by a cloud-resolving model with double-moment bulk microphysics and fully interactive radiation", to be submitted to *J. Atmos. Sci.* (2005b)

V. T. J. Phillips, A. Pokrovsky, and A. Khain, "The influence of melting on the dynamics and precipitation production in maritime and continental storm-clouds", submitted to *J. Atmos. Sci.* (2005c)

Progress Report: **Regional Climate Impacts due to the South Asian Haze**

***Principal Investigator**:* S.Ramachandran (Princeton Visiting Research Staff)

Other Participating Researchers: V.Ramaswamy (GFDL)

Theme #1: Earth System Studies/Climate Research

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

Objectives: The objective of the work is to understand the regional and global climate change due to the tropospheric aerosols present over South Asia in the winter monsoon season in terms of changes in precipitation, surface temperatures, atmospheric temperature and dynamic response.

Methods and Results/Accomplishments:

The study has been undertaken by implementing the aerosol heating rates into the Global Atmospheric Model in GFDL, Princeton. A regional distribution of the heating perturbation computed from the observed aerosol optical depths, aerosol composition and cloud distribution has been imposed in the new atmospheric model. The forcing used in the study is based on a synthesis of observations, is more realistic when compared with several other model studies performed to estimate the global effects of aerosols, and takes into account the absorbing aerosols.

A vertical distribution of heating rates has been prescribed in the model between the surface and the 3-km altitude. The heating rate perturbation has been applied with a diurnal cycle in the model. The forcing is applied every winter season repeatedly during the model integration and several ensemble runs have been performed to obtain statistically significant results. The changes in precipitation and surface temperatures due to the prescribed haze are obtained by comparing the model response with several years of control integration performed with no haze aerosols. It has been found that the ratio R of the haze forcing at the surface to the forcing within the atmosphere is found to vary from -0.5 (overcast conditions) to -1.5 (clear skies) over the Indian Ocean region.

Preliminary model simulations have been conducted after implementing the heating rates in the atmospheric model. The forcing at the surface and the column integrated atmospheric forcing have been computed over the South Asian and Indian Ocean regions, and are found to compare well with the observed forcings. Long term model simulations with R = -1.5, -1.0, -0.5, in which the net surface solar flux reduction is prescribed to be 1.5, 1, 0.5 times as large as the imposed atmospheric heating and prescribed seasonal cycle of sea surface temperatures have been completed. We are currently investigating in detail the regional climate impacts due to the haze aerosols.

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

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

Other Participating Researchers: Princeton Advisor: V. Ramaswamy , Committee Members: Lynn M. Russell (Scripps Institute of Oceanography), Paul Ginoux and Hiram Levy (GFDL), Collaborator: Omar Torres (Goddard Space Flight Center).

Theme #1: Earth System Studies/Climate Research

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

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

Methods and Results/Accomplishments:

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

With the previous work culminating in a publication (see below), Randles is now examining the climatic effects of black carbon (BC) over Asia. In this study, she is employing the Geophysical Fluid Dynamic Laboratory's atmospheric Global Climate Model (GCM) AM2 to examine the impact of increased BC (and thus increased absorption) over China and India. In this study, AM2 is being run with fixed sea-surface temperatures (SSTs) and greenhouse gasses (GHGs) so that only the impact of aerosol changes is considered. The purpose is to understand how the model response, particularly surface temperature, clouds, and the hydrologic cycle, is altered with changes in the heating rate of different atmospheric layers. She is currently investigating changes in radiative forcing resulting from increasing the single scattering albedo throughout the atmospheric column and layer-by-layer over China.

Randles is also looking at the effects of biomass burning OC and BC over Southern Africa. Of particular interest will be the sensitivity of radiative forcing and climate response to the vertical profile of the aerosol and to the mixing state of the biomass burning aerosol. The parameter space for these sensitivity studies can be limited by employing measured data. In particular, Randles will use ground-based remote sensing (AERONET) and satellite (TOMS) measurements to constrain the range of optical depths and single scattering albedo considered.

Publications:

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

Progress Report: **Atlantic Storm-track Variability and its Relation with the North Atlantic Oscillation**

Principal Investigator: Gwendal Rivière (Princeton Research Associate)

Other Participating Researchers: Isidoro Orlanski (GFDL)

Theme #1: Earth System Studies/ Climate Research

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

Objectives: To understand the mechanism of the North Atlantic Oscillation

Methods and Results/ Accomplishments:

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

The first objective, using NCEP reanalysis dataset was to confirm (following the recent results of Orlanski, 2003 and Benedict et al. 2004) that the jet displacement characteristic of the NAO phenomenon depends strongly on the dynamics of the high frequency synoptic-scale waves and the way they break. Positive and negative phases of the NAO are indeed closely related to respectively anticyclonic and cyclonic wave breaking. Diagnostics based on high-frequency momentum fluxes have been found to be a proper manner to quantify wave breaking and its relation with NAO (see figure for the large difference of wave breaking over the Atlantic for positive and negative NAO phases). The next step was to investigate the properties that make the wave break cyclonically or anticyclonically. It is shown that wave breaking over the Atlantic is strongly sensitive to the spatial length scale of the waves coming from Eastern Pacific and North America as well as the quantity of humidity over the Gulf of Mexico and the Carribean region.

The goal of the numerical simulations made with the high resolution ZETAC simulations is the following; first to reproduce a similar behavior to that previously shown in reanalysis data and secondly to explain it by performing a number of sensitivity runs by modifying different parameters. December 1987 and January 1988 are two consecutive months particularly interesting to study since they correspond to negative and positive phases of the NAO. We successfully reproduced the behavior of these two months with the regional ZETAC model by forcing it with real SST and a western boundary condition corresponding to the reanalysis data over the Eastern Pacific. Sensitivity runs prove that the difference between the two months is not due to SST but rather to the western boundary condition showing that the properties of the waves coming from the Pacific are crucial to determine the North Atlantic Oscillation. These results can lead to the identification of precursors of the different NAO phases and are thus especially important for predictability issues related to the climate in the Atlantic sector. It also can help to improve GCMs simulation of the atmospheric low-frequency variability.

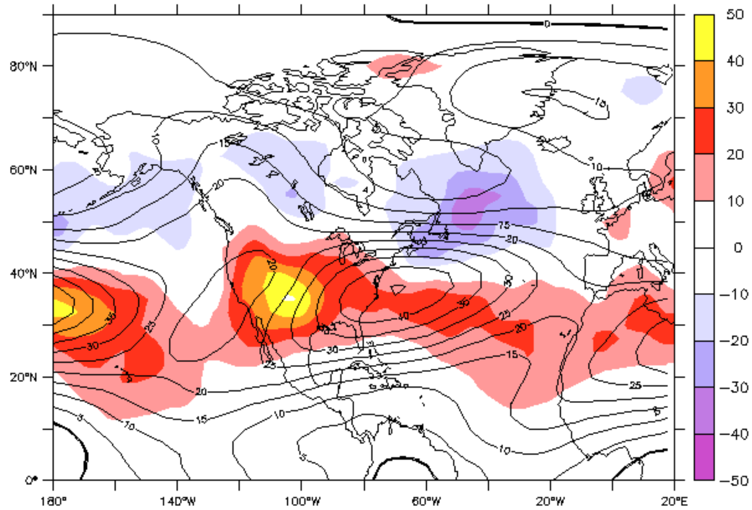
References:

I. Orlanski, 2003: Bifurcation in Eddy Life Cycles: Implications for Storm Track Variability. Journal of Atmospheric Sciences, 60, 993-1022.

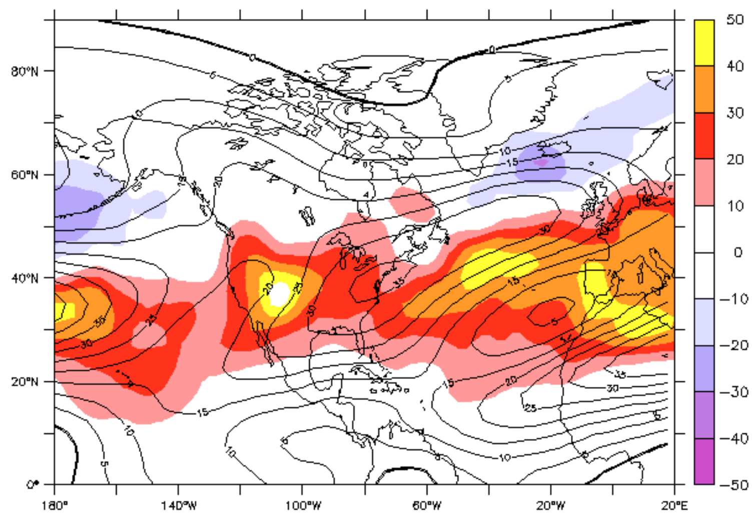
J. J. Benedict, S. Lee, S. B. Feldstein, 2004: Synoptic View of the North Atlantic Oscillation. Journal of Atmospheric Sciences, 61, 121-144.

Publications:

Our future work will consist of presenting the above results in papers to be submitted for publication.



(a)



(b)

Figure: (a) Negative and (b) positive phases of the NAO. Black and color contours correspond respectively to the zonal wind and the meridional high-frequency momentum fluxes. Positive (negative) fluxes are associated with anticyclonic (cyclonic) wave breaking. Positive NAO occur more with positive fluxes and negative NAO more with negative fluxes.

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

Principal Investigator: Ignacio Rodriguez-Iturbe (Princeton Faculty)

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

Theme #1: Earth System Studies/Climate Research

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

Objectives: To develop a theoretical framework for the modeling of the space time variability of soil moisture.This framework should account for the stochastic spatio-temporal structure of rainfall as well as for the random spatial nature of vegetation. Specifically, the objective is to derive the space-time correlation structure of soil moisture and from there obtain the sampling requirements to estimate the averaged soil moisture content - in space and/or in space and time -with a prescribed statistical variance of estimation.

Methods and Results/Accomplishments:

A simplified spatial-temporal soil moisture model driven by stochastic space-time rainfall forcing was developed.The model is mathematically tractable,and allows the spatial and temporal structure of soil moisture fields,induced by the spatial-temporal variability of rainfall and the spatial variability of vegetation to be explored analytically.The influence of the main model parameters ,reflecting the spatial scale of rain cells and their temporal rate of occurence,the soil storage capacity,the rainfall interception,the vegetation characteristics controlling evapotranspiration,and the spatial vegetation pattern have been studied in detail.

The space-time statistical structure of soil moisture is characterized by its covariance function which depends in the above parameters.The model allows for heterogeneous vegetation in the region.Importantly,the statistical properties of the soil moisture process averaged in space and time have also been analytically derived.

The above results have then been used to derive the sampling requirements to estimate with a prescribed statistical precision the average soil moisture over a give time interval (e.g.,daily) and over a given area.

Publications:

Representation of Space-Time Variability of Soil Moisture,by V.Isham,D.R.Cox,I.Rodriguez-Iturbe,A.Porporato and S.Manfreda. Submitted for publication to Proceedings of the Royal Society,Series A (mathematics and physics).June 2005.

Space-Time Modeling of Soil Moisture:Stochastic Rainfall Forcing with Heterogeneous Vegetation,by I.Rodriguez-Iturbe,V.Isham.D.R.Cox,S.Manfreda,A.Porporato.Submited for publication to Water Resources Research,August 2005.

Design of Soil Moisture Sampling Networks in Space and Time,by S.Manfreda and I.Rodriguez-Iturbe.In preparation,to be submitted to Water Resources Research,September 2005.

Progress Report: **Southern Hemisphere Westerly Winds: Keeping the Door Open to the Deep Ocean**

Principal Investigator: Joellen L. Russell (Princeton Research Staff)

Other Participating Researchers: Advisor: J.R. Toggweiler (GFDL), Anand Gnanadesikan (GFDL), Ronald Stouffer (GFDL), Keith W. Dixon (GFDL)

Theme #1: Earth System Studies/Climate Research
Theme #2: Biogeochemistry

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

Objectives: To forecast the impact of the poleward intensification of the Southern Westerlies on global climate.

Methods and Results/Accomplishments:

In two coupled models recently developed at GFDL, the position of the Southern Hemisphere extra-tropical westerly jet differs substantially under 1990 radiative forcing. Russell exploited the differences in the position of the zero wind stress curl and changes in the position and magnitude of the divergence-driven upwelling of deep waters in the Southern Ocean between GFDL's CM2.0 and CM2.1 coupled climate models under the SresA1B warming scenario to identify the future impact of changes in the Southern Hemisphere westerlies. Russell demonstrated that a coupled climate model with poleward-intensified westerly winds forecasts significantly higher uptake of heat and anthropogenic carbon dioxide by the Southern Ocean in the future when compared to the uptake in a model with weaker, equatorward-shifted westerlies. This difference in the inferred uptake of heat and anthropogenic carbon dioxide results from the larger outcrop area of the dense waters around Antarctica and more vigorous convection, which remains robust even as warming and freshening reduce the density of surface waters in the Southern Ocean. These results imply that if the current trend in the Southern Annual Mode continues the impact of warming on the stratification of the global ocean on the ocean heat and carbon uptake may be reduced by the poleward shift of the Westerly Winds, allowing the ocean to remove additional heat and anthropogenic carbon dioxide from the atmosphere.

Other analysis by Russell focuses on the Southern Ocean as simulated in a set of global coupled climate model control experiments conducted by international climate modeling groups. Factors such as the Southern Ocean's wind forcing, heat and salt budgets are linked to the structure and transport of the Antarctic Circumpolar Current and explored here in a coupled model context by analyzing 18 of pre-industrial control experiments associated with the forthcoming Intergovernmental Panel on Climate Change's 4th Assessment Report. A framework was developed that uses measures of coupled model simulation characteristics, primarily those related to the Southern Ocean wind forcing and water mass properties, to allow one to categorize and to some extent predict, which models do better or worse at simulating the Southern Ocean and why.

Publications:

Russell, J.L., & J.M. Wallace (2004), Annual carbon dioxide drawdown and the Northern Annular Mode, Global Biogeochem. Cycles, 18, GB1012, doi:10.1029/2003GB002044.

Delworth, T.L., et al., GFDL's CM2 Global Coupled Climate Models-Part 1: Formulation and Simulation Characteristics. J. Climate, in press.

Russell, J.L., R.J. Stouffer & K. Dixon, Intercomparison of the Southern Ocean Circulations in the IPCC Coupled Model Control Simulations. J. Climate, accepted.

Russell, J.L., & J.M. Wallace, On the Nature and Causes of Year-to-Year Variability in the Carbon Cycle. Global Biogeochem. Cycles, accepted.

Toggweiler, J.R., J.L. Russell & S.R. Carson, The Mid-Latitude Westerlies, Atmospheric CO2, and Climate Change during the Ice Ages, Paleoceanography, accepted.

Gnanadesikan et al. GFDL's CM2 global coupled climate models - Part 2: The baseline ocean simulation, J. Climate, accepted.

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

Principal Investigator: Hatim Sharif (Princeton Research staff); Rafal Wojcik (Princeton Research staff)

Other Participating Researchers: Princeton Advisor Eric F. Wood; Elena Shevalikova and Sergey Malyshev (Princeton), Chris Milly (USGS), Chris Kerr (UCAR)

Theme #1: Earth System Studies/Climate Research

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

Objectives: The long term objective of the research is to improve the sub-grid parameterization of LM2 and LM3 land surface parameterizations so as to improve the performance of LM2/AM2 climate model.

Methods and Results/Accomplishments:

The work consisted of a number of tasks that included: (1) to understand and identify the influence of physiographic and climatic controls on spatial variability of terrestrial hydrologic fluxes and states, and the scales at which they are most dominant, including examining the spatial scaling properties of soil moisture. A particular interest is in large scale topography (mountains), which is not well resolved at AM2/LM2-grid scales, and the orographic effect on precipitation and snow cover; (ii) to develop a statistical sub- grid parameterization approach to account for these controls at spatial scales that are appropriate for AM2/LM2; (iii) implement the parameterization scheme in the GFDL land surface model and evaluate its performance in off-line and coupled mode.

1) Understanding physiographic and climatic controls on spatial and temporal variability. To obtain scientific understanding, a high quality, high resolution data set of terrestrial hydrologic states and fluxes is needed. Thus one aspect of the work used a 51-year simulation of water and energy fluxes over the entire 560,000 sq. km Arkansas/Red basin was performed using the fully distributed TOPLATS land surface model run at 1-km, 1-hour resolution. The simulations were performed at this fine temporal (hourly) and spatial (1 km^2) resolutions in an effort to bridge the gap between scales were hydrologic processes can vary due to non-linear effects and the coarser scales of climate models. The modeled range of scales allows for scaling analyses unavailable if the land surface models are run at only coarse scales. Forcing data (precipitation, incoming radiation and surface meteorology) were interpolated from meteorological and rain gauge observations. For this study an archive of various forcing data for 314 sub-basins at 1 x 1 km spatial and hourly temporal resolution spanning the period 1949-2000 was assembled. This archive is available for interested researchers. Analysis of the simulations showed that the spatial patterns of temporally averaged water balance components are similar to published climatological patterns and clearly illustrate the strong east-west gradients of precipitation, runoff, and ET. Streamflow validation at the sub-basin scale showed good agreement betweens simulated and observed streamflow for several unregulated watersheds within the Arkansas/Red River system. Analysis of the spatial distribution of precipitation and runoff highlights the similarities and differences between the two. A notable difference is that surface runoff did not show a distinct shift of the east-west gradient during the summer months observed for precipitation.

The preliminary validation results give us confidence with the quality of the soil moisture and surface and latent heat fluxes simulations, which can be used as 'high resolution truth' for comparisons with LM2 simulations. The soil moisture fields are being used for scaling studies by Dr. Salvatore Manfreda under a related CICS Scaling of Space, Time, Heterogeneous Hydrologic Dynamics project supervised by I. Rodriguez-Iturbe.

2) Develoingp a statistical sub- grid parameterization approach to account for these controls at spatial scales that are appropriate for AM2/LM2. Following meetings at GFDL with Drs. Chris Milly, Sergey Malyshev and Christopher Kerr) a experimental plan was developed that will utilize high resolution (1-

km resolution from the above data set for the Red-Arkansas basin to a 1/8th degree CONUS NLDAS land hydrology data set) to run a series of experiments with LM2 land surface model on a transect across the United States that encompasses a range of climate and terrain. The developed plan suggested a strip 2-degrees in latitude wide across the U.S., running through the Red-Arkansas basin, where there is access to ultra-high resolution land surface simulations at 1-km. To get an insight into scaling behavior of energy fluxes and their sensitivity to particular set of physiographic/climatic controls the plan proposes two types of simulations to be performed:

"control run a" simulations in which LM2 will be forced off- line with the high resolution NLDAS data. Its output will be aggregated to a variety of spatial scales up to 2-degrees. These up-scaled outputs will be then used as a benchmark for assessing the performance of sub- grid parameterization scheme(s).
an ensemble of "dual runs" in which the inputs will be aggregated to the same spatial scales as outputs from the control run. This will identify the magnitude and scale dependence of the errors in aggregation.
"control run b" simulations in which a current ("LM2 potential") sub-grid parameterizations is implemented to evaluate the impact of specific sub- grid parameterizations may have on AM2/LM2 performance (at AM2/LM2 grid-scales.)

The idea of the above twin- like experiment is to evaluate and develop schemes for sub-grid representation for terrestrial hydrologic processes related to mountains, sub-grid precipitation and snow cover. The efficiency criterion for this scheme is to reproduce the scaling characteristics of the energy fluxes in control run a as close as possible. At this time we are waiting on Dr. S. Malyshev to complete the off-line LM2 runs.

Publications:

Sharif, H. O., W. T. Crow, N. L. Miller, and E. F. Wood, “Multi-decadal High-resolution Land Surface Modeling Study in the Southern Great Plains”, to be submitted to *J. of Hydrometeorology*, 2005

Two more manuscripts are under preparation

Progress Report: **Performance on Real-World Applications on Large Parallel Machines**

Principal Investigator: Jaswinder P. Singh (Princeton Faculty)

Other Participating Researchers: Limin Jia (Princeton graduate student)

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: Our goal is to improve the performance on real-world applications on large parallel machines, especially with respect to applications in climate modeling. We propose to use is the large-scale cluster of shared-address-space multiprocessors at GFDL, which allows us to experiment not only with large-scale applications and systems and with different programming models, from a hardware-supported shared address space to software-supported message passing with different performance characteristics, to intermediate and hybrid models..

Methods and Results/Accomplishments:

Specific research includes understanding how to scale the performance of the GFDL ocean codes up to the range of 256 processors. We continue to understand and improve the performance of this application, especially trying to uncover programming/algorithmic methodologies that extend to other applications as well. We incorporate some of the initial techniques found into other parts of the application, as appropriate, to improve its overall performance. So far, we have not dealt with input-output or computational and memory issues, focusing mostly on communication. We expect to examine these issues as well, and develop ways to improve them. We will examine input/output and methods to restructure it both in a single-application-performance as well as in terms of impact on the rest of the system and hence on throughput. The key deliverables here will be a version of the application that achieves 25-50% better performance than the original, together with a set of programming and algorithmic guidelines for how that improvement is obtained. We expect that the performance improvement will be greater at larger scale, and will come in part from computational/communication/memory behavior and in part from input/output behavior.

Thus far we have developed a new, flexible timing tool that allows users to much better understand performance bottlenecks that are very difficult to uncover otherwise. We continue to develop this tool, as well as develop other tools that allow easy performance debugging from perspectives that we determine to be valuable, and deliver these to users at GFDL for incorporation in their applications. While the longer-term goal here is to understand how best to structure programs and application-specific parallel libraries to greatly improve performance on different types of architectures and programming models, a near-term deliverable is a specific set of programming techniques and guidelines that we use to achieve the performance improvements on this application.

Once done with this first application, we will also extend similar work to other applications at GFDL. Alternatively, depending on time available and the needs of the lab, we will explore the tradeoffs in using different programming models that the underlying GFDL LSC system supports for this application (specifically, a shared address space, message passing, and SHMEM), and we will explore the use of hybrid programming models within the same application (and even within the same node of the LSC) to achieve even higher performance and scalability, attempting to find a good compromise between ease of programming and performance. Given the existence of a machine that has a fundamentally hybrid structure (a cluster of SGI Origins) and that supports multiple programming models, the results of this work and the extensibility of the methods should be of great relevance to the lab. The results will also speak to the performance portability of the applications, written in different programming models, to other types of systems than a cluster of SGI Origins.

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

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

Other Participating Researchers: Stephen Garner (Princeton), Isaac Held (GFDL), Olivier Pauluis (NYU)

Theme #1: Earth System Studies/Climate Research

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

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

Methods and Results/Accomplishments:

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

Smith-Mrowiec began her PhD study two years ago, and has been working with Garner and Pauluis to investigate what sets the RMW. This is an ongoing project. The first stage of this investigation involved the use of an axisymmetric, nonhydrostatic hurricane model (ZETAC). The model uses the GFDL radiation package and Lin microphysics and convection is fully resolved. The resolution of the model for the preliminary study was 2.5 km and the domain size was 500 km. Initial simulations were made for 15 days of hurricane life, with the objective of generating a steady state and investigating how the RMW depends on model parameters. The preliminary study revealed, however, that even generating a steady state was very challenging. Figure 1 shows the tangential wind evolution in the preliminary simulation.

Before investigating the RMW directly with this model, other more basic studies must be performed. We are investigating the effects of larger domain size and higher resolution. At the present we are simulating pure radiative-convective equilibria for the model atmosphere in an attempt to generate a set of self-consistent atmospheric states for each sea surface temperature we want to use. These states are going to be used in the RMW experiments as reference atmospheric profiles. All of the changes should improve the stability of the resulting hurricanes. Figure 2, for example, shows the positive effect of a larger domain size on the stability of the vortex. We have set up the model to run in both 2D and 3D. 3D is interesting because convective dynamics is altered and also the azimuthal wave instability can be observed.

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

References:

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

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

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

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

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

Fig.1

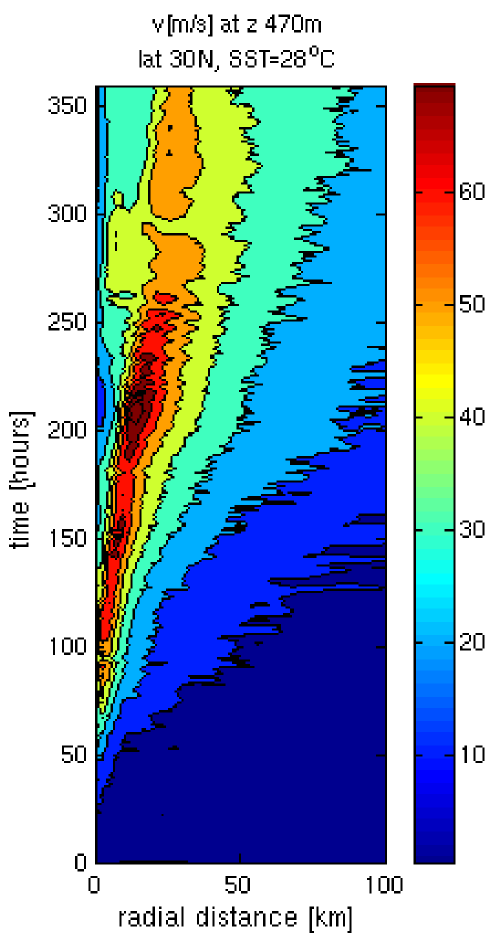
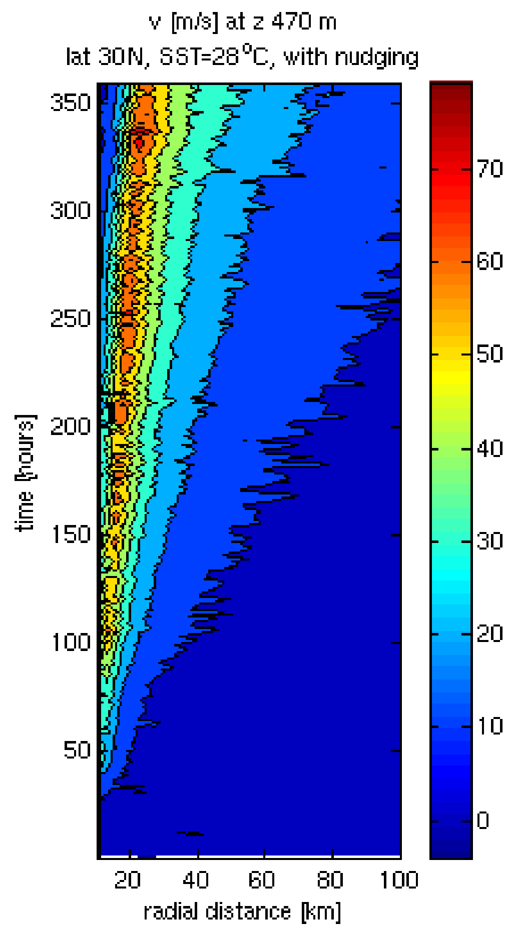


Fig.2



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

Principal Investigator: Qian Song (Princeton Research Associate)

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

Theme #1: Earth System Studies/Climate Research

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

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

Methods and Results/Accomplishments:

Song has been making use of the GFDL coupled climate model to investigate the dynamics of the Indian Ocean variability. As a first step, we analyze the simulation of the so-called Indian Ocean Dipole (IOD) in the CM2.1 1990-control run[1]. A composite of the IOD events during the 300-year simulation reveals that the eastward shift of the deep convection in early boreal spring is a precursor for IOD events in the model. Although the co-occurrence of IOD and El Nino events are often, it is not always. Explaining the absence of IOD events during El Nino years can be a key to understand the Indian-Pacific relationship. In this respect, we propose that tropical storms occurring during boreal summer in the Eastern Tropical Indian Ocean and the inappropriate timing of the evolution of some El Nino events may prevent the development of IOD events when El Nino occurs in the Pacific.

By performing a perturbation experiment where the Indonesian Throughflow (ITF) is blocked in using the CM2.1 model, we explore the effects of the ITF on the variability of the Indo-Pacific basin. Preliminary results show that the closure of the ITF causes significant changes in both magnitude and time scale of the variabilities in both the Indian Ocean (i.e. IOD events) and the Pacific Ocean (i.e. ENSO). Physical mechanisms responsible for these changes arising from the blocking of the ITF are under investigation.

In order to further explore the relation between the Indian and Pacific oceans, we conduct two perturbation experiments in the CM2.1 coupled model where either the Indian Ocean sea surface temperature (SST) or the Pacific Ocean SST are restored to climatology. Those two experiments, when compared to the control experiment (i.e. CM2.1 1990-control), could shed light on how ENSO affects the Indian Ocean variability and how the Indian Ocean influences ENSO evolution.

Publications:

Song, Q., G. A. Vecchi and A. Rosati: Indian Ocean variability in the GFDL coupled climate model. (submitted to Journal of climate).

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

Principal Investigator: Eli Tziperman (Harvard Professor)

Other Participating Researchers: Jake Gebbie (Harvard), Anthony Rosati, Matthew Harrison and Andrew Wittenberg (GFDL), Shaoqing Zhang (UCAR), Benny Cheng and Tony Lee (JPL)

Theme #1: Earth System Studies/Climate Research

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

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

Methods and Results/Accomplishments:

Significant progress was achieved during the past year since we started the project. Geoffrey (Jake) Gebbie has coordinated the effort of all three institutions, as well as carried out the bulk of the work at Harvard on this project. Jake also coordinated with Ralf Giering the significant work that was required to improve the adjoint compiler to make it compatible with the adjoint development. We have been in close contact with the GFDL scientists involved in this project (Tony Rosati, Matt Harrison, Andrew Wittenberg and Shaoqing Zhang) and with the JPL scientists. Together we devised a plan for dividing the work into three main parts:

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

These three different parts of the work will be carried out by GFDL, Harvard, and JPL, correspondingly. Some of the work on these stages was carried out in parallel. Stage (1) at GFDL is close to being completed (still need to do this for the momentum equations). Good progress was achieved on (2) at Harvard. At this stage the adjoint for the tracer equations, a partial adjoint for the momentum equations

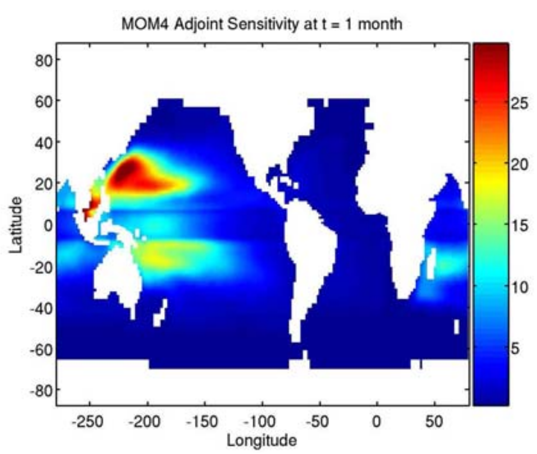


Figure 1: Adjoint-calculated sensitivity results from the MOM4 parallelized (16-pe), adjoint advection-diffusion model over a one-month integration. The sensitivity is defined as the gradient of a scalar cost function with respect to the SST one month earlier. In this case, the scalar cost function is the global sum of temperature over all grid boxes at the end of one month. The sensitivity field has the units of [degrees C/degree C]. The adjoint code has been developed for use with the tripolar grid, telescoping horizontal resolution in the tropics, and a 16-processor decomposed domain for parallel computations (the adjoint code now allows for any number of processors).

The adjoint is derived using the TAF adjoint compiler; some of work of dealing with "recomputation" and "storage" directives was done, and some more is still ahead of us. This involved adding comments to the MOM4 code that will be interpreted by the adjoint compiler to store a forward model variable in order to use it in the adjoint run.

We plan to have all work done so far merged from the CVS built for the adjoint project into the general MOM4 CVS code within the next few weeks for easy access and use by the wider community. After quite a bit of work, we now use the global tri-polar grid model with all state-of-the-art mixing parameterizations. The adjoint will be of this MOM4 configuration coupled to a statistical atmospheric model which will be appropriate for ENSO studies Harrison et al. (2002).

We have been meeting Tony, Matt, Andrew and Shaoqing regularly, and we plan a meeting in GFDL this fall of all participants to refine our future plans.

We are all optimistic that these efforts will lead to a working adjoint model for GFDL's MOM4, and later to a working data 4dvar assimilation system based on the adjoint method. We are looking forward to the eventual application, on a time scale of 2-3 years, of the developed assimilation system to the ENSO prediction problem using a full-fledged MOM4 version at a 1 degree resolution (and a higher resolution near the tropics).

We have been involved with the work on the MOM adjoint for some 8 years now, beginning with the development by Eli Galanti of an adjoint of an early MOM4 version. At this stage we are completing a manuscript using the hybrid coupled forward model to be adjointed to study the role of westerly wind bursts (Gebbie et al., 2005), and we anticipate being able to use the adjoint code itself for a scientific sensitivity study within the next year of the project. With the current level of commitment from the involved GFDL scientists, with the support of the MOM4 developers, and given our strong collaboration, we are confident that we should be able to achieve our fairly ambitious goals in this project.

References:

Gebbie, G., Eisenman, I., Wittenberg, A., and Tziperman, E. (2005). Modulation of westerly wind burst occurrence by warm pool sst as an intrinsic part of enso's dynamics. *in prep*, :.

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

Progress Report: **Oceanic and Atmospheric Dynamics**

Principal Investigator: Geoffrey Vallis (Princeton Faculty)

Other Participating Researchers: Rong Zhang and Ed Gerber (Princeton), Cara Henning (UCB), Jolene Loving (UCSC), Bill Dewar (FSU), Roger Samelson (OSU)

***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 large-scale circulation of the atmosphere and ocean, and the associated climate variability.

Methods and Results/Accomplishments:

Vallis continues research in a variety of topics in large-scale oceanic and atmospheric circulation, using a combination of theoretical arguments and numerical modeling. Recent accomplishments include:

- The development of a theory of *mode water*. Mode water is a mass of water of a particular type that is commonly found at the polewards edge of subtropical gyres. In collaboration with colleagues at Florida State University and Oregon State University a theory has been proposed for this that is formally a simple extension of ventilated thermocline theory.
- Progress in understanding the role of mesoscale eddies in the ocean circulation. In particular, it was shown that eddies likely affect the Southern Ocean at first order, but have a smaller impact on the subtropical gyres.
- Progress in understanding the North Atlantic Oscillation, a major source of climate variability on the timescale of weeks and months in the North Atlantic. It was shown how the variability of the North Atlantic Storm track is intimately tied to the variability of the NAO.
- The development of a hypothesis for the nature of the underlying climate variability on the millennial timescale of glacial climates, and the relative stability of the Holocene. Numerical model results suggest that the growth of sea ice in cold climates will lead to a weakening of the oceanic meridional circulation. This weakened circulation is unstable, leading to so-called Dansgaard-Oeschger cycles.
- A demonstration that *Great Salinity Anomalies* can have a significant effect on the climate variability of the Atlantic on the decadal timescale.

Current work includes the development of a new parameterization of mesoscale eddies in ocean climate models as part of the joint NSF/NOAA initiative called 'Climate Process Teams.', and, on a longer term basis, the testing of theories of the oceanic general circulation with models and the growing amount of data that is becoming available, from satellites, floats, and in situ measurements.

Publications:

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

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

Henning, C and Vallis, G. K. 2005. The effect of mesoscale eddies on the main subtropical thermocline. *J. Phys. Oceanogr.,* 34, 2428–2443.

Gerber, E. P. and Vallis, G. K. 2005. A stochastic model of the spatial structure of the annular patterns of variability and the NAO. *J. Climate,* 18, 2102–2118.

Cash, B., P. Kushner and G. K. Vallis. 2005. Zonal asymmetries, teleconnections and annular modes in a GCM. *J. Atmos. Sci.,* 62, 207–219.

Loving, J. and Vallis, G. K. Mechanisms for climate variability during glacial and inter- glacial periods. *Paleoceanography,* (in press).

Anadadesikan, A, Swathi, P, Slater, R. S. and Vallis, G. K. 2005. Energetics of large-scale ocean circulation. *J. Climate.* (in press).

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

Progress Report: **Management of Tropospheric Ozone by Reducing Methane Missions: Global Health Benefits**

Principal Investigator: J. Jason West (Princeton Research Staff)

Other Participating Researchers: Arlene Fiore (GFDL), Larry Horowitz (GFDL), and Denise Mauzerall (Princeton, Woodrow Wilson School).

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 methane emissions on radiative forcing of climate and on global surface ozone air quality, and quantify the impacts of changes in ozone due to mitigation of methane emissions

***Methods and Results/Aaccomplishments*:**

We have used the MOZART-2 model of atmospheric chemistry-transport to study the effects of changes in methane emissions on global concentrations of ozone. We consider a 20% reduction in current global anthropogenic methane emissions, relative to the projected 2030 baseline (using emissions from the IPCC SRES A2 scenario). We find that the 20% emission reduction would decrease 8-hr. surface ozone in populated regions by ~1 ppbv, which agrees well with other recently published results. The change in ozone is fairly uniform globally, but is largest in polluted temperate regions of the Northern Hemisphere.

We are interested in whether methane mitigation can be justified for ozone air quality purposes. Our first (published) analysis of this problem found that the potential for reducing ozone using methane abatement measures that have already been identified as cost-saving can reduce ozone globally by ~0.5 ppb, which is not negligible. An analysis of the benefits of ozone reductions suggest that substantial methane reductions can be justified for air quality purposes.

We then estimate the global health benefits of reduced ozone, resulting from the methane control scenario discussed earlier. We use the epidemiological relationship between ozone and premature mortality to estimate the reduced incidences of premature human mortality attributed to the reduction in ozone, and find that the global mortality benefits are substantial. This work highlights methane emission mitigation as a cost-effective means of managing air quality globally, while reducing greenhouse forcing.

Related to this work, I contributed to a review article on transboundary air pollution and international air pollution management.

***Publications*:**

West, J. J., and A. M. Fiore (2005) Management of tropospheric ozone by reducing methane emissions, *Environmental Science & Technology*, 39(13): 4685-4691, doi: 10.1021/es048629f.

West, J. J., A. M. Fiore, L. W. Horowitz, and D. L. Mauzerall (submitted) Mitigating ozone pollution with methane emission controls: global health benefits.

Bergin, M., J. J. West, T. J. Keating, and A. G. Russell (in press) Regional atmospheric pollution and transboundary air quality management, *Annual Review of Environment and Resources*.

Progress Report: **A Hydrologic Ensemble Seasonal Forecast System Over the Eastern U.S.**

Principal Investigator: Eric F. Wood (Princeton Faculty)

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

Objectives: The primary goal of this research project is to understand the predictability of the terrestrial hydrologic cycle at seasonal time scales and to develop methodologies that facilitate the development and testing operational seasonal hydrologic forecasts over the Eastern U.S.

Methods and Results/Accomplishments:

The major research activities in the first year of the project can be summarized as the following:

1) Develop the methodology for producing seasonal hydrologic forecasting
2) Construct a VIC-base seasonal hydrologic ensemble forecast system
3) Identify regions to carry out the experimental forecasting
4) Make experimental forecasts and hindcasts over the selected regions, and evaluate the performance of the system
5) Monitor the U.S. drought in realtime

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

Although the seasonal climate model forecasts are not very skillful, they still provide useful information. Thus what is needed is a better method to extract more fully the useful information from the climate model forecasts. During the last year we developed a Bayesian approach for merging multiple seasonal climate model forecasts to produce a more reliable and skillful seasonal forecast, following on and expanding the work of super-ensemble forecasts. In our Bayesian framework, the climatological distribution is selected as the prior distribution, which reflects our best estimate of the possible outcome, both in its mean and variability, in the absence of any seasonal climate model forecast. The climate model forecasts are used to update the prior distribution through a likelihood function. Each climate model is evaluated by comparing its hindcasts against observations; hence a proper weight can be assigned to each model based on its past performance (i.e. skill). A likelihood function is built based the current forecast and past forecast performance. From this and the prior distribution, a posterior probability distribution is calculated and used to estimate monthly precipitation (and temperature) and its uncertainty. In principle, climate models that are lack precipitation (temperature) forecast skill will contribute less to the posterior distribution. Therefore, such an approach is expected to extract useful information from each model/data sources that will result in our best estimate. This approach was initially tested with sea surface temperature (SST) seasonal forecast from ECMWF DEMETER project, in which each of the seven climate models produce a 9-member ensemble forecast with lead time up to 6 months. Figure 1 illustrates how the posterior (multi-model posterior) is better than the climatology and the original model forecasts. The merged forecast shows the smallest root mean square (RMS) error in comparison to the climatological forecast and the original model forecasts (see Figure 2).

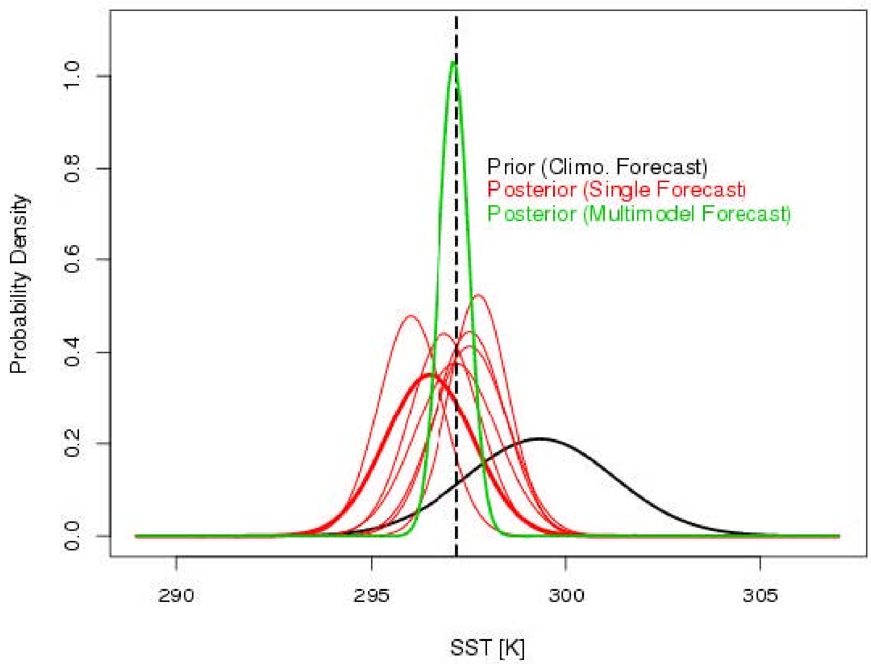


Figure 1: The prior distribution (solid black), single model posterior forecasts (red) and the multi-model posterior forecast (green) for a forecast of SST of 1 grid box over the Nino 3.4 region. The ECMWF DEMETER forecasts are used here. The vertical dashed line indicates the actual observation for that forecast.

A VIC-based seasonal hydrological ensemble forecast system has been developed. The system consists of four building blocks as illustrated by Figure 3. The Bayesian merging approach is one of the central elements in processing the atmospheric ensemble forcing. In our system, the ensemble forecast from NCEP Climate Forecast System (CFS) are merged with observed climatology to produce a posterior distribution of monthly precipitation and air temperature at a 1/8th-degree spatial scale during the forecast period. The merging effectively takes care of bias correction and spatial downscaling at the same time as when the likelihood function is computed. The downscaled atmospheric forcing is then used to drive the VIC model to produce ensemble forecasts of soil moisture and streamflow. Using the computed posterior distribution, allows us to generate as many ensembles as desired for forcing the VIC hydrologic model.

The forecast has been implemented over the Southeastern U.S., and we now routinely produce seasonal forecasts with lead-times up to 9 months. In the retrospective mode, the forecast system

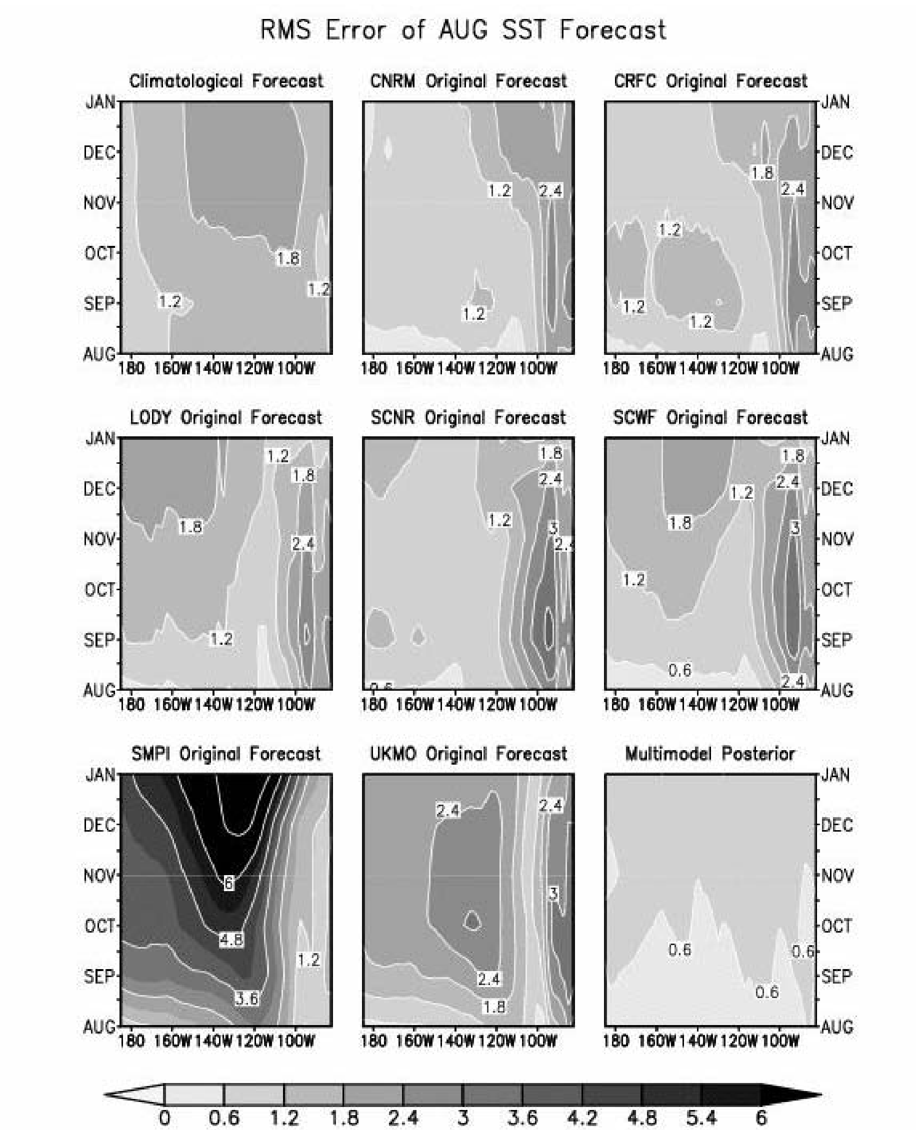


Figure 2: The variation of RMS error with lead time and location from difference forecasts: climatological forecast, original forecast from seven DEMETER climate models, and the posterior forecast using the seven model forecast and the climatological forecast. This is for all the forecasts starting from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

takes seasonal forecast from CFS and seven ECMWF DEMETER climate models and produces a multi-model posterior forecast before driving the VIC hydrological model. The retrospective period covers the last 20 years and will be used to evaluate the performance of the forecast system. Figure 4 shows an example of the downscaled precipitation forcing from the posterior forecast and compared with observations. The CFS-based forecast and multi-model forecast resemble the anomaly patterns of the observed precipitation, which is shown at the 3-month lead-time. Figure 5 shows the streamflow forecast from one selected USGS gage. The shaded background area is the climatological distribution of the monthly streamflow at this gauge. The actual realization is plotted as black. The system shows some skill over at the 3-month lead-time.

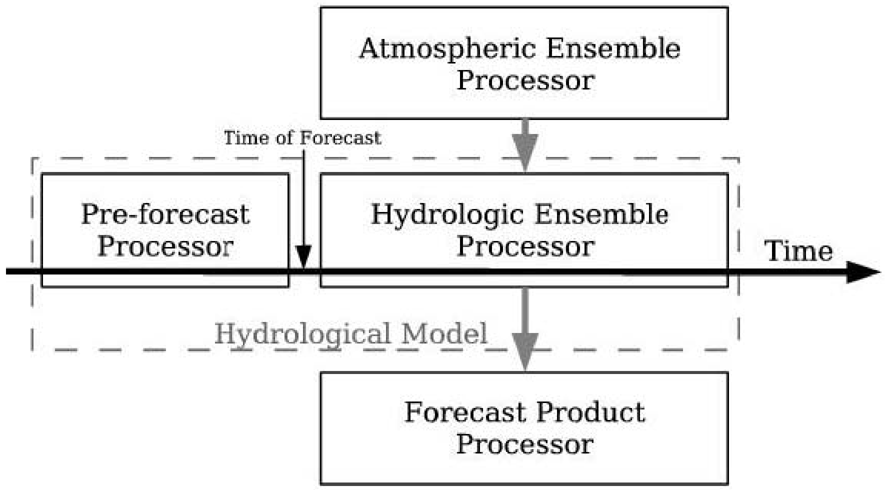


Figure 3: The seasonal hydrologic ensemble forecast system consists of four basic elements. The hydrological model (VIC) is used in both the pre-forecast processor and hydrologic ensemble processor. The Bayesian merging is implemented in the atmospheric ensemble processor.

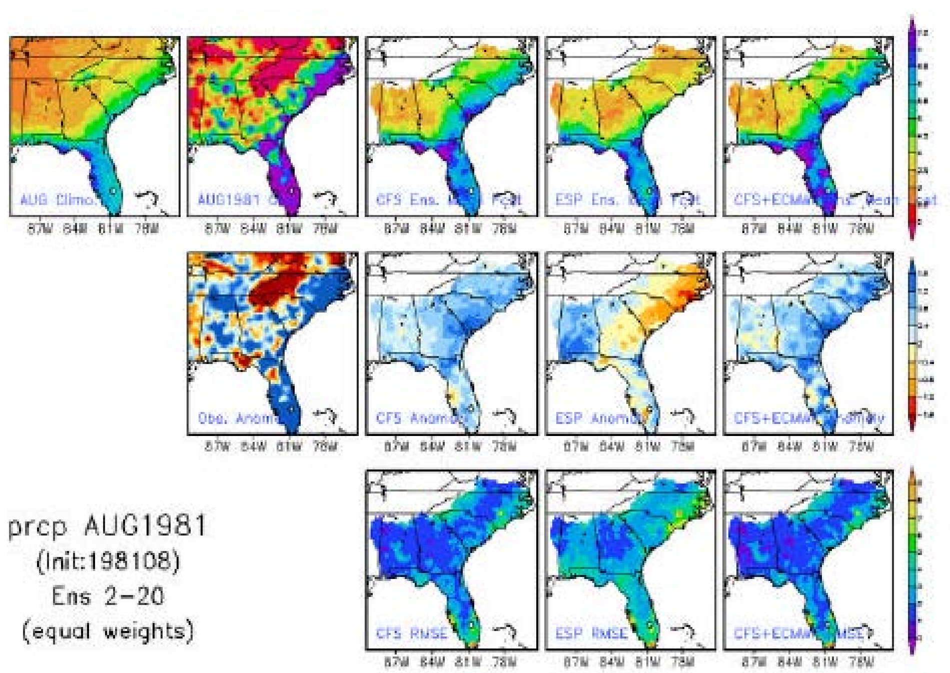


Figure 4: Precipitation forecast for the Southeastern U.S. targeted for Aug. 1981 initialized at May 1981. The second row shows the anomalies with respect to the same observed climatology. The third row is the root mean square (RMS) error of the ensemble with respect to the actual realization.

In conjunction with the hydrologic forecasting, we also developed a real-time (nowcasting) drought monitoring system over the U.S. using VIC model and North American Land Data Assimilation (NLDAS) products. Our system produces a real-time drought map based on continuous hydrologic modeling. The drought anomalies are similar to the official NOAA drought monitor but avoid the qualitative assessment used in that product, and has greater spatial detail (see figure 6). We have set up a web site (http://hydrology.princeton.edu/forecast) for this project where the latest forecasts and drought nowcasts can be accessed.

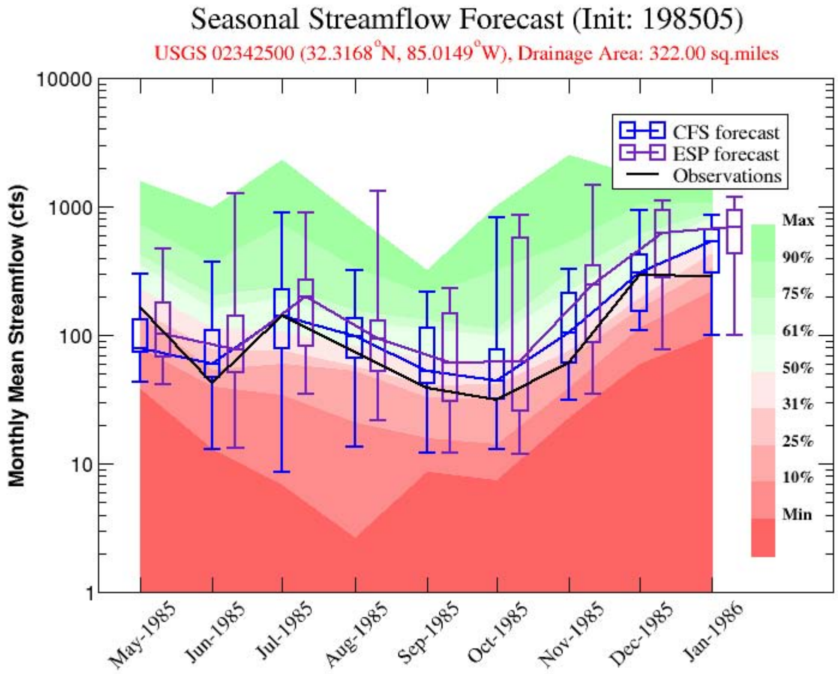


Figure 5: Streamflow forecast for one selected USGS gage.

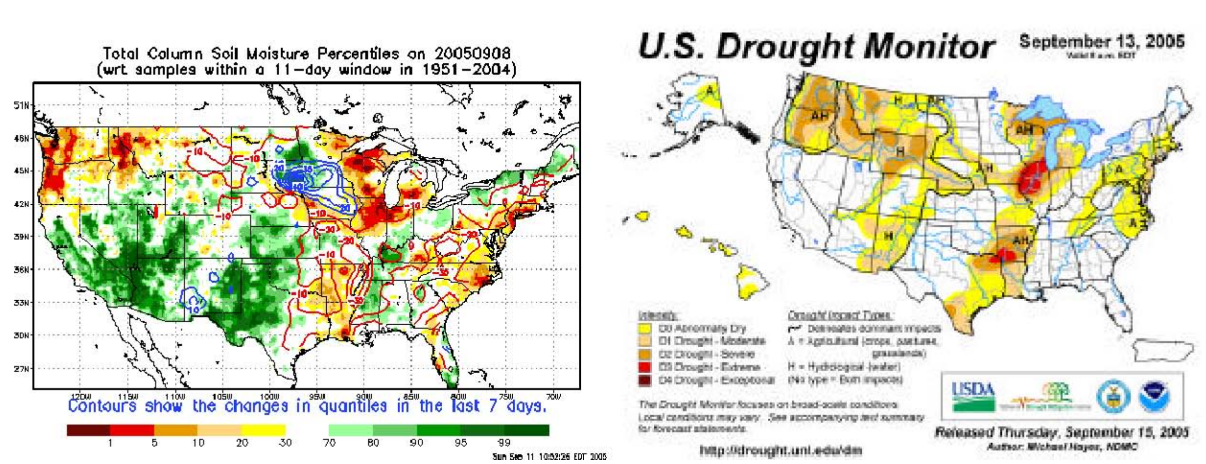


Figure 6: Real-time drought monitoring using VIC and NLDAS compared with official NOAA drought monitor.

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

Principal Investigator: Youlong Xia (Princeton Research Staff)

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

Theme #1: Earth System Studies/Climate Research

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

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

Methods and Results/Accomplishments:

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

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

These methods reduce forcing data errors (i.e., precipitation) and improve streamflow simulations in the United States and globally. At the same time, GFDL land dynamics model (LM2) is also well optimized. This optimization technique and work experiences from LM2 work now are being transferred to optimize a preliminary version of the new GFDL land model (LM3W) with respect to hydrological and soil physics processes. Eventually, this algorithm can be used to tune new land-vegetation dynamics model (LM3) consisting of LM3W used as water component and LM3V used as dynamic vegetation component.

Publications:

Xia, Y., P. C. D. Milly, and K. A. Dunne, 2004: Optimization and Uncertainty Estimates of WMO Regression Models for Precipitation-Gauge Bias in the United States, *EOS Tans. AGU, 85(47. Fall meet. suppl. abstract*.

Xia, Y., Z. L. Yang, P. L. Stoffa, M. K. Sen, 2005a: Using different hydrological variables to assess the impacts of atmospheric forcing errors on optimization and uncertainty analysis of the CHASM surface model at a cold catchment, J. Geophys. Res., 110, D01101, doi:10.1029/2004JD005130.

Xia, Y., P. C. D. Milly, and K. A. Dunne, 2005b: Calibration of the LaD model in northeastern US using observed streamflow, in preparation for submission to J. Hydromet.(internal review).

Xia, Y., P. C. D. Milly, and K. A. Dunne, 2005c: Impacts of systematic precipitation bias on simulations of water and energy balances in northwestern United States, in preparation for submission to J. Geophys. Res. (internal review).

Xia, Y., P. C. D. Milly, and K. A. Dunne, 2005d: Adjustment of Global Precipitation Data for Orographic Effects Using Observed Annual Streamflow and the LaD Model, in preparation for J. Hydromet.

Progress Report: **The Transformation of Black Carbon Aerosol from Hydrophobic to Hydrophilic and the Impact on its Global Distribution**

Principal Investigator: Huiyan Yang (Princeton graduate student)

Other Participating Researchers: Hiram Levy II (Princeton Advisor) (GFDL), 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: To understand the mechanisms in the transformation of black carbon aerosol from hydrophobic to hydrophilic, and the impact on its global distribution

Methods and Results/Accomplishments:

A box model was set up for the study of the role of H2SO4 vapor. The model has four species: H_2SO_4 vapor, sulfate nuclei, hydrophobic BC aerosols, and pre-existing accumulation mode aerosols. Aerosol microphysical processes included are: nucleation and condensation of H_2SO_4 vapor, self-coagulation of sulfate nuclei, coagulation of sulfate nuclei on hydrophobic BC aerosols and other aerosols. The production rate of H_2SO_4 vapor by SO_2 oxidation with OH is the input of the model. The coagulation with pre-existing water-soluble aerosols and cloud droplets is also studied. A parameterization scheme for the transformation time is developed and applied to a 3D global photochemistry model MOZART II.

It is found that the transformation is more than 10 times faster in polluted than in remote areas. The Condensation of H_2SO_4 vapor ranges from the most important to the least important mechanism among the three, depending on the supersaturation of the precipitating clouds. The coagulation of hydrophobic BC aerosols with pre-existing water-soluble aerosols is fast in polluted areas, while the coagulation with cloud droplets is relatively more important in remote areas.

A global chemistry model, MOZART II, is applied to assess the impact of a parameterized variable transformation time on BC aerosol distribution. The results are compared with simulations using a global uniform transformation time (control run). It is found that by setting the cloud supersaturation at 0.8%, BC aerosol concentration is reduced in polluted areas, and is increased in biomass burning and remote areas when using a parameterized transformation time (parameterized run). The increase is especially prominent in South Africa and South America (the major biomass burning areas), Antarctic areas, and at higher atmospheric levels. Setting the cloud supersaturation at 0.1% produces a weaker reduction, and a much stronger increase, when compared with the control run. A preliminary comparison of the control run with observations indicates that the variable transformation rate in the parameterized run (the supersaturation of 0.8% case) improves the agreement between model and observations.

Publications:

Yang, H., L. Horowitz, H. Levy II, The transformation of black carbon aerosol from hydrophobic to hydrophilic and the impact on its global distribution, first draft.

Progress Report: **Investigating the Response of the Thermohaline Circulation to Past and Future Climate Changes**

Principal Investigator: Jianjun Yin (Princeton Research Associate)

Other Participating Researchers: GFDL Advisor: Ronald Stouffer/Keith Dixon, Mike Spelman, Bill Hurlin and Stephen Griffies (GFDL), Jonathan Gregory (Hadley Centre), Andrew Weaver (University of Victoria)

Theme #1: Earth System Studies/Climate Research

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

Objectives: To study the causes of past and future changes of the thermohaline circulation (THC); To reduce the large uncertainties in modeling this critical system and projecting its future evolution

Methods and Results/Accomplishments:

Yin has intensively participated in the data analyses of the CMIP/PMIP "water-hosing" experiments. In these experiments the sensitivity of the THC to external sources of freshwater is studied. The THC is responsible for much of the northward heat transport in the Atlantic Ocean. Many studies have shown that the THC weakens when the radiative forcing increases. It is also susceptible to external freshwater sources and has been studied systematically through a model intercomparision of 14 participating climate models using varying degrees of complexity.

In response to 0.1 Sv freshwater perturbation in 50^o~70^oN of the North Atlantic (NA) which resembles the projected freshwater anomalies in the NA high latitudes under realistic future CO_2 scenarios, the THC weakens by 30% after 100 years in the multi-model ensemble (Fig. 1). No model simulates a shutdown of the THC during the 100-year hosing period. After the slowdown of the THC, the surface air temperature shows a complex anomaly pattern with a pronounced cooling (up to 3^oC) south of Greenland and a warming (up to 1^oC) around the Barents Sea. The Atlantic ITCZ tends to shift southward.

In response to 1 Sv freshwater perturbation, the THC switches off rapidly (Fig. 2). Most of the northward oceanic heat transport in the Atlantic ceases and a large local cooling (up to 14^oC) occurs in the NA and surrounding regions. The entire Atlantic ITCZ moves into the Southern Hemisphere. The shutdown of the THC is reversible in some models, while it is irreversible in the others. The results from the 1 Sv "water-hosing" experiment have implications for past abrupt climate changes.

A second area of study for Yin is investigating the use of a virtual salt flux upper boundary condition in the oceanic components of AOGCMs. Some uncertainties in the model response to changes in the freshwater flux come from the wide usage of the virtual salt flux. Using the virtual salt flux method could lead to large errors in the surface salinity (and associated implied water fluxes) in regions where the surface salinity is low. We have performed corresponding "water-hosing" experiments with a real freshwater flux version and a virtual salt flux version of the GFDL CM2.1. A paper describing both the similarities and differences is in development.

Publications:

J. Yin, R. J. Stouffer, M. J. Spelman and S. M. Griffies: The Influence of the Virtual Salt Flux as an Oceanic Boundary Condition on "Water-Hosing" Experiments. (In preparation)

R. J. Stouffer, J. Yin, J. M. Gregory, K. W. Dixon, M. J. Spelman, W. Hurlin, A. J. Weaver and participating groups: Investigating the Causes of the Response of the Thermohaline Circulation to Past and Future Climate Changes. *J. of Climate* (Submitted).

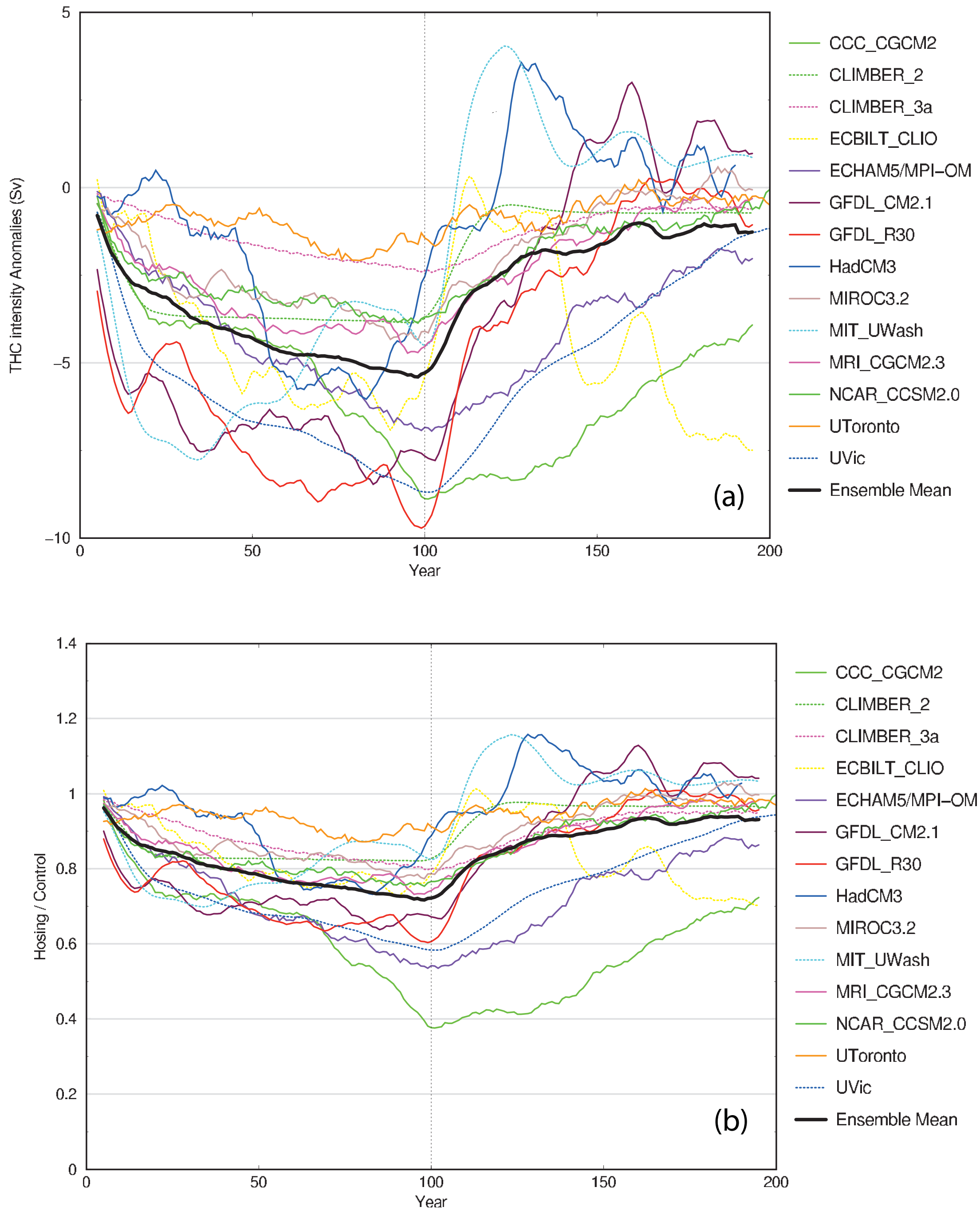


Figure 1. Time series of the THC intensity anomalies in the 0.1 Sv "water-hosing" experiment. 0.1 Sv freshwater flux is input into 50^{o}~70^{o}N of the North Atlantic during the first 100 years of the experiment, and then removed to study the recovery of the THC. (a) The absolute reduction of the THC intensity (Sv); (b) The weakening of the THC relative to the control runs. Solid curves indicate results from the fully coupled AOGCMs. Dashed curves indicate results from the Earth Models with intermediate complexity.

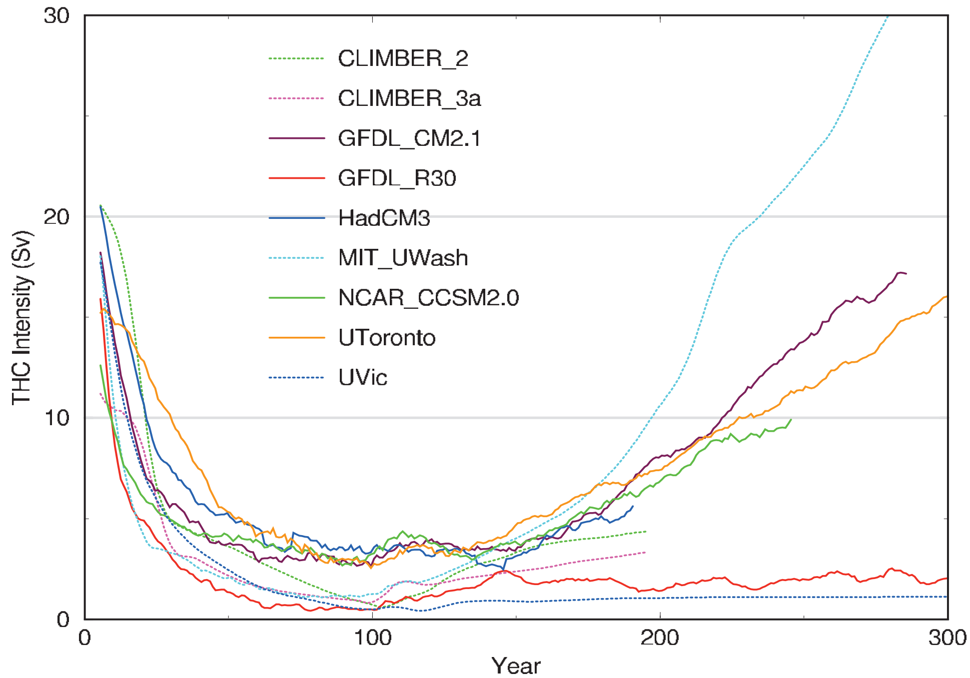


Figure 2. Time series of the THC intensity in the 1 Sv "water-hosing" experiment. A much larger freshwater flux of 1 Sv is input into the perturbation region. The THC switches off rapidly in all model simulations. Some models show a rapid recovery of the THC once the freshwater perturbation is removed after the 100th year, while the THC keeps inactive in the others.

Progress Report: **The Role of the Deep Western Boundary Current in the Gulf Stream Path and Northern Recirculation Gyre**

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

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**:* Studying the mechanism affecting the Gulf Stream path and the formation of northern recirculation gyre.

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

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

References:

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

***Publications**:*

Zhang, R. and G. K. Vallis, 2005. The Role of the Deep Western Boundary Current in the Gulf Stream Path and Northern Recirculation Gyre, In review with *Journal of Physical Oceanography*.

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

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

Other Participating Researchers*:* 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*:* Understanding the mechanism of North Atlantic low frequency variability

Methods and Results/Accomplishments:

Observed North Atlantic low frequency variability is often thought to be driven directly by the atmospheric North Atlantic Oscillation. Zhang and Vallis show that coherent large-scale low frequency variability in the North Atlantic, including variations of thermohaline circulation, deep western boundary current, northern recirculation gyre and Gulf Stream path, can be induced by the observed high-latitude oceanic Great Salinity Anomaly events, using a global 1^o ocean general circulation model coupled to a 2-dimensional atmospheric Energy Balance Model with hydrological cycle. Recent atmospheric studies have suggested that a positive low frequency North Atlantic Oscillation phase can be forced by a dipolar sea surface temperature anomaly (warming off US east coast and cooling south of Greenland). Zhang and Vallis show that such dipolar anomaly can be triggered by the Great Salinity Anomaly events some years in advance and this can provide long-term predictability to the system. Their diagnoses of the 20th century observations show on multi-decadal timescales that the positive (negative) Great Salinity Anomaly phase, associated with more (less) Iceland sea ice extent, leads Labrador Sea surface cooling (warming) and a positive (negative) North Atlantic Oscillation phase (Figure 2.1). The multidecadal variations of the Iceland sea ice extent and Labrador Sea SST (Figure 2.1) may have contributed to the cool phases in the North Atlantic during 1905-1925 and 1970-1990, and the warm phase in the North Atlantic in the middle of the 20th century, i.e. the observed Atlantic Multidecadal Oscillation (AMO).

References:

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

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

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

Wallevik J. E. and H. Sigurj´onsson, 1998. The Koch Index. Formulation, corrections and extension. Report, Icelandic Meteorological Office (V´I-G98035- ´ UR28).

Publications:

Zhang, R. and G. K. Vallis, 2005. Impact of Great Salinity Anomalies on the Low Frequency Variability of the North Atlantic Climate. *Journal of Climate*, accepted.

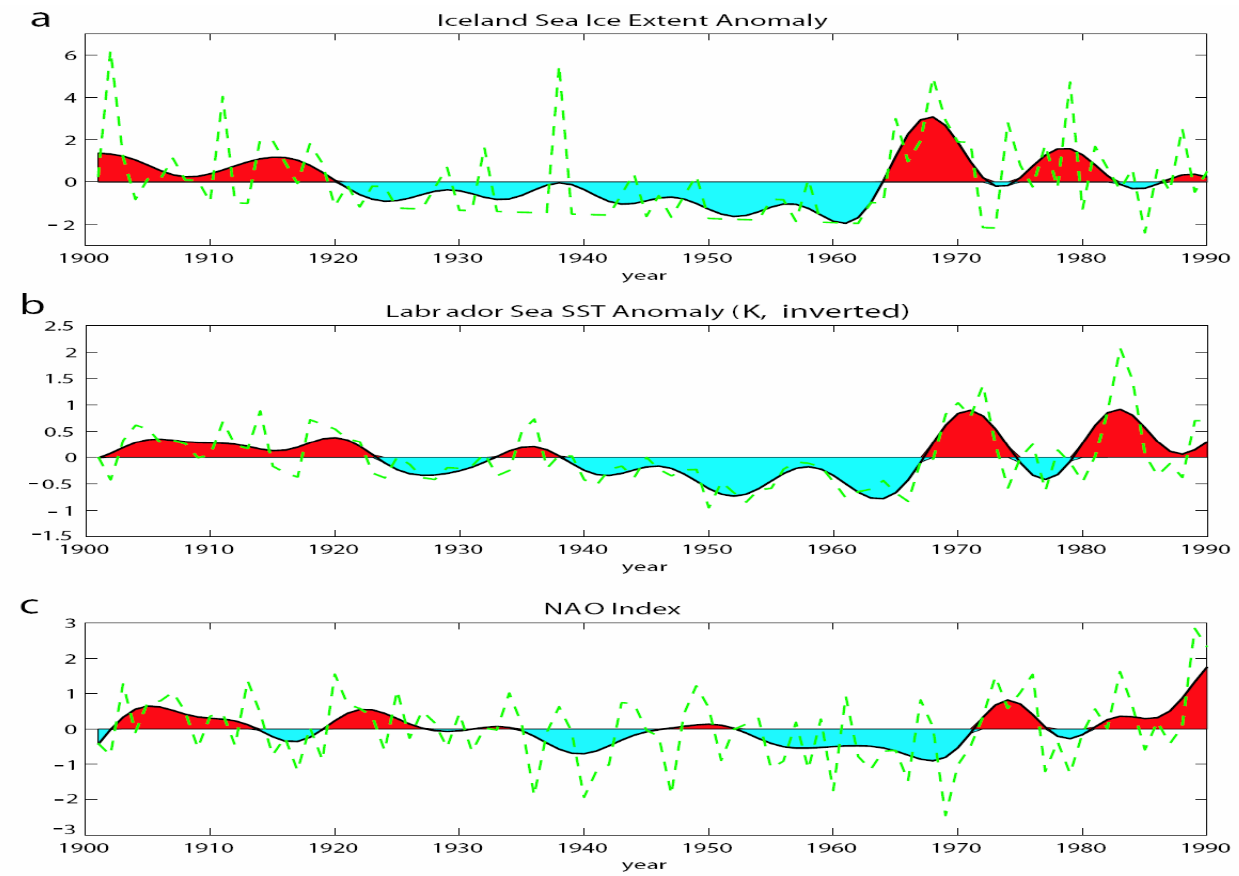


Figure 2.1 Observed time series during the 20th century. **a**, Annual Iceland sea ice extent anomaly, the original dataset is maintained by the Icelandic Meteorological Office (Wallevik and Sigurjonsson, 1998) **b**, Central Labrador Sea annual mean SST anomaly from HadISST dataset (K, inverted) **c**, Winter (Dec-Mar) principal component based NAO Index (Hurrell, 1995). The green dash line is the unfiltered data and the color shade is the 8-yr low-pass filtered data. The linear trends for the whole period (1901-1990) of the time series are removed.

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

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

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

Theme #1: Earth System Studies/Climate Research

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

Objectives:

1) To understand the difference in the low-latitude cloud trends in the GFDL, NCAR and GMAO models when CO2 is doubled.
2) To use observations and recent advances in understanding the component physical processes to improve both models.
3) To reduce, or better estimate, our uncertainty about the sensitivity of climate to low-latitude marine boundary layer clouds.

Methods and Results/Accomplishments:

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

Understanding the complex Earth climate system demands model hierarchies. As a component model targeting studies of column physics, we have made available an idealized setting of the GFDL atmospheric model AM2, which can be run over a limited area using Cartesian coordinate. This model has doubly periodic lateral boundary with lower-boundary being either fixed or mixed-layer ocean. Unlike a single-column model (SCM**),** this model allows physical processes of convection, clouds, radiation and surface fluxes to interact explicitly with model dynamics and therefore provides a possible venue for testing ideas about these interaction that is simple enough to be understandable, but rich enough to be useful in interpreting some of the full model behavior. We explore the model sensitivities to physics parameters as well as SST under 2 simple boundary forcings. One is horizontally-uniform SSTs and the other is sinusoidally-varying SST. The 1^{st} corresponds to radiative-convective equilibrium (RCE) simulations and the 2^{nd} we refer to as mock Walker simulations. Below we give a brief summary of the results.

A set of RCE simulations with a range of SSTs, resolutions and choices of convection parameters may be classified into two regimes based on the presence of significant amount (~15%) of large-scale precipitation (LSP). The cloud feedback (CF) to warming depends sensitively on the transition to significant LSP, which further depends on the details of convection parameters as well as model resolution. For the experiments in which no significant amount of LSP develops throughout the simulation range of SST, we find no systematic CF trend with warming. For the experiments in which a significant amount of LSP does occur, it develops at warmer SST. The development of LSP in the simulations is abrupt and associated with a sharp increase of liquid/ice water path and low-cloud cover. These together produce a stronger enhancement of short-wave (SW) reflection but only a mild increase of long-wave (LW) cloud forcing, leading to a net negative CF to warming. Given a fixed SST, we have also examined the cloud sensitivities to a particular convection parameter, the deep-cloud entrainment-rate limiter (DEL), which controls the magnitude of parameterized deep convection and therefore the fraction of LSP in RCEs. The liquid/ice water path and low-cloud fraction all systematically increase with the amount of deep convection limiting, resulting in dramatic increase of SW reflection. Motivated by the idealized experiments, we have also carried out a series of AM2 CESS-type simulations (perturbing SSTs uniformly) for different values of DEL. We find similar cloud sensitivities to DEL in the full model. However, the character of cloud response to warming does not carry over to the full model, indicating more complex climate response to warming in the full model.

The simulated mock Walker circulation using modified AM2 physics shows time-mean structure and intensity that compare reasonably well with observations, the AMIP-type GCM simulations and also cloud resolving simulations. Interestingly, the dominant transient in this simulation is a 30-50 day oscillation. Cloud radiative forcing (CRF) dominates the time-mean net energy input over the warm-pool, indicating its possible strong enhancement of the thermally-direct circulation. However, significant amount of energy exports from the warm-pool are also associated with horizontal advection and transient flow, which are themselves encouraged by the CRF. Therefore, the simulated cloud feedback presents two competing processes to the time-mean circulation. On the one hand, large magnitude CRF, which are nearly in phase with precipitation, narrows deep convective region, intensifies precipitation and strengthens the flow. On the other hand, CRF generates organized oscillatory transient, which tend to smooth the time-mean circulation. This complex behavior of cloud-radiative feedback puts in question the use of simple models/theories which neglect completely the energy transport by transient flow and horizontal advection.

Publications and Manuscripts in Preparation:

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

I. M. Held, M. Zhao and B. Wyman 2005: Radiative-Convective Equilibrium Using GCM Column Physics. *Manuscript in preparation.*

M. Zhao, I. M. Held and B. Wyman, 2005: The Role of Cloud Radiative Forcing in an Idealized Walker Simulation. *Manuscript in preparation.*

Progress Report: **Parameterization of Mesoscale Eddies for Upper Ocean Boundary**

Principal Investigator: Rongrong Zhao (Princeton Research Associate)

Other Participating Researchers: Geoffrey Vallis and Laura Jackson (Princeton), Shaffer Smith (NYU), Robert Hallberg (GFDL)

Theme #1: Earth System Studies/Climate Research

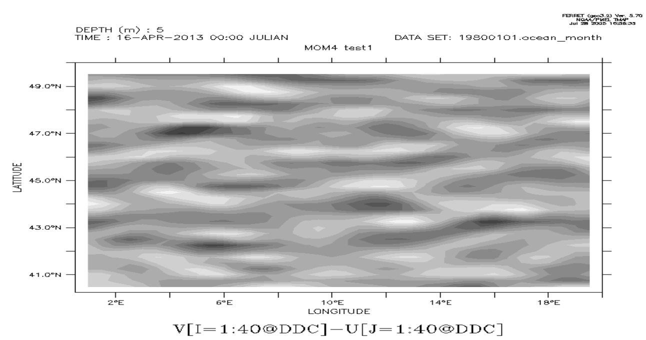
NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

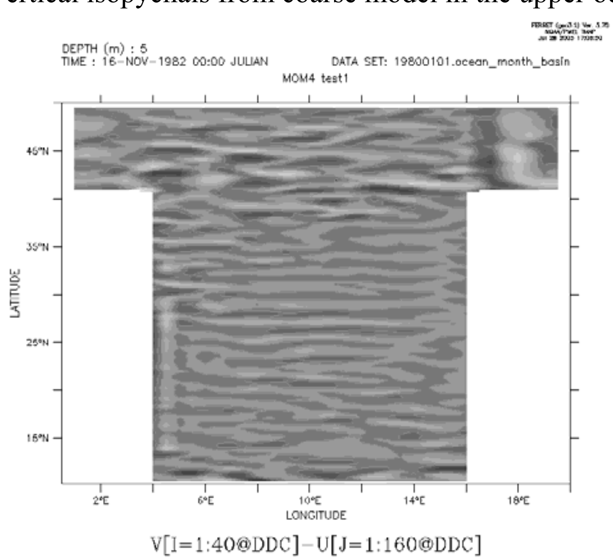
Objectives: Develop suitable parameterization of mesoscale eddies for upper ocean boundary.

Methods and Results/Accomplishments:

Mesoscale eddies transport large-scale momentum and exert a profound influence on the ocean circulation, for example, Henning and Vallis (2004) found mesoscale eddies are important in setting up the stratification of the ocean, especially for channels. In current climate models, mesoscale eddies are not resolvable since the ocean horizontal resolution is usually about 100 km or higher, hence parameterization is needed.

To study the dynamics of how mesoscale eddies affect ocean circulation, two idealized physical models are set up and simulated using Modular Ocean Model. Both low and high resolution numerical simulations are practiced. The first is a pure channel model with flat bottom (20 degree long, 10 degree wide (40N to 50N) and 3500 meters deep). The channel is driven by buoyancy and wind. Model was run with a coarse grid (2 degree zonal and 1 degree meridional) for 1200 years for stabilization, and the end state was interpolated into fine grid (1/2 degree zonal and ¼ degree meridional) for further integration. For high resolution run, instability starts from warmer end of the channel and eddies show up in a couple of years. A snapshot for the vorticity on the ocean surface is in the right figure. Eddies are found to largely readjust stratification and flat out the vertical isopycnals from coarse model in the upper ocean.





A more realistic model for southern ACC was set up with a rectangular domain open to a circumpolar channel at its poleward end. Same low and high resolution as channel model were applied for non-eddying and eddy permitted simulation. For ¼ degree resolution run, eddies are found in the channel region and western side of the basin (see the vorticity snapshot in left figure).

Based on the base model, current focus is to build up more experiments to study the detailed dynamics, such as the influences from diffusivity, viscosity, wind stress and as well as topography.

References:

C. C. Henning and G. K. Vallis: The effects of mesoscale eddies on the stratification and transport of an ocean with a circumpolar channel, Journal of Physical Oceanography, 35, 880-896

C. C. Henning and G. K. Vallis: The effects of mesoscale eddies on the main subtropical thermocline, Journal of Physical Oceanography, 34, 2428-2443

S. M. Griffies, R. C. Pacanowski, and R. W. Hallberg: Spurious diapycnal mixing associated with advection in a z-coordinate ocean model, 128, 538-564

Progress Reports:

Biogeochemistry

Progress Report: **A Direct Budgeting Approach to Estimate CO_2 Sources and Sinks in North America**

Principal Investigator: Cyril Crevoisier (Princeton Research Associate)

Other Participating Researchers: Emanuel Gloor, Colm Sweeney and Jorge Sarmiento (Princeton), and A. Andrews(NOAA/CMDL)

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. To constrain this problem, measurements of CO_2 vertical profiles by aircraft and continuous CO_2 data along tall towers will soon be available at fifteen locations across the United States within the framework of the North American Carbon Plan (NACP). In order to exploit these data to infer CO_2 sources and sinks in North America, we are developing a direct budgeting approach.

Direct budgeting puts a control volume on top of North America, balances air mass in- and outflows into the control volume and solves for the surface fluxes. Different upper bounding surfaces like the PBL-free troposphere interface are imaginable. To interpolate the CO_2 fields from the stations to estimate atmospheric CO_2 above North America we use geostatistical Kriging method. A direct budgeting approach may have the advantage of providing flux estimates independent of prior information that is generally used to infer carbon surface fluxes through top-down inversions. Another advantage of direct carbon budgeting is that problems caused by covariation of fluxes and atmospheric transport, the so-called rectification effect, may be avoided entirely.

To test the approach, use is made of CO_2 fields simulated by the atmospheric transport model MOZART (*Horowitz et al.* 2003) that take into account monthly fossil fuel emissions (*Blasing et al.* 2004), air-sea fluxes from the GFDL oceanic model (*Dunne et al.*, in prep.) and air-land fluxes from the land model LM3 (*Shevliakova et al.*, in prep.).

These simulations indicate that the main variation of CO_2 at the edge of the volume is due to advection, whereas the contributions of convection and diffusion are small. They have already given access to the expected correlation between CO_2 measured at the stations and the surrounding area which is used for the interpolation algorithm to obtain the 3D CO_2 field. Figure 1 shows correlations greater than 0.7, between each station and every other model grid point, at an altitude of 2 km (800 hPa) for the month of March. The East coast is particularly well covered by the stations, which should allow a good interpolation of CO_2 between the stations and thus a accurate estimate of CO_2 outflow from USA. The northern US border is quite well covered (even if some gaps may be there). However, large data gaps are apparent in the South-East. This may be due to the complex variation of winds that can be found in this region.

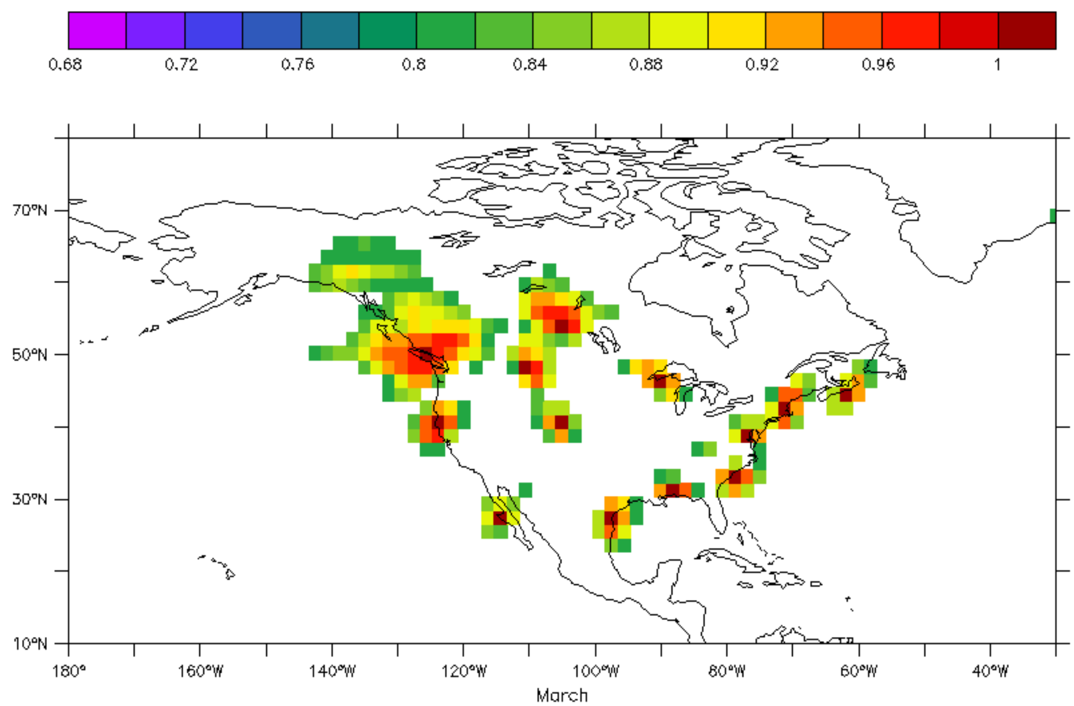


Fig. 1 Correlation between vertical CO_2 profiles measured at already existing or planned locations across North America and adjacent CO_2 field as simulated by the Mozart model and realistic surface fluxes.

Progress Report: **Development of Fire Model for Boreal Forests Ecosystem**

Principal Investigator: Cyril Crevoisier (Princeton Research Associate)

Other Participating Researchers: C. Wirth, Emanuel Gloor and 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: Estimating and Predicting Carbon Emissions from Fires

Methods and Results/Accomplishments:

Boreal regions are important for the global carbon cycle because it is the largest forested area on earth and there are large belowground carbon pools, partially in a frozen state or in form of peat (altogether ~1000 PgC, *Jobaggy and Jackson*, 2000; *Zimov et al.*, 1999; *Gorham*, 1991). It is also a region where largest warming trends on the globe over the last decades have been observed and changes of the land ecosystems have already started. A major factor that determines the structure and carbon dynamics of the boreal forest is fire. As fire frequency depends strongly on climate increased fire occurrence and related losses to the atmosphere are likely, and have already been reported (*Kajii et al.,* 2002). In order to predict with more confidence the occurrence and effect on forest ecosystems in the boreal region, we are developing a fire model that takes advantage of the large on-ground, remote sensing and climate data from Alaska and Siberia.

The design of the fire model consists of two parts: an ignition function, which indicates in which circumstances a fire may start, and an estimation of the surface burnt by the fire. Both take into account information from various origins: climate (air temperature, air humidity, precipitation), human impact (distance to the nearest roads and to the populated zones) and history (last fires in the area).

The higher the air temperature (T), the lower the precipitation and the air relative humidity (RH), the closer the roads or the higher the population density, the higher the risk for a fire to start. The influence of the first two parameters is well seen on the following figure which shows the number of fires occurring for a given couple (T,RH) for two kind of situations: no fire (left) and fire (right). One may see that fires are likely to appear in a given region (high T, low RH) where few "no-fire" situations appear. Using simultaneously both information (along with other ones) may allow us to design a powerful ignition function by using a logistic regression based technique.

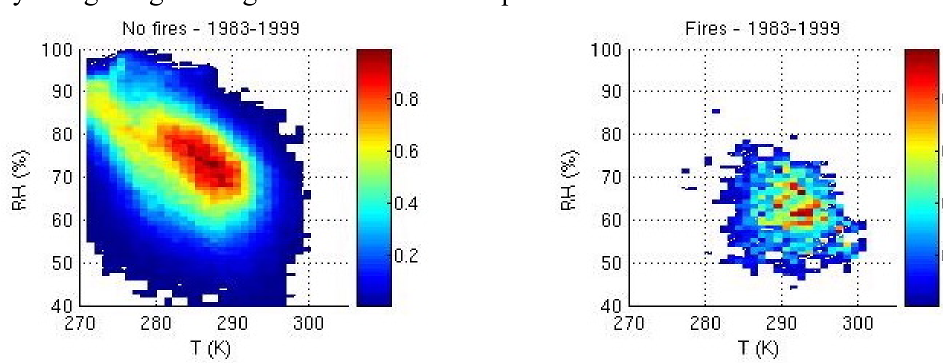


Fig.1 Climate conditions in Alaska during days with no fire (left panel) versus days with fire occurrence (right panel).

Such an approach is currently applied to the boreal forest of Canada. We are using a database listing all the fires that have occurred in this region during the last 50 years, together with high-spatial-resolution climate fields. These data were used to make the above figure. The first results obtained are encouraging and give an ignition prediction error of about 20%. The use of information of population density from the Oak Ridge Laboratory should further decrease this value. We are currently developing also a predictor of burnt area based on the Canadian database on fire occurrence in synergy with satellite observations from AVHRR. Ultimately we will use the empirically based fire model into the Land vegetation models developed by S. Pacala, E. Shevliakova and S. Malyshev.

Progress Report: **Inverse Model Development for Estimation of Monthly CO_2, CO and CH_4 Fluxes Using Atmospheric Data**

Principal Investigator: Erwan Gloaguen (Princeton Research Associate)

Other Participating Researchers: Emanuel Gloor, Jorge Sarmiento, Cyril Crevoisier, Andrew Jacobson (Princeton), Larry Horowitz (GFDL)

Theme #2: Biogeochemistry

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

Objectives: Understanding interannual variability of atmospheric CO_2

Methods and Research/Accomplishments:

An understanding of interannual variability of atmospheric CO_2 is of interest as it may provide insights on the possible future behavior of the earth climate system to increased radiative forcing. As CO and CH_4 in the atmosphere are oxidized on time-scales of months to years to CO_2 and are partially coupled to CO_2 release processes they hold additional clues to interpreting atmospheric CO_2 variability. We have therefore started to develop inversion schemes to estimate global source and sink distributions of CO_2, CO and CH_4 on a biweekly / monthly basis using atmospheric data and models. The methods are based on pulse response functions simulated with the Mozart transport model. Response function simulations for the years 2003 and 2004 are completed and available for use. We will also profit from the ocean flux estimates obtained using ocean data discussed in the section of Jacobson et al. earlier on by using them as constraints in a similar way as Jacobson et al. Spatial resolution of the inversions is 28 ocean and 50 land regions. Land regions are chosen according to main ecozones which directly reflect climate. To take into account volume sources and sinks for CO and CH_4 due to oxidation by OH we rely on the OH predictions of the Mozart model in its standard configuration. We then linearize the inverse estimator around the Mozart first guess OH field and possibly iterate. To solve the estimation problem we test two algorithms. The primary one follows a geostastistical approach. A main feature is the use of full, non-diagonal flux covariance matrices estimated from the data in combination with the flux response functions. No prior constraints are necessary in this approach. The geostatistical structural analysis underlying the approach yields as a byproduct global monthly mean atmospheric CO_2, CO and CH_4 surface distributions. An example for CO_2 is displayed in Figure 1.

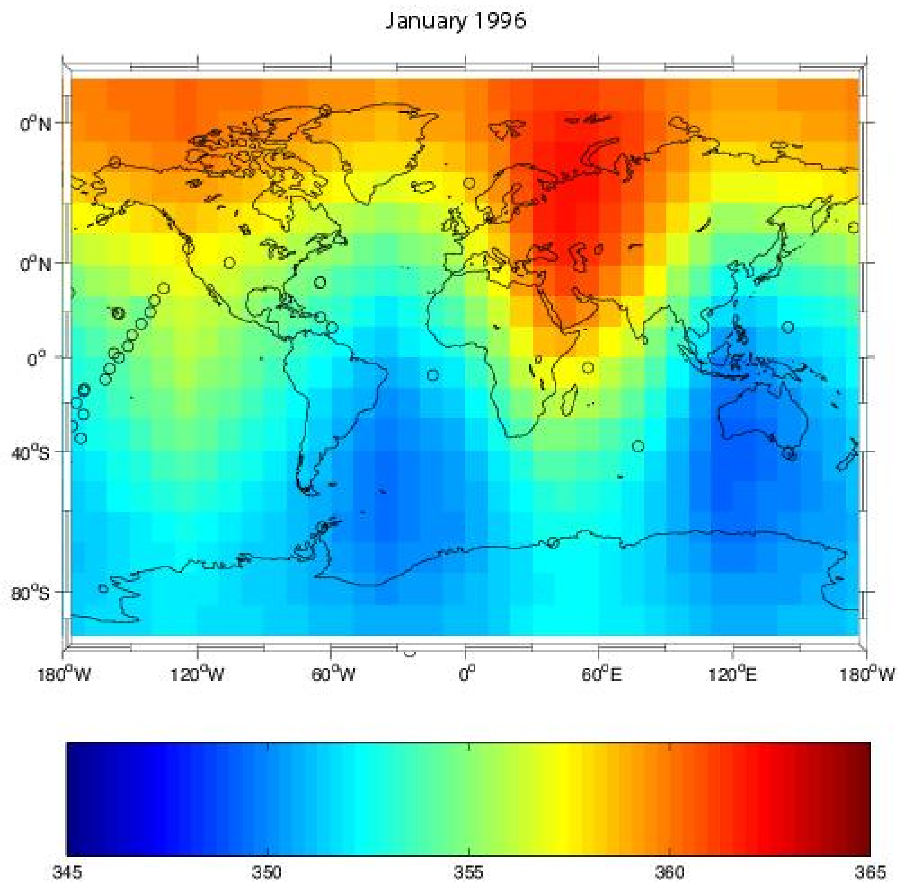


Fig. 1 Atmospheric surface CO_2 distribution based on surface station data from NOAA/CMDL and a geostatistical method.

Progress Report: **Latitudinal Atmospheric O_2 and CO_2 Distributions Across the Western Pacific**

Principal Investigator: Emanuel Gloor (Princeton Reseach Scholar) with Y. Tohjima (National Institute for Environmental Studies, Tsukuba, Japan)

Other Participating Researchers: H. Mukai, T. Machida, and Y. Nojiri (National Institute for Environmental Studies, Tsukuba, Japan).

Theme #2: Biogeochemistry

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

Objectives: Understanding the Oxygen Cycle

Methods and Results/Accomplishments:

Atmospheric O_2 carries information about a range of ocean processes. Unfortunately this signal is somewhat overshadowed by the seasonally varying oxygen fluxes associated with photosynthesis and respiration on land. However because of the tight negative stoichiometric coupling between O_2 and CO_2 fluxes during these processes it is possible to largely eliminate this land signal. This is achieved by using the tracer APO=O_2+1.1xCO_2 instead of O_2 only (*Stephens et al.*, 1998), where 1.1 is the O_2:C stoichiometric ratio for land biotic photosynthesis and respiration (*Severinghaus*, 1995). Because APO is conservative with respect to terrestrial biotic exchanges its seasonal variation and global distribution are predominantly determined by and therefore reflect mainly ocean processes. These processes include ocean productivity, large-scale ocean transport like equatorial upwelling and inter-hemispheric transport, and high-latitude convection.

Several modeling studies have attempted to confront APO predictions with observations to learn more about the processes determining atmospheric oxygen as well as to examine the realism of the underlying models. One particular prediction by both the forward modeling results of the *Stephens et al*. (1998) study and an ocean inversion study of the Princeton group (*Gruber et al.*, 2001) APO is a maximum in the annual mean latitudinal APO distribution in the tropics. A possible explanation for the predicted APO maximum in the tropics is that it is an artifact caused by water upwelling along the equator from unrealistically large depth in these models, or alternatively that equatorial upwelling is too strong. As atmospheric oxygen data in the tropics were missing at the time of these studies it was not possible to confirm or disprove this prediction.

In contrast to the model predictions of the *Stephens et al.* (1998) study, the *Gruber et al.* (2001) annual mean oxygen air-sea flux estimates are based on ocean model transport inversions applied to the oceanic analogue O_2*=O_2+(1/170)xPO_4 of APO and thus are strongly data based. Seasonal variation of O_2 air-sea gas exchange is predicted in this latter study based on O_2 and CO_2 air-sea partial pressure differences and gas exchange parameterizations based on wind speed (*Najjar & Keeling*, 2000; *Takahashi et al.,* 1999). Finally there is also a fossil fuel contribution to APO which is prescribed according to National Energy Statistics (*Marland et al*., 1998).

In order to close the observational gap in the tropics Y. Tohjima and colleagues have started in December 2001 to observe the latitudinal distribution of atmospheric O_2 and CO_2 across the Western Pacific using flask sampling on board cargo ships (Fig. 1). The analysis of the data reveals excellent agreement with the *Gruber et al*. (2001) predictions of both the seasonal cycle of the signal as well as of the annual mean latitudinal distribution (Fig. 2 and 3). This suggests that there are two hemispherically closed transport cells with oceanic branches transporting APO to low latitudes where they are outgassing and causing a return flow in the atmosphere to high latitudes. These two cycles are superimposed on more uniform global uptake of CO_2 by the oceans caused by increased atmospheric CO_2 due to fossil fuel burning and a North-South flow of fossil burning CO_2 in the atmosphere. The tropical APO outgassing signal indicates that ocean biota are not stripping out enough nutrients in equatorial upwelling waters to prevent biospheric production in surface waters flowing from the equator towards mid latitudes and thereby losing APO to the atmosphere. The results also support the realism of ocean transport simulations as well as to some extent model representation of ocean biology.

References:

Y. Tohjima, H. Mukai, T. Machida, Y. Nojiri and M. Gloor (2005). First measurements of the latitudinal atmospheric O_2 and CO_2 distributions across the Western Pacific. *Geophys. Res. Lett.*, in press.

N. Gruber, M. Gloor, S.-M. Fan and J. Sarmiento (2001). Air-sea flux of oxygen estimated from bulk data: Implications for the marine and atmospheric oxygen cycles. Glob. Biogeochem. Cycles, 15, 783-803.

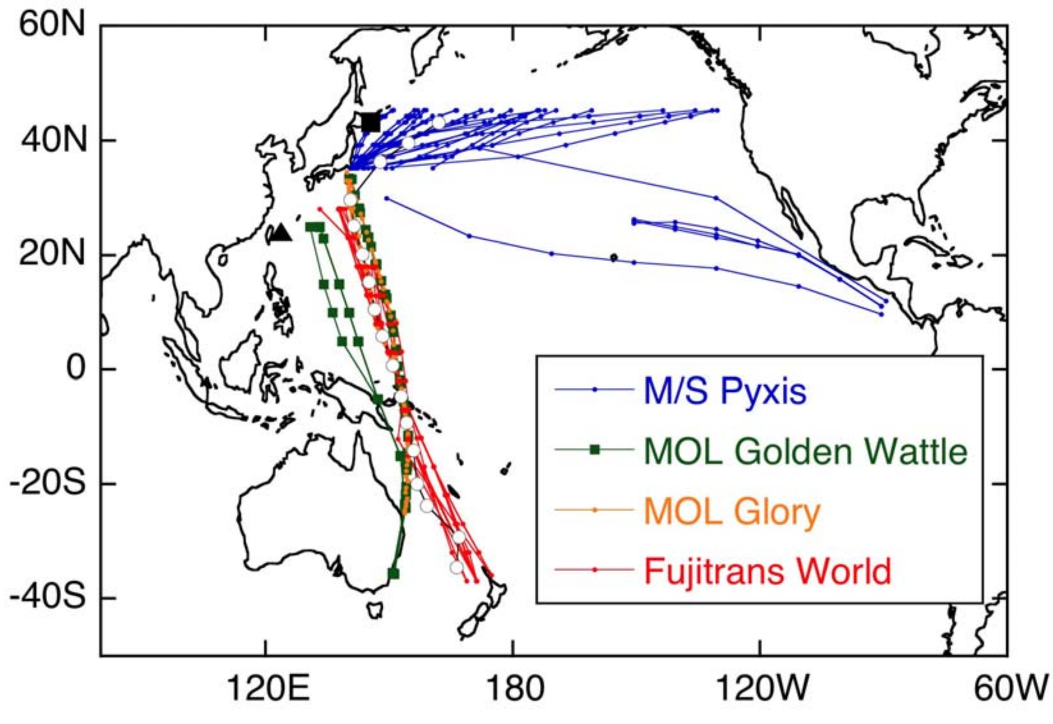


Fig. 1. Positions of sampling taken on board of cargo ships during the period from December 2001 through August 2004. Each color corresponds to a different ship. Open circles represent average positions for the binned data (see text). The closed square and the triangle indicate the location of Hateruma Island and Cape Ochi-ishi, respectively.

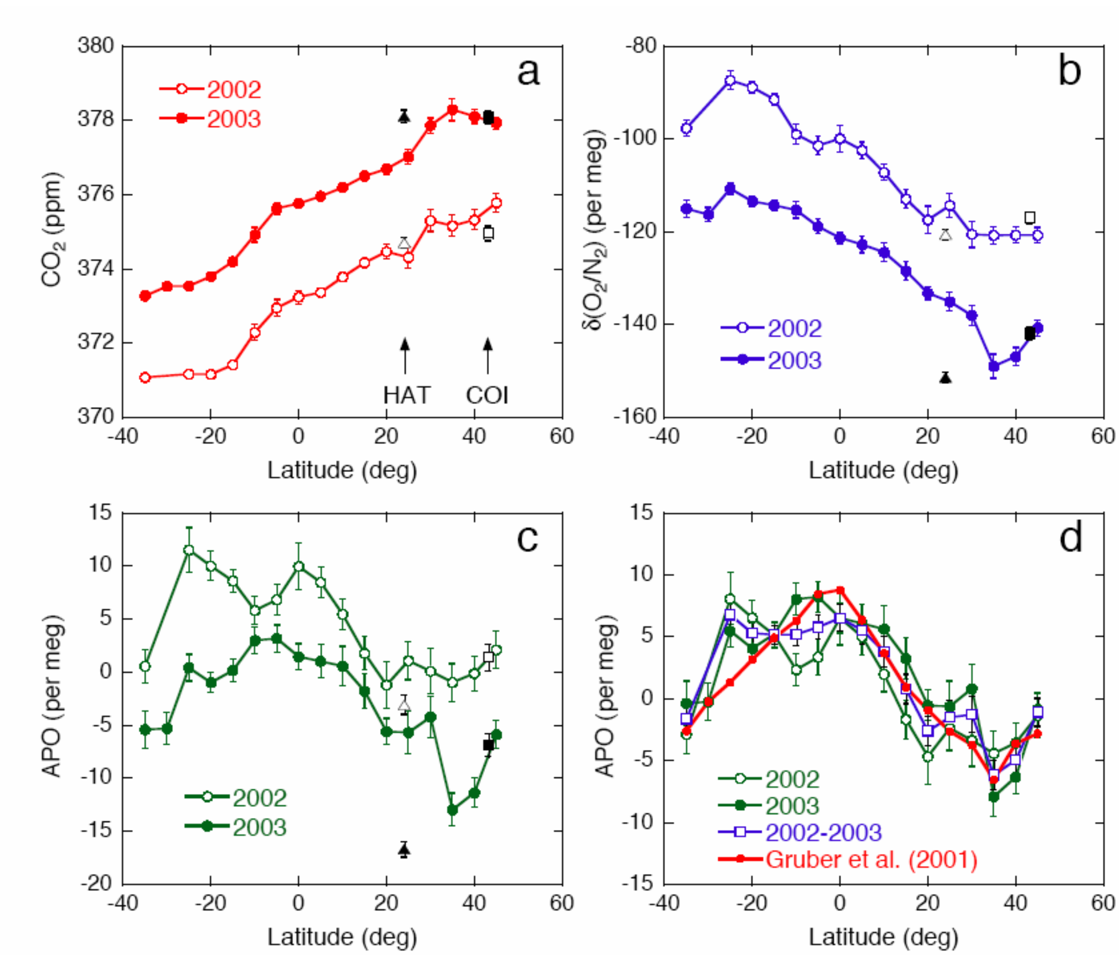


Fig. 2. Latitudinal distribution of annual mean (a) CO_2, (b) O_2/N_2, and (c) APO. Circles represent shipboard data, and squares and triangles represent the data at Ochi-ishi and Hateruma, respectively. Open and solid symbols indicate averages for 2002 and 2003, respectively. (d) Comparison of observed annual mean APO with the model simulation results of *Gruber et al.* (2001). Individual profiles of the observed APO are shifted to visually fit the model-simulated APO profile.

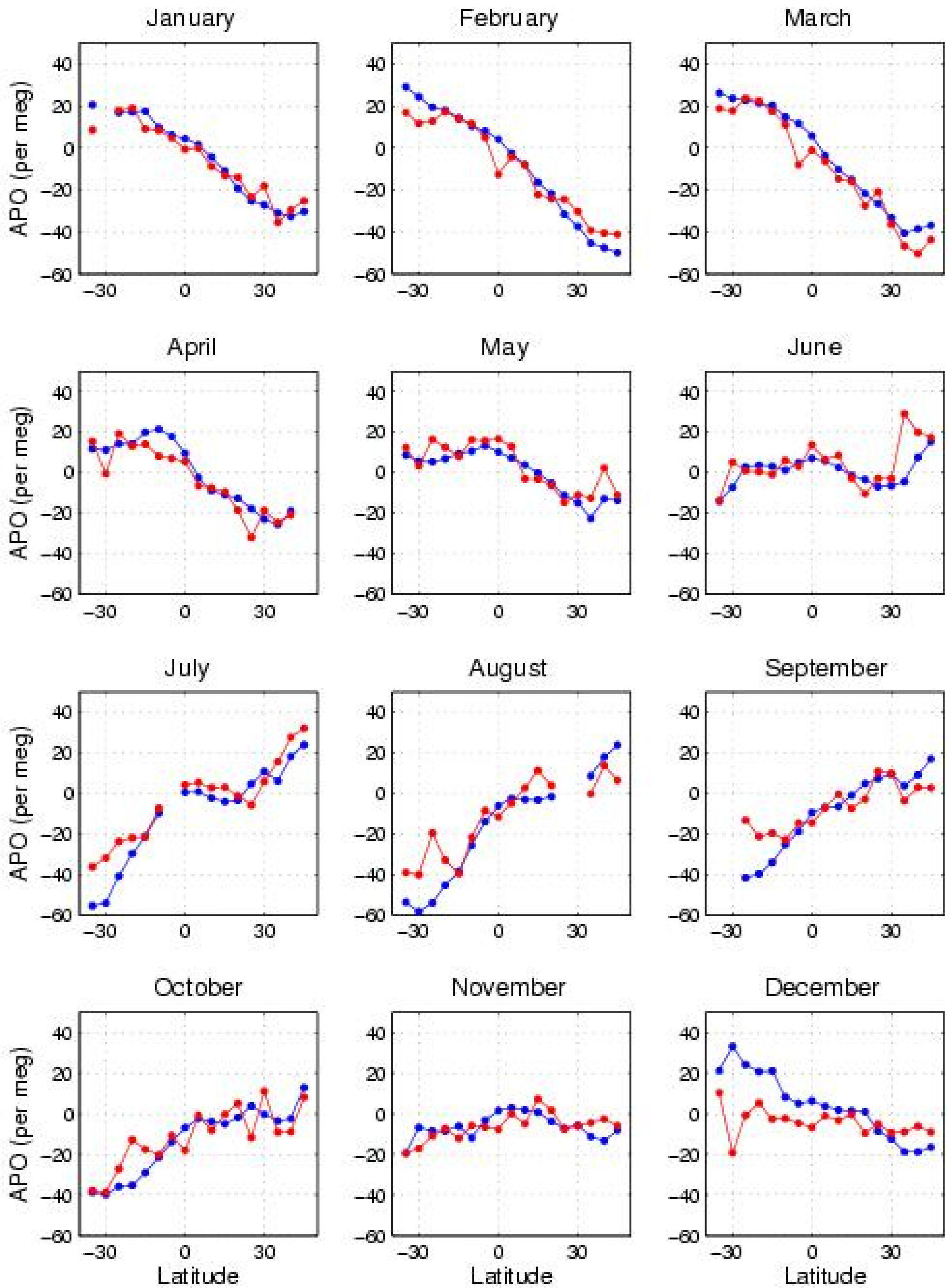


Fig. 3. Latitudinal distribution of monthly mean APO data (red) with predictions of *Gruber et al.* (2001) (blue).

Progress Report: **Non-reactive Tracer Transport Evaluation of the Mozart Atmospheric Transport and Chemistry Model Using SF_6**

Principal Investigator: Emanuel Gloor (Princeton Research Scholar)

Other Participating Researchers: E. Dlugokensky, P. Bakwin, Pieter Tans (NOAA/CMDL Boulder, Colorado), Larry Horowitz (GFDL), and Cyril Crevoisier (Princeton)

Theme #2: Biogeochemistry

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

Objectives: Evaluation of model transport of medium-to-long lived tracers

Methods and Results/Accomplishments:

A precursor step for developing time-dependent inverse modeling of atmospheric transport to estimate sources and sinks using atmospheric CO_2, CH_4, and CO concentration data, is to evaluate model transport of medium-to-long lived tracers of the underlying transport model. One standard tracer for this purpose is SF_6 which has been used for example by the Transcom Model inter-comparison study. SF_6 has a life-time of ~3200 years and its source is almost entirely man made. Major applications are its use as an insulating gas in high voltage switch gear and as a blanket gas for magnesium production. Based on production and sales statistics it is therefore possible to estimate the spatial distribution and magnitude of its emissions fairly well. Such estimates are available up to the year 1995.

In 1997 CMDL/NOAA has started to measure SF_6 routinely at many surface stations and more recently also vertical profiles up to 6-8 km height are measured with help of aircraft. Vertical profiles are available at several stations in the USA as well as in Alaska, the Amazon, Mauna Loa and Cook Islands. In addition there are continuous records from the Wisconsin tall tower station. To the extent that surface emissions are known the available data permit to evaluate model representation of (i) inter-hemispheric air-mass exchange, (ii) planetary boundary layer free troposphere air-mass exchange and (iii) variation of transport pathways due to synoptic as well as longer-term variation like the one associated with the seasonal cycle of the ITCZ location.

In order to extend existing surface emission distributions in time for data – model comparison we have used a global composite of atmospheric observations to estimate a global growth rate and scaled the 1995 emissions distribution for use in the models accordingly to later years. For the comparisons an offset is added to the simulations which is based on the Mauna Loa record. Data model comparisons of the annual mean inter-hemispheric gradient (Figure 1) for three subsequent years reveal quite good agreement. Southern hemisphere SF_6 in the year 2000 is slightly under-predicted while simulated concentrations North of 40 degrees for the year 2001 are a bit too high. Comparison of simulation predictions with continuous data from the Wisconsin tall tower station (Figure 2) reveals that episodic pollution events are also captured very well by the model while the concentrations associated with these events are over-predicted during winter. This indicates that wintertime PBL-free troposphere exchange over the USA and probably generally over northern mid-hemisphere continents is too weak in the model. This conclusion is supported by vertical aircraft profile data measured at the Wisconsin site as well as other locations in the USA (not shown). Based on this latter finding we will retune the PBL-free troposphere exchange parameterizations in Mozart.

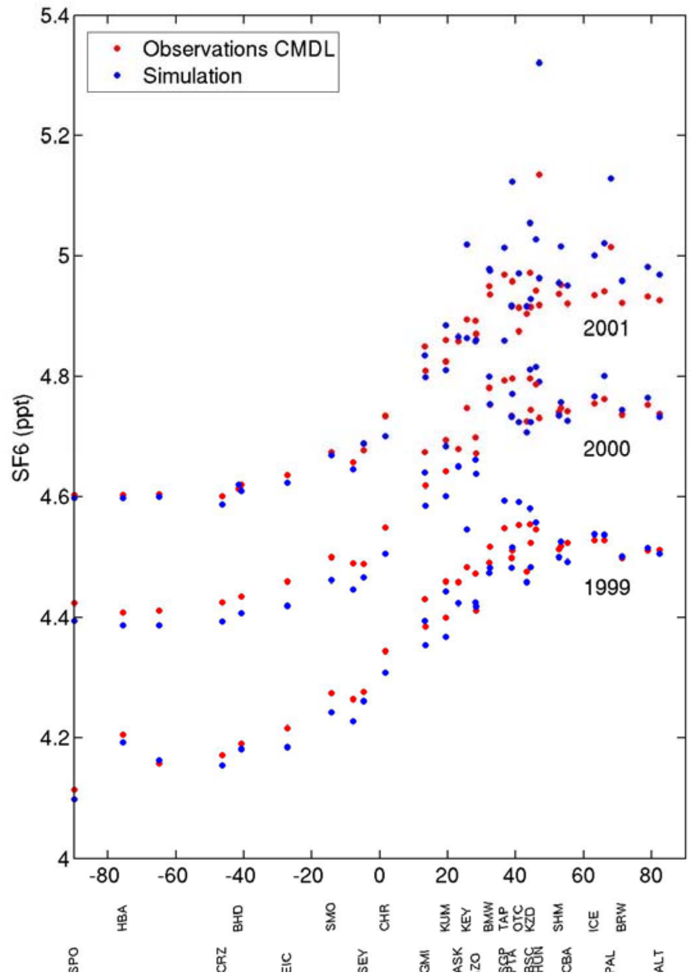


Fig. 1 Observed and simulated latitudinal distribution of annual mean atmospheric SF_6 concentration.

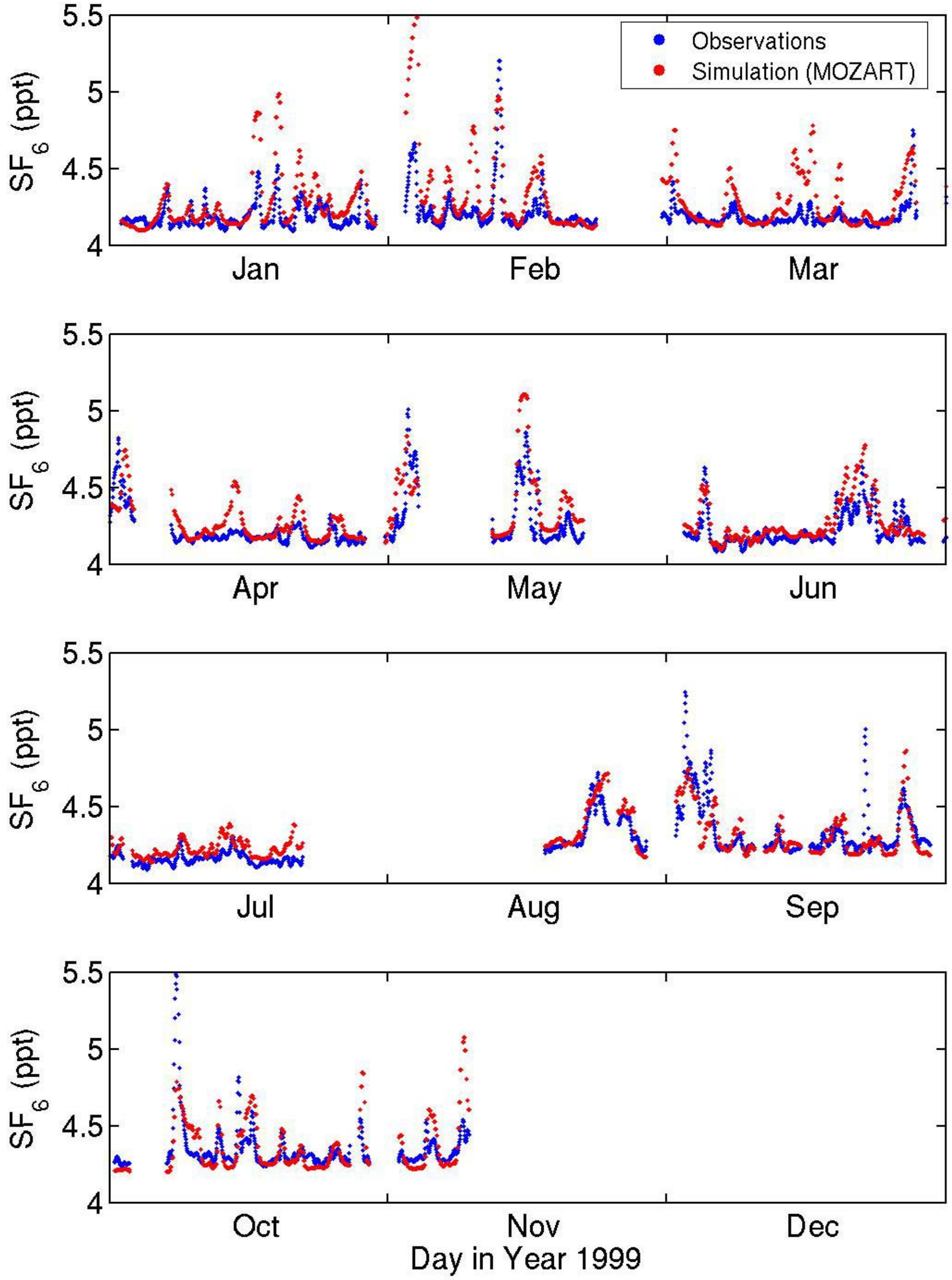


Fig. 2 Observed and simulated SF_6 during 1999 observed 396 m above ground at the Wisconsin tall tower station.

Progress Report: **Implementation of a Nitrogen Cycle into GFDL's Existing Earth System Model**

Principal Investigators: Lars Hedin and Michael Oppenheimer (Princeton Faculty)

Other Participating Researchers: Stefan Gerber and Stephen W. Pacala (Princeton)

Theme #2: Biogeochemistry

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

Objectives: To understand the role and feedbacks of the terrestrial nutrient cycle in a changing climate.

Methods and Accomplishments:

Since Stefan Gerber joined our group, we have over the past year developed a strategy for adding nitrogen to the current Land Model 3 of NOAA/GFDL. A first version of this nitrogen model is now being implemented. We have spent considerable effort on strategies for representing soil nutrients in general, and the decomposition of soil organic matter in particular. The climate-dependence of such decomposition-nutrient dynamics constitute a major feedback within land-based systems, and must therefore be characterized appropriately in earth system models. We are currently addressing the following questions, each of which is of fundamental importance to the dynamical properties of the soil-nutrient feedback:

- Carbon to nutrient ratios in fresh litter suggest that decomposers should be limited by inorganic nutrients such as nitrogen (but not carbon). In contrast, fertilization experiments show that additions of carbon increases decomposition rates more that addition of nutrients. How should carbon vs. inorganic nutrient limitation best be represented in the soil feedback model?
- Decomposers are considered as better competitors for nutrients than plants. How can plants acquire nutrients in a system with low nutrient availability?
- Humic soil organic matter turns over on time scale of decades, is rich in nitrogen, but the materials from which they are formed (i.e. lignin, tannin) have a very low nitrogen content. It is believed that the incorporation of nitrogen into slow soil organic matter is mediated by decomposers (mainly heterotrophic microbes). How may this process affect nutrient supply to plants and decomposers, and how should it be represented in a global model?

We derived a formulation for decomposition of soil organic matter that includes nitrogen based on simple equations for heterotrophic microbes as the main decomposers responding to supply of carbon and nitrogen. As the microbial pool turns over relatively fast compared to soil organic matter pools, nutrient demand by plants and other such internal ecosystem processes, we consider the microbial biomass to be in steady state with respect to carbon and nitrogen supply rates. A minimum model that can address the questions above consists of three soil organic matter pools: Two litter pools with turnover times of months to a few years. One is fueled by easy decomposable plant material such as leaves and fine roots that have high nitrogen concentration, while the other is fueled by of structural plant materials that have low nitrogen content. A third non-litter pool represents humic material formed by the decomposition litter that decays on time scales of decades. In our model, the microbially mediated nitrogen enrichment during formation of humic material can cause a reduction in the decomposition rate of the structural litter pool, when nitrogen supply is small enough. However, the intensity of nitrogen limitation during decomposition is kinetically sensitive to how much microbial nitrogen contributes to the newly formed humic material, and also affects the nitrogen supply to plants after a disturbance event. Finally, leaching rates are based on soil mineral nitrogen concentration and water discharge, while plant uptake is a function of the soil mineral nitrogen content and soil fine root concentration. The model is in the process of implementation and initial evaluation.

In addition we consider introducing a biogeochemical layering within the soil environment, where the decomposers only have access to the nutrient supply in each respective layer. Such formulation is analogous to how hydrologists deal with vertical soil water distribution in analogous modeling efforts. Simple models assuming a layering in combination with the above setup predict a nitrogen limitation during decomposition on the top while at a lower level the system switches to net mineralization. While assuming superiority of the decomposers in acquiring the nitrogen net mineralization in lower levels allows nitrogen supply to plants. Layering can also provide a basis to improve the formulation of other biogeochemical processes, such as the decomposition rates depending on the availability of oxygen, the formulation of an improved wildfire module, and possibly denitrification rates.

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

Principal Investigator: George M. Hurtt (University of New Hampshire Faculty)

Other Participating Researchers: Steve Frolking (Assistant Research Professor)

Theme #2: Biogeochemistry

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

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

Methods and Results/Accomplishments:

Human activities have altered the land surface and terrestrial ecosystems in significant ways. Important physical properties, biogeochemical cycles, and hydrological stocks/fluxes have all been substantially altered by land-use activities. In order to include these effects in the new GFDL Earth System Model, two essential advances are required: (1) spatio-temporal datasets on land-use activity and management (e.g. location of crop and pasture, land-use transitions, dominant crop types, irrigation, fertilizer use, livestock populations, logging, fire management, fate of products etc.); and (2) the capacity to simulate biogeochemical cycling in these agricultural systems, including the impacts of changing management practices. For 2004-05, we proposed to focus on the patterns of land use, and initiate work with Princeton/GFDL scientists on developing submodels of the relevant biogeochemical cycling. We also proposed to begin work on several other key land-use phenomena needed for ESM applications including: patterns of fire risk/management, maps of agriculture management, fate of agricultural products, and biogeochemical dynamics. We proposed to work with Princeton/GFDL scientists to support the integration of these products, and to pursue scientific applications using them.

During the past year, we made substantial progress on all of these fronts. First and foremost, we completed the development and initial application of a new Global Land-Use Model (GLM) that provides global gridded estimates of the land-use history needed to characterize the state of the land surface. GLM is a synthesis model. For input, it uses available historical records of land-use patterns, remote sensing, and global census datasets. It incorporates the HYDE (Goldewijk 2001) and SAGE Ramankutty et al. 1999) global gridded land-use datasets, global human population estimates for 1700-1990, and FAO (2003) national wood harvesting statistics 1961-1990. Pre-1961 national wood harvest totals are estimated from per capita wood harvest rates during the period of FAO record and estimates of historic population density. Whereas previous studies have focused on the patterns of permanent agriculture alone, the output GLM consists of annual global (1°x1°) estimates of forward land-use transition rates that specify the fraction of each grid cell that is modified by humans through time (e.g. crop, pasture, shifting cultivation, logging, recovering lands, …). A scenario approach has been used to produce an ensemble of products with which to assess the sensitivity of important unknowns. Our results include the first global gridded estimates of land conversion events (land-use transitions), wood harvesting, and resulting secondary lands annually, for the period 1700-2000. Using data-based historical scenarios, 42-68% of the land surface was impacted by land-use activities (crop, pasture, wood harvest) during 1700-2000, some areas multiple times. Secondary land area increased 10-44 x 10^6 km^2; about half of this was forested. Wood harvest and shifting cultivation generated 70-90% of the secondary land by 2000; permanent abandonment and relocation of agricultural land accounted for the rest. This work is undergoing revision for the journal Global Change Biology (Hurtt et al., in review), has been presented at numerous high-profile scientific meetings/conferences, and provides key input to the new GFDL land model LM3V (Shevliakova et al., in review) and other IPCC modeling teams.

In 2004-2005, we also made progress on the secondary objective of beginning work on several additional key land use phenomena needed for ESM applications. Our work focused in two areas. (1) Our fire submodel was revised, coupled to a global DGVM, and shown to produce reasonably spatial/temporal dynamics in response to El Nino oscillations (Girod et al 2004). In addition, a model for fire dynamics and fire-suppression activities was been developed and parameterized and applied for estimating future fire risk for the U.S. (Girod et al, in prep). (2) We supplemented our maps of agricultural activities with detailed maps on crop types (e.g. C3 annual, C3 perennial, C4 annual, …), functional parameters for crop plants (e.g. allometry, physiology, allocation, LAI, …), and preliminary estimates of planting/harvest dates. Results of these activities are a priority for accurately simulating management activities, and are currently being incorporated offline modeling studies at UNH, and will be included into future versions of the LM model at GFDL/Princeton.

Publications

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Progress Report: **Inverse Modeling of Surface Carbon Fluxes**

Principal Investigator: Andrew Jacobson (Princeton Research Staff)

Other Participating Researchers: J. Sarmiento, M. Gloor, (Princeton), N. Gruber, and S. Mikaloff-Fletcher (UCLA)

Theme #2: Biogeochemistry

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

***Objectives**:* Estimating Carbon Sources and Sinks

Methods and Results/Accomplishments:

We have constructed an estimate of annual-mean surface fluxes of carbon dioxide for the period 1992-6 using observational constraints from the atmosphere and from the ocean interior. The method interprets *in situ* observations of carbon dioxide concentration in the ocean and atmosphere using transport estimates from global circulation models. Uncertainty in the modeled circulation is explicitly considered in this inversion by using a suite of 16 atmospheric and 10 oceanic transport simulations. We estimate that the open ocean took up 2.1 $PgCyr^{-1}$ of anthropogenic carbon during this period, offset by the natural outgassing of about 0.5 $PgCyr^{-1}$ of carbon fixed on land and transported through rivers to the open ocean. Despite a comprehensive effort to quantify sources of error due to modeling biases, uncertain riverine carbon load, and biogeochemical assumptions, the uncertainty on this global air-sea flux estimate is driven down to ±0.2 $PgCyr^{-1}$ by the large number of oceanic observations used. While atmospheric data have little impact on the final air-sea flux estimates, the inclusion of ocean data drives a substantial change in terrestrial flux estimates. Our results indicate that the tropical and southern land regions together are a large source of carbon, with a 77% probability that their aggregate source size exceeds 1 $PgCyr^{-1}$. This value is of similar magnitude to estimates of fluxes in the tropics due to land-use change alone, making the existence of a large tropical CO_2 fertilization sink unlikely. This terrestrial flux result is strongly driven by ocean inversion estimates of a relatively small Southern Ocean sink (south of 44°S) and a relatively large sink in the southern temperate latitudes (44°S-18°S).

We perform independent atmospheric and oceanic inversions using standard techniques of weighted linear least squares optimization. The atmospheric inversion differs from commonly used methods in that no priors or regularization techniques are used. The oceanic inversion follows the methodology of *Gloor et al.* (2003), and yields separate estimates of pre-industrial and anthropogenic fluxes. These air-sea flux estimates are tightly constrained by the large number of ocean interior data used (more than 67,000 observations). The atmospheric and oceanic flux estimates are then statistically combined *ex post facto* by exploiting the fact that they both provide independent estimates of air-sea flux. In combining the results, the small oceanic uncertainty drives a readjustment of terrestrial fluxes. This is due to the interdependence of flux estimates for proximate regions in the atmospheric inversion, owing to the sparseness of observations and vigorous zonal mixing in the atmosphere. We exploit such flux correlations, and specifically those between land and ocean regions, to produce our joint estimate. Mathematically, information is communicated from the ocean to the land via the flux covariance matrix resulting from the atmospheric inversion.

In the southern hemisphere south of 18°S, air-sea flux estimates deriving from the oceanic inversion differ significantly from the ΔpCO_2-based climatology of *Takahashi et al.* (2002), and

OCMIP2-style forward simulations of the ocean carbon cycle (Fig. 1). In particular, we find a smaller Southern Ocean sink and a larger temperate sink than predicted by other methods. These differences can be attributed to preindustrial fluxes, and are robust in the face of transport uncertainty, identified biases in the determination of anthropogenic carbon content, and assumptions about the stoichiometry of remineralized organic material (*Jacobson et al.,* submitted to *Global Biogeochemical Cycles*). These oceanic inversion flux results are also consistent with those from inversions using a more diverse suite of models (*Mikaloff Fletcher et al.*, submitted to *Global Biogeochemical Cycles*).

The different meridional distribution of air-sea fluxes has a strong impact on the atmospheric inversion, since the southern hemisphere and tropical regions are particularly poorly constrained by available atmospheric observations. We find that while the land regions of the tropics and southern hemisphere cannot be reliably distinguished from one another, their aggregate can be reasonably constrained. This aggregate region becomes a statistically significant source of carbon (1.8 ± 1.1 $PgCyr^{-1}$) when the oceanic constraint is considered. Atmosphere-only inversions do not detect this source. This source, which represents the net land-atmosphere exchange, is of a size comparable to satellite- and field-based estimates of tropical land use change fluxes due principally to deforestation, which range from 1-2 $PgCyr^{-1}$. It is therefore unnecessary to invoke the existence of a large CO_2 fertilization sink in the tropics to close the carbon budget.

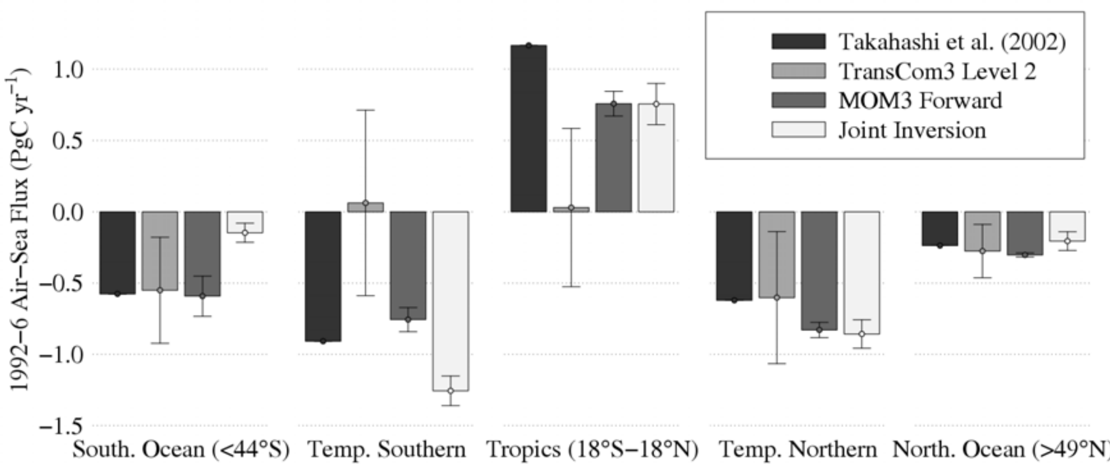

Fig. 1. Air-sea flux estimates from various sources for 1992-6, aggregated by broad latitude band. From left to right within each latitude band, the estimates are the ΔpCO_2-based climatology of *Takahashi et al.* (2002), the TransCom3 atmospheric inverse estimate of *Gurney et al.* (2004), forward simulations of five configurations of the MOM3 ocean general circulation model, and the present results ("joint inversion"). Error bars represent one standard deviation for estimates that include uncertainties

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

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

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

Theme #2: Biogeochemistry

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

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

Methods and Results/Accomplishments:

In large part this work represents a continuation and natural extension of the Global Ocean Data Analysis Project (GLODAP). The primary goal of GLODAP was too use the massive oceanographic data set collected during the1990s to quantify the inventory of anthropogenic carbon dioxide in the ocean. The current project has three components: (1) data recovery, (2) data collection and (3) analysis and inovation, each discussed briefly below.

(1) Data recovery is primarily aimed at salvaging a large collection of oceanographic measurements made by the European scientific community during the 1980s-1990s. All of these data are from the North Atlantic and are critical for two reasons. First the WOCE/JGOFS Atlantic data set from the 1990s is particularly sparse relative to the importance of the North Atlantic region to global scale issues and the European data will fill that data gap, and second the European data has the potential to extend what we know about the carbon chemistry of the North Atlantic backward in time by almost a decade. The European data were originally accumulated into a collection known as CARINA (Carbon Dioxide in the North Atlantic). Unfortunately, that effort failed largely due to lack of funding. We have retrieved approximately 50 cruises that included ocean carbon measurements. Contact principal investigators have been identified for each data set and the initial quality control has been completed (flagging and meta-data collection). All of the data have been formatted and the individual files returned to the originators with problems identified, etc. We are now awaiting response from the originators. At that point final calibration will be initiated. Initial investigation indicates that approximately 75% of the data will be of sufficient quality to use for anthropogenic investigation. Analysis of the calibrated data will be done by the data originators in collaboration with Key. The final calibrated data will be published as a merged data set via CDIAC. The final completion date of this project is beyond our control, but we are hopeful to finish by early 2006.

(2) Members of this group and others (primarily Frank Millero (U. Miami, RSMAS) and Andrew Dickson (UCSD, SIO) are participating in current ocean sampling as part of the U.S. led CLIVAR project. These cruises are covering some of the same lines sampled during the 1990 in order to document the change in anthropogenic carbon dioxide on a decadal time scale. All of the CLIVAR carbon data collected thus far are extremely high quality. In keeping with CLIVAR goals, these new data have been through the initial quality control and calibration procedures and made public through CDIAC by approximately one year after the end of each cruise. In addition to the U.S. generated data, Key and Kozyr have applied the same procedures to a series of Japanese cruise data sets which are part of the Japanese CLIVAR effort. A totally independent effort having similar goals is being executed by the European community. This project is known

as CarboOcean and is focused on carbon in the North Atlantic. Key is participating in this effort to help assure that the two projects coordinate as well as possible and to help assure that data sharing between the groups is as easy as possible.

(3) The analysis phase of this project is in the very early stages. As new data become available we have compared anthropogenic carbon dioxide estimates derived from CLIVAR cruise sections to those collected during WOCE. With a time separation of 5-10 years for the cruises, the challenges are significant. We expect increases of anthropogenic carbon dioxide in the upper ocean to approximately track the increase in the atmosphere – that is, the equivalent of 1 part per million pCO_2 per year. Not surprisingly, differences along the repeat sections are complex. Routine comparison methods yield difference plots which can only be described as messy. This result derives from the fact that the increase is near the detection limit of the procedure and the fact that the upper ocean is not static. We are currently investigating improved methods, but are very encouraged by the fact that large scale mean differences indicate that the oceanic increase is approximately keeping pace with the atmosphere. That is, we can monitor decadal time scale changes. In most instances, once the data are sufficiently smoothed, the pattern of change agrees with known oceanographic ventilation and mixing patterns. Totally new insights are expected as we gather more data and look in detail at the smaller scale changes. Two totally new investigation tools are being developed. The first is in collaboration with Darryn Waugh and Tim Hall who have devised a new method to discriminate anthropogenic carbon dioxide from the background (natural) signal. This new method does a much better job of accounting for ocean mixing than the method initially used during GLODAP and of almost equal importance, it is much easier to apply. This new technique is currently being applied to the same data set used for the initial GLODAP anthropogenic carbon dioxide estimates so that direct and detailed comparisons are possible. The second is a totally novel approach in which information from the suite of ARGO floats is used in effect to extrapolate the sparse CLIVAR carbon data to basin-wide scales. Early results are very promising, however, it is also already obvious, that the method would be significantly improved if/when the ARGO temperature and salinity data are supplemented - initially with oxygen and then with one or more carbon species sensors.

Publications:

No refereed publications have yet resulted from this work, however several talks and posters will be presented at the carbon symposium in Boulder and at the AGU/ASLO meeting early next year.

***Progress Report*:** **Development of Dynamic GFDL/Princeton University Land Model LM3 and Analysis of Land-Atmosphere Interactions**

Principal Investigator: Stephen Pacala (Princeton Faculty)

Other Participating Researchers: Elena Shevliakova and Sergey Malyshev (Princeton)

Theme #2: Biogeochemistry

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

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

Methods and Results/Accomplishments:

A dynamic land model LM3V has been implemented and evaluated (Shevliakova et al., submitted). The model is capable of simulating global distribution and functioning of terrestrial carbon sources and sinks as well as the exchange of water and energy between land, vegetation, and atmosphere. The land model tracks carbon dynamics of vegetation and soil in response to environmental conditions, ambient concentration of CO_2, natural disturbances (e.g. fire), and anthropogenic land use changes (e.g. deforestation, agricultural cropland abandonment, secondary forest harvesting). Additionally, changes in distribution of vegetation and its structural characteristics are affecting key land surface parameters such as albedo and surface roughness. The model has capabilities to run in the "static mode" (i.e. with a prescribed set of vegetation state variables).

The land model has undergone a series of experiments with prescribed climate and coupled to the GFDL atmospheric model (Andersen et al., 2004). A suite of experiments with LM3V and prescribed climate was performed in order to reconstruct the global terrestrial carbon sink from 1700 to present and to partition its causes among land use (Hurtt et al., submitted), climate change and CO_2 fertilization. The results will be presented at ICDC7 conference in Boulder, CO (September 2005) and will be described in a paper. Additionally, these runs were analyzed to explore the relationships between land carbon fluxes and different modes of climate variability (in collaboration with Joellen Russell, AOS, Princeton University). The findings of this analysis will be presented at ICDC7 conference as well.

Currently, Shevliakova and Malyshev are working on evaluation and improvements in simulations of regional distribution of carbon and water fluxes, their diurnal and seasonal patterns and different modes of variability. A number of experiments with the land model coupled to the GFDL atmospheric and slab ocean climate models are underway with two foci: 1) interactions and feedbacks between climate and land cover over the XXth century; and 2) implications of the future increasing greenhouse gas concentrations (IPCC scenarios) on land-atmosphere-climate system.

Shevliakova and Malyshev are preparing to explore the full range of land-climate interactions with the coupled climate model CM2.1 (Delworth et al., 2005). Additionally, they are evaluating performance of LM3V as a component of the GFDL Earth System model (including interactive CO_2 capability).

Sergey Malyshev is continuing to work on the integration of LM3V described above with the improved soil hydrology model LM3W developed by P.C.D.
Milly (USGS), to result in more comprehensive model capable of describing hydrological and biological processes on the land surface with high degree of realism on time scales from minutes to centuries.

Sergey Malyshev has been involved in the joint GFDL/Princeton University project to study the influence of soil moisture treatment on the quality of seasonal forecasts. Together with Dr. C. T. Gordon, they developed a scheme to initialize GFDL's atmospheric data with the atmospheric state obtained from reanalysis and soil moisture from standalone land model simulations forced with observed data. Special attention has been paid to the method of generating atmospheric initial conditions for different ensemble members to cover the error space of the analysis and thereby provide better ensemble forecast at the initial period of the simulations. Two presentations on the results of this work are going to be made at the NOAA's 30th Annual Climate Diagnostics and Prediction Workshop in October 2005, with planned follow-up publications.

Sergey Malyshev has also participated, together with C.T. Gordon (GFDL), in collaborative Global Land-Atmosphere Coupled Experiment (GLACE, http://glace.gsfc.nasa.gov/). The purpose of this project is to establish the coupling strength between land and atmosphere components in a number of GCMs, to improve understanding of land processes in general, and understanding of differences among models in particular. Currently the simulations with GFDL models and the results of other modeling groups are being analyzed by the project team and prepared for publications. First results of the study have been recently published in Koster et al. (2004).

Two additional papers describing GLACE in detail are currently under review (Koster et al., in review and Guo et al., in review)

Publications:

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Malyshev, Bryant McAvaney, Ken Mitchell, David Mocko, Taikan Oki, Keith Oleson, Andrew Pitman, Y. C. Sud, Christopher M.Taylor, Diana Verseghy, Ratko Vasic, Yongkang Xue, and Tomohito Yamada, Regions of Strong Coupling Between Soil Moisture and Precipitation. Science 20 August 2004; 305: 1138-1140

Progress Report: **Ocean Carbon Model Development**

Principal Investigator: Jorge L. Sarmiento (Princeton Faculty)

Other Participating Researchers: Jennifer Simeon and Richard Slater (Princeton), John Dunne and Anand Gnanadesikan (GFDL)

Theme #2: Biogeochemistry

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

Objectives: Development of ocean circulation and ocean carbon biogeochemistry models for simulating the air-sea balance of carbon, the oceanic uptake of anthropogenic carbon, and the influence of climate change on these.

Methods and Results/Accomplishments:

While it is well-known that on long time scales the ocean will absorb the bulk of CO_2 emitted by human activities to the atmosphere, the rate at which it does so is slow. As a result, the rate of ocean carbon uptake can play a major role in controlling the peak concentrations of atmospheric carbon dioxide. Funded in part by the NOAA, the Sarmiento group has played a major role in developing models for this process, embedding carbon cycle models in GFDL's general circulation models and examining what processes control the cycling of natural and anthropogenic carbon in these models.

The air-sea balance of carbon dioxide is determined by a combination of the solubility and biological pumps in the ocean. Simulating the solubility pump requires modeling the chemistry of carbon in the ocean, gas exchange at the air-sea interface, and ocean circulation. The chemistry of carbon is well understood and modeling it correctly is straightforward. NOAA scientists are playing a major role in estimating the air-sea flux of carbon dioxide, using both surface measurements of pCO_2 and profiles. Two CICS projects by Sweeney et al. and Jacobson et al. (described separately) are addressing the issue of air-sea gas fluxes as inferred from the observed interior distributions of radiocarbon and dissolved inorganic carbon. Both point towards serious inconsistencies in present air-sea flux estimates of radiocarbon and CO_2, the full implications of which are presently being evaluated.

CICS scientists have also been examining the sensitivity of the carbon cycle to unresolved physics in ocean models. The large tracer data set obtained during the World Ocean Circulation Experiment, particularly measurements of chlorofluorocarbons (CFC) and radiocarbon, have provided us with an unprecedented opportunity for evaluating the wide range of ocean circulation models that are currently in use around the world for studying the ocean carbon cycle. The publications by *Doney et al.* [2004] and *Gnanadesikan et al.* [2004] describe both an international and an internal (to CICS and GFDL) set of model comparison studies and evaluate the models vis-à-vis the observations. These studies highlight the importance of realistic levels of Southern Ocean ventilation for a realistic carbon cycle-and show that the wind field within the Southern Ocean can play an important role in setting this ventilation. The suite of models developed by CICS for use in the Ocean Carbon Model Intercomparison Project (OCMIP) has also been used to examine the energetics of heat transport in the ocean (*Gnanadesikan et al.* [2005]) and the processes in the Southern Ocean that control the uptake of anthropogenic carbon in that region (*Mignone et al.* [submitted]), are laying the groundwork for improving models of ocean circulation used for biogeochemical simulations.

Simulating the biological pump in the ocean requires models of the production, export and remineralization of organic matter by organisms. In *Dunne et al.* [submitted), we describe components of and results from the new ecosystem model that GFDL/CICS has developed. In *Jin et al.* [submitted], we describe an effort to diagnose the biological production of various biological functional groups using observed nutrient distributions together with ocean circulation models. This approach enables us to estimate the production of opal by diatoms, $CaCO_3$ shells by coccolithophorids and foraminifera, as well as total uptake of nutrients. We use the simple ecosystem model of *Dunne et al.* [submitted) to further separate the total uptake of nutrients into that due to small versus that due to large phytoplankton. We are presently examining how to use the results of this diagnostic analysis to develop new empirically-based models of production by the different functional groups. A completely independent empirical model of biological production is also being developed based on satellite observations. This is described in the Ocean Biological Response to Climate Change project. Finally, in her PhD thesis completed in 2005, Irina Marinov studied the interactions between the biological and solubility pumps, examining the extent to which they compensate each other.

The ocean carbon models being developed as part of this CICS project are being implemented in the GFDL Earth System Model (ESM), and members of this group are contributing in various ways to the further development of the ESM. Accomplishments include implementation of the *Dunne et al.* [submitted] model in the ESM, and the use of lessons learned from the OCMIP suite of models in guiding the choices made in tuning the ocean model for the GFDL coupled climate model. *Sweeney et al.* [2005] implemented a data-based parameterization for the absorption of shortwave radiation in the upper ocean. This parameterization, which is currently being implemented in the GFDL isopycnal model, has a noticeable impact on sea surface temperatures. Slater has developed a generalized gas flux-coupler between the ocean, atmosphere and land models in the context of the GFDL Flexible Modeling System (FMS). The framework allows an arbitrary number of gases to be transferred across the ocean-atmosphere and land-atmosphere interfaces. The ocean-atmosphere scheme is based on user-specifiable gas flux formulations based on wind speed, Schmidt number, solubility and oceanic and atmospheric concentrations. Carbon dioxide, oxygen and CFCs have been implemented within our ocean biogeochemistry models and land models. Work now is focusing on integrating this code into the latest release of the FMS so that it will be the default coupling scheme in FMS.

Finally, a new coarse resolution ocean model is currently under development by Simeon, Dunne, and Gnanadesikan, for simulating the global carbon cycle within a new coarse resolution ESM model over past millennia. Computational feasibility of century-long simulations requires conversion of the ocean component of the GFDL coupled climate model, MOM4, to a coarse-resolution ocean model capable of supporting a state-of-the-art prognostic biogeochemistry model (*Dunne et al.,* in prep). At present, the coarse-resolution ocean model is being analyzed and tuned to optimize the overturning circulation and surface boundary conditions.

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Progress Report: **Ocean Carbon Model Simulations and Analysis**

Principal Investigator: Jorge L. Sarmiento (Princeton Faculty)

Other Participating Researchers: Jennifer Simeon and Richard Slater (Princeton), John Dunne and Anand Gnanadesikan (GFDL)

Theme #2: Biogeochemistry

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

Objectives: Application of ocean carbon models to simulating the air-sea balance of carbon, the oceanic uptake of anthropogenic carbon, and the influence of climate change on these.

Methods and Results/Accomplishments:

The ocean carbon models that have been developed in CICS and at GFDL are being applied to a wide range of important problems, including estimates of the uptake of anthropogenic CO_2 by the oceans and an examination of carbon mitigation strategies. The study by *Matsumoto et al.* [2004] re-evaluated estimates of the uptake of CO_2 by ocean models after eliminating those whose fit to the CFC and radiocarbon observations was outside the range of uncertainty in the observations. The air-sea flux estimate of 1.7 ± 0.2 Pg C yr^{-1}, of which 2.2 Pg C yr^{1} is anthropogenic and the remaining ~0.45 Pg C yr^{-1} pre-anthropogenic, has a far smaller uncertainty than previous model based analyses, and is in complete agreement with the new joint inverse estimate of *Jacobson et al.* [submitted]. Taken together with other recent estimates of the air-sea CO_2 flux shown in the attached table, it is clear that the uncertainty in the ocean carbon uptake flux has dropped significantly since the IPCC Third Assessment Report to the point where it is now almost comparable to the uncertainty in the observed atmospheric increase and fossil fuel emissions.

Ocean carbon mitigation by deep sea injection has been studied by *Mignone et al.* [2004], who examined how the efficiency of the sequestration varied with ocean circulation in a suite of ocean circulation models developed at CICS/GFDL. This work shows that the efficiency is a strong function of the vertical diffusivity. The sensitivity of the sequestration efficiency to ocean circulation is particularly high in the Southern Ocean. The studies by *Edmonds et al.* [2004], *Greenblatt et al.* [2004], and *Marinov et al.* [2004], provide an overview of the ocean sink for anthropogenic carbon, the processes that control it, its sensitivity to climate change, and, in *Edmonds et al.* [2004], an assessment of how our understanding of the oceanic carbon sink might influence assessments of what would be required to mitigate future increases of atmospheric CO_2.

Publications:

Edmonds, J., F. Joos, N. Nakicenovic, R. G. Richels, and J. L. Sarmiento, 2004. Scenarios, targets, gaps, and costs. In: The Global Carbon Cycle, ed. C. B. Field and M. R. Raupach, Island Press, Washington, D.C., pp. 77-102.

Greenblatt, J. B., and J. L. Sarmiento, 2004. Variability and climate feedback mechanisms in ocean uptake of CO_2. In: The Global Carbon Cycle, ed. C. B. Field and M. R. Raupach, Island Press, Washington, D.C., pp. 257-275.

Matsumoto, K., J.L. Sarmiento, R.M. Key, O. Aumont, J.L. Bullister, K. Caldeira, J.-M. Campin, S.C. Doney, H. Drange, J.-C. Dutay, M. Follows, Y. Gao, A. Gnanadesikan, N. Gruber, A. Ishida, F. Joos, K. Lindsay, E. Maier-Reimer, J.C. Marshall, R.J. Matear, P. Monfray, A. Mouchet, R. Najjar, G.-K. Plattner, R. Schlitzer, R. Slater, P.S. Swathi, I.J. Totterdell, M.-F. Weirig, Y. Yamanaka, A. Yool, J.C. Orr, 2004. Evaluation of ocean carbon cycle models with data-based metrics. Geophys. Res. Lett., 31, L07303, doi:10.1029/2003GL018970.

Mignone, B. K., J. L. Sarmiento, R. D. Slater, and A. Gnanadesikan, 2004. Sensitivity of sequestration efficiency to mixing processes in the global ocean. Energy, 29: 1467-1478

Marinov, I., and J. L. Sarmiento, 2004. The role of the oceans in the global carbon cycle: An overview. In: The Ocean Carbon Cycle and Climate, ed. M. Follows and T. Oguz, NATO

ANNUAL MEAN OCEANIC UPTAKE OF TOTAL CARBON INCLUDING THE PRE-INDUSTRIAL COMPONENT
($Pg\ C\ yr^{-1}$)

Reference	Method	Uptake
IPCC TAR [2001]	Based on measured atmospheric O_2 and CO_2	1.7 ± 0.5
	New Estimates	
Takahashi, et al. [2002]	Measurements of sea-air pCO_2 difference and [*Wanninkhof*, 1992] U^2 gas exchange model	1.6
	Measurements of sea-air pCO_2 difference and [*Wanninkhof and McGillis*, 1999] U^3 gas exchange model	2.3
Gurney, et al. [2002]	Inversions based on atmospheric transport models and observed CO_2	1.3 ± 1.0
McNeil, et al. [2003]	Ages estimated from observed CFC's	1.5 ± 0.4
Gloor, et al. [2003]	Inversions based on ocean transport models and observed DIC	1.5 ± 0.4
Matsumoto, et al. [2004]	Model simulations evaluated with CFC's and pre-bomb radiocarbon	1.7 ± 0.2
Jacobson, et al. [submitted]	Joint inversion based on atmospheric and oceanic observations and models	1.7 ± 0.2

Fluxes are normalized to 1992-1996 and include a pre-industrial degassing flux of ~0.45 $Pg\ C\ yr^{-1}$. For example, the anthropogenic carbon uptake obtained by *Jacobson et al.* [submitted] is 2.2 ± 0.2.

Progress Report: **Ocean Biological Response to Climate Change**

Principal Investigator: Jorge L. Sarmiento (Princeton Faculty)

Other Participating Researchers: Jennifer Simeon and Richard Slater (Princeton), John Dunne and Anand Gnanadesikan (GFDL).

Theme #2: Biogeochemistry

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

Objectives: Development and analysis of models for determining the impact of climate change on ocean biology.

Methods and Results/Accomplishments:

Anthropogenic CO_2 can affect ocean biology both through its direct effect on ocean chemistry and through its indirect effect on global climate exacerbated by anthropogenically induced changes in other greenhouse gases as well as aerosols. Understanding the potential impact of these chemical and climate changes on marine biology is critical to enhancing society's ability to plan and respond to the anthropogenic CO_2 increase. We have carried out a wide range of studies to examine the fundamental processes that control biology in the ocean, and have developed a number of simulations to examine how changes in those processes might affect ocean biology.

In *Orr et al.* [2005], we examined the effect of the CO_2 increase on ocean chemistry together with a wide group of other oceanographers. As the CO_2 concentration of the ocean increases, it becomes more acidic and the concentration of the carbonate ion decreases. Such chemical changes have previously been shown to have a significant direct impact on calcification rates in the ocean. Another effect of these chemical changes is that the saturation horizon of both aragonite and calcite rise in the ocean. Our re-examination of this problem in *Orr et al.* [2005], revealed that the rise in the saturation horizons is so rapid in the Southern Ocean, that the surface ocean becomes undersaturated with respect to aragonite by the middle of this century. This would very likely have highly deleterious effects on organisms such as pteropods and cold-water corals, that live in these waters and form their shells from aragonite.

In *Sarmiento et al.* [2004], we developed a biome classification scheme for the ocean based on upwelling and deep wintertime mixed layer depths as well as ice cover. We further developed a new model of ocean biology based on an empirical multiple linear regression of the log of chlorophyll estimated from satellite color observations to various physical properties predicted by coupled climate models, such as the depth of the wintertime mixed layer, the growing season length, and the surface temperature. This empirical chlorophyll model was used to predict the impact of global warming based on predictions by six different coupled climate models. The chlorophyll changes are relatively modest, as are the changes in global primary production estimated from the chlorophyll. However, there are dramatic regional changes associated with the poleward shift of all the biomes. We are presently developing a greatly improved empirical model based on new satellite observations.

In separate research, we demonstrated through a series of model simulations in a coarse resolution global ocean model that the Subantarctic Mode Water (SAMW) is ultimately responsible for about three-quarters of the biological production outside of the Southern Ocean (*Sarmiento et al.* [2004]; and *Marinov et al.* [submitted]). The response of this water mass to climate change is thus likely to have a significant impact on global biological production. We thus have undertaken a series of model simulation to examine the pathways by which the SAMW enters the base of the main thermocline from the Southern Ocean, and how it then upwells across the isopycnals to penetrate through the thermocline into the euphotic zone. We find that the primary pathway for lateral entry into the thermocline is the northward flowing eastern boundary currents of the subtropical regions of the ocean primarily driven by the geostrophic transport but also including an Ekman component (Figure 1). Upwelling of the nutrients occurs primarily on the eastern margins of the continents and along the equator. We use model simulations to separate the thermocline nutrients into a remineralized component as well as components that originate in the high latitudes. This analysis demonstrates that most of the production in the low latitudes is driven by remineralized nutrients that originally entered the main thermocline by the SAMW pathway (Figure 2).

Publications:

Marinov, I., A. Gnanadesikan, J. R. Toggweiler, and J. L. Sarmiento, submitted. Southern Ocean circulation decouples global biological production from atmospheric pCO_2. Nature.

Orr, J. C., V. J. Fabry, O. Aumont, L. Bopp, S. C. Doney, F. A. Feely, A. Gnanadesikan, N. Gruber, A. Ishida, F. Joos, R. M. Key, J. Sarmiento, and R. Slater, et al., September 2005: Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. Nature, 437(7059), 681-686

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

Sarmiento, J. L., R. Slater, R. Barber, L. Bopp, S. C. Doney, A. C. Hirst, J. Kleypas, R. Matear, U. Mikolajewicz, P. Monfray, V. Soldatov, S. A. Spall, and R. Stouffer, 2004. Response of ocean ecosystems to climate warming. Global Biogeochem . Cycles, 18, GB3003, doi:1029/2003GB002134.

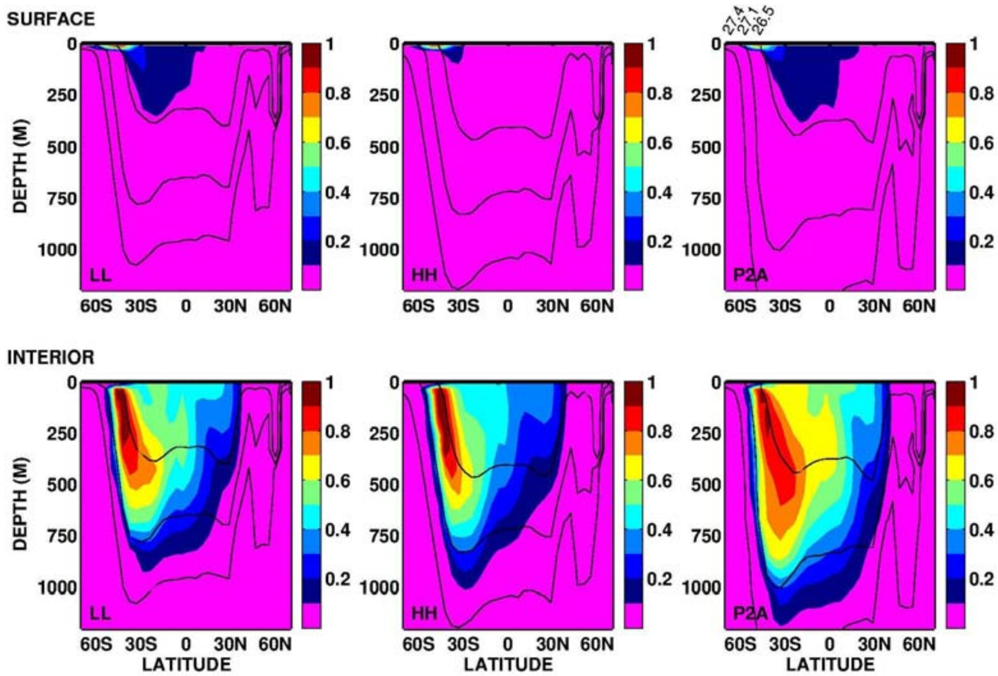

Fig. 1 Dye tracers are used to trace the Ekman and geostrophic equatorward transports away from the SAMW outcrop. A small fraction of SAMW outcrop water enters the shallow eastern boundary currents, while the majority of the SAMW outcrop water is subducted and then transported geostrophically away from the outcrop. Three different models are shown that differ in the magnitude of the diffusive mixing (it is higher in the HH model, which drives more equatorial upwelling and less Ekman transport) and the Southern Ocean winds (they are higher in model P2A, which gives both more Ekman and geostrophic transport).

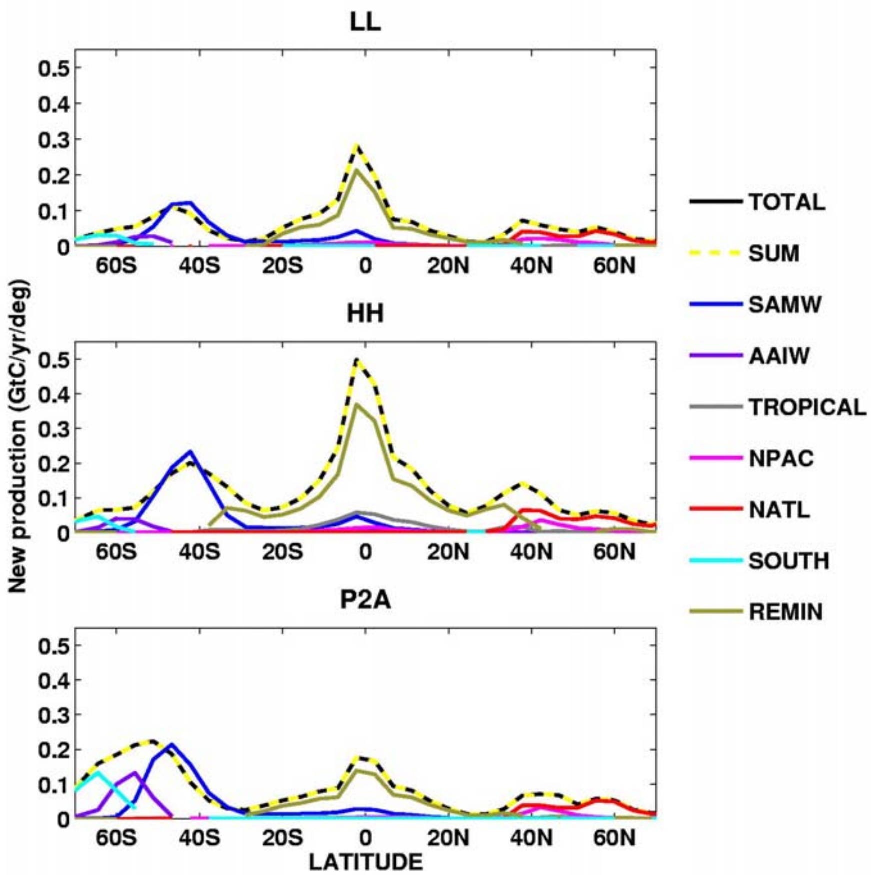

Fig 2 New production simulated in three model realizations of the global ocean overturning circulation. The top panel shows the "control" model, LL, where North Atlantic Deep Water returns to the surface at the equator and the Southern Ocean. Middle panel shows the results for a model with the configuration of large equatorial upwelling (HH) and the bottom panel for a model with strong Southern Ocean upwelling (P2A). The new production associated with the source region nutrients appears to be large close to the source region, only a small portion being utilized in the low-latitudes. Most new production in low-latitudes is supported by recycled nutrients originating from various source regions.

Project Report: **Atmosphere and Coastal Ocean CO_2 Measurement Platform – SABSOON**

Principal Investigator: Colm Sweeney (Princeton Research Staff) now at Univ. of Colorado-Boulder

Other Participating Researchers: Wade McGillis (Columbia University/LDEO),Pieter Tans and Thomas Conway (NOAA/CMDL)

Theme #2: Biogeochemistry

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

Objectives:
- Measure the pCO_2 in the atmosphere and ocean at South Atlantic Bight Synoptic Offshore Observational Network (SABSOON). High-resolution IR detection of CO_2 will be compared to flask measurements.
- Determine ΔpCO_2 at the tower using the high-resolution IR technique in order to estimate the coastal air-sea CO_2 flux variability.
- Quantify and describe the temporal variability in atmosphere and ocean CO_2 concentrations.
- Determine the relative importance of biological and physical controls on CO_2 concentrations and air-sea CO_2 exchange at a coastal site.
- Determine the influence of coastal ocean carbon on the North American terrestrial carbon cycling.

Methods and Results/Accomplishments:

The stated objectives of this project require development of the following:
- Autonomous infrared measurements of atmospheric CO_2 designed:
  - To have a measurements accuracy of 0.1 ppm
  - To operate for up to 2 months without any direct on sight intervention
  - Control all temperature fluctuations in IR cell temperature passively (to conserve amount of power required for instrument operation) to less than 1 C hr^{-1}.
  - A gas flow control system that can handle heavy aerosol load expected in tower environment with minimum amount of dead volume.
  - Long term air drying system
- Autonomous measurements of seawater CO_2 from tower
  - Develop equilibrator system which can handle big wave action but does not require pumping of seawater greater than 1 meter above mean high water

Development progress:

1) Autonomous infrared measurements of atmospheric CO_2 designed:

   Air flow control system

   Because of the large temperature variations and large aerosol load, the flow of gases through the IR detector is very hard to control in conditions that we expect on the tower over the long term. Previous attempts to use off the shelf flow controller have been problematic due to dead volume and aerosol fowling. In an attempt to rectify these problems we have developed a stepper motor controlled needle valve system which seems to very nicely control gas flow rates over a variety of pressure regimes (Fig 1).

   Passive control of IR cell temperature

   A key to achieving measurement accuracy at the 0.1 ppm level is control of incoming gas and IR detector cell temperature. While this can be achieved using active temperature control we are interested in doing this passively to reduce the power consumption. We are doing this by using a thermal mass (seawater) stored in a 150 L barrel. Air is circulated between a heat exchanger (tubing) in the barrel and an insulated box that contains the IR detector. The results of the initial design show that temperature change can be controlled to within 1 C /hr which on a normal day that might vary in temperature as much 20 C. While we would like to reduce the temperature change to 0.1 C/hr, the results shown here indicate a very linear change in IR cell temperature despite non linear changes in outside temperature. This suggests that drift corrects with hourly standard analysis will be sufficient to account for temperature changes.

Remote operation

In an effort not to loose time we have decided to delay the deployment on the SABSOON tower until all new developments have been tested on similar conditions on the Martha's Vineyard Tower or the RV LM Gould. With the new gas flow control system installed on our RV LM Gould pCO2 system, we now have a means to test its long term robustness.

0.1 ppm accuracy test

In addition to testing the flow controlled system on the RV LM Gould we will also be doing an inter-calibration exercise with NOAA/CMDL flask sample in the end of March during a Drake Passage crossing to test the accuracy of our measurements.

Long term air drying system

A system for drying air which uses a combination of Nafion and a chemical dryer similar to those used on land-based Tall Towers has been built and is being tested on the Martha's Vineyard Towers. No conclusive results on its efficacy can be reported at this time.

2) Autonomous measurements of seawater CO_2 from tower

Develop an equilibrator system

The major challenge to measuring seawater from towers is choosing a robust system for equilibrating seawater with an air stream that can be measured with infrared analyzers. Because towers are not free floating, a high position of the equilibrator on a stable platform would require excessive power to pump water to such heights. To reduce power requirements we are testing a small compact system on the Martha's Vineyard Tower that is mounted separately on the leg of the tower about 2 meters above mean water height.

Fig 1. Prototype atmospheric and ocean pCO2 system for SABSOON tower. This system features a standard/sample gas flow control system controlled by stepper motor (red) and needle valve in a feedback loop with the Gas flow meter. The photograph shows a prototype installed on the RVIB LM Gould where inter-calibration with NOAA/CMDL Flasks will take place.

Progress Report: **Estimating Global Air-Sea Gas Exchange Rate Using Bomb ^{14}C:Revisited**

Principal Investigator: Colm Sweeney (Princeton Research Staff) now at Univ. of Colorado-Boulder

Other Participating Researchers: M. Gloor, A. R. Jacobson, R. M. Key, J. L. Sarmiento, (Princeton) G. A. McKinley (University of Wisconsin), and R. Wanninkhof (NOAA/AOML Florida)

Theme #2: Biogeochemistry

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

Objectives: Estimating global air-sea gas exchange rate using bomb ^{14}C: revisited

Methods and Results/Accomplishments:

Wind-speed dependent bulk formulations of gas transfer velocity have traditionally been scaled to the oceanic inventory of bomb ^{14}C (1992, *Wanninkhof and McGillis 1999*) using wind fields from *Esbensen and Kushnir (1981*). Recent advances in our ability to estimate both the first two moments of global wind-speeds and the inventories of bomb ^{14}C inventories call for a reanalysis of this anchor point as well as an exploration of its implications on oceanic carbon uptake. We present a reanalysis of the globally averaged air-sea transfer velocity of CO_2 using an inverse calculation of bomb $^{14}CO_2$ air-sea fluxes from point measurements of ^{14}C in the ocean interior and several oceanic transport General Circulation Models (GCMs). This inverse calculation permits us to estimate both the total inventory of bomb $^{14}CO_2$ that has entered the ocean from 1953 to 1998 (Figure 1) and the temporal and spatial evolution of surface $p^{14}CO_2$ from 1954 to 1998. Using a best fit, in a least squares sense, between 8,000 measurement-based estimates of bomb ^{14}C in the upper 1500 m of the water column and three different configurations of a GCM we see a discrepancy between the resulting gas transfer velocity and the *Broecker et al.* (1985 and 1995) gas transfer velocity which was used by *Wanninkhof* (1992) and *Wanninkhof and McGillis* (1999) to formulate their gas-exchange parameterizations. Our results suggest that the average global piston velocity may be over-estimated by as much as 50%. Combining this result with more recent estimates of world ocean wind speeds from the National Center for Environmental Prediction (NCEP, *Kalnay, et al. 1996*) we calculate that the anchor point tying the relationship between wind speed and air-sea gas transfer velocity to the oceanic radiocarbon inventory is roughly 44% lower than previously thought (Figure 1). Using the *Takahashi et al.* (2002) surface ocean air-sea gradient in CO_2 for 1995, we estimate an air-sea flux of 0.9+0.5=1.4 PgC yr^{-1} (quadratic dependence of gas exchange velocity on wind speed) and 1.3+0.5=1.8 PgC yr^{-1} (cubic dependence on wind speed) of carbon into the world oceans. The 0.5 PgC yr^{-1} added to the estimates based on partial pressure differences and gas exchange parametereization alone take into account the oceanic branch of the river carbon loop which is associated with outgasssing of ~ 0.5 PgC yr^{-1}. Our analysis supports other work (i.e. *Hesshaimer, et al. 1994, Peacock 2004, Key, et al. 2004*) which suggest that *Broecker et al*. (1985 and 1995) may have overestimated the ocean bomb ^{14}C inventory by as much as 25%. Our results also suggest that previous estimates, which depend on box models, may not have taken account a significant back flux of bomb-derived $^{14}CO_2$ into the atmosphere as well as variability in CO_2 solubility and surface ocean $^{14}CO_2$ that has been suggested by our inverse estimates.

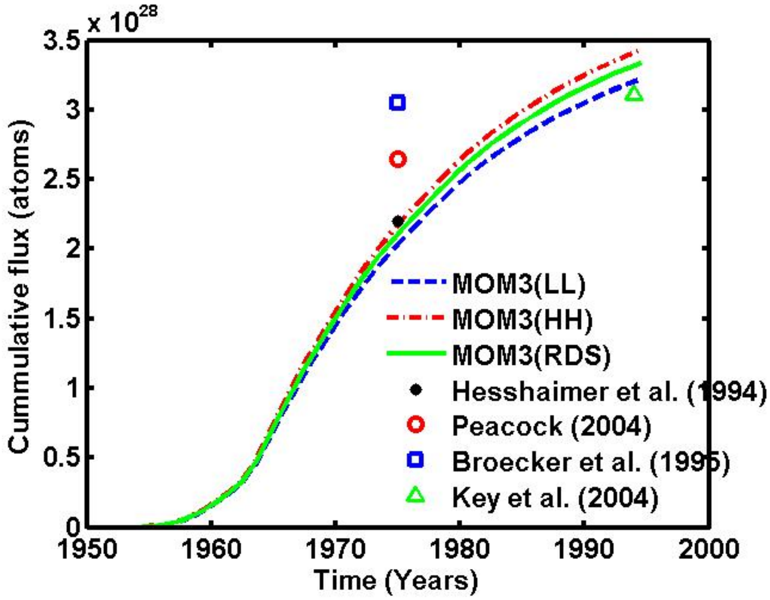

Figure 1 Time history of bomb $^{14}CO_2$ inventory in the world oceans. Blue (dashed), red (dot-dashed) and green lines show cumulative inventory of $^{14}CO_2$ over the last 50 years using a suite of the GFDL MOM3 models to represent possible spread in time history of inventory due to model parameterizations of isopycnal velocity and diapycnal diffusion. The open blue box shows the *Broecker* (1995) estimate while the black circle shows the *Hesshaimer et al.* (1994) inventory estimate for 1975 and the green triangle is from GLODAP (*Key et al.* 2004). This figure indicates that our results agree very well with that of *Hesshaimer et al.* (1994) and *Key et al.* (2004).

Progress Reports:

Paleoclimate

Progress Report: **The Tropics and the Global Climate**

Principal Investigator: Marcelo Barreiro (Princeton Research Associate)

Other Participating Researchers: George Philander (Princeton), Ronald Pacanowski (GFDL), and Alexey Fedorov (Yale)

Theme #4: Paleoclimate

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

Objectives: The study of possible tropical ocean-atmosphere states, and their influence in past and future climates.

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

The present mean state of the tropical oceans with a cold tongue in the east and a warm pool in the west is the result of interactions between the surface ocean and the atmosphere. However, this state of affairs may not have been the case several million years ago. Recent paleo-data suggest that during the mid-Pliocene (about 5-3 Ma) the eastern side of the tropical oceans was as warm as the western side and coastal upwelling regions did not exist. We are interested in studying how this state was created, how can it be maintained, and what are the consequence of such a state for the global climate. Answering these questions may shed light on possible future warm climates.

To address these issues I have used atmospheric and oceanic general circulation models (GCMs) developed at the GFDL and other institutions. Atmospheric GCMs with imposed sea surface temperatures that mimic Pliocene conditions were used to study the tropical atmospheric circulation at that time. Major differences with today's climate include the collapse of the equatorial easterlies and Walker circulation and the large reduction of the low level clouds which decreases the Earth's albedo. The sensitivity of the tropical response was addressed using several SST patterns and different models with distinct physical parameterizations. The simulated atmospheric fluxes of momentum, heat and freshwater were then used to force ocean GCMs to determine the oceanic state consistent with these fluxes. We are currently using a coupled GCM to further advance our understanding on the physical processes involved. We also plan to develop an intermediate coupled model that would allow exploring a larger range of possibilities.

Publications:

Barreiro, M., G. Philander, R. Pacanowski, and A. Fedorov, 2005: Simulations of warm tropical conditions with application to middle-Pliocene atmospheres. *Submitted to Climate Dynamics.*

Progress Report: **The Effect of Whole Ocean Temperature Change on Deep Ocean Ventilation**

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

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

Theme #4: Paleoclimate

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

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

Methods and Results/Accomplishments:

In order to isolate the effect of the non-linearity of the equation of state from other climate-related feedbacks, we changed the model ocean temperature only where it is used to calculate the density (to which we refer below as 'pseudo–'temperature change). We find, in agreement with scaling analysis, that a pseudo-cold ocean is globally less ventilated than a pseudo-warm ocean. Upon pseudo-cooling, convection decreases markedly in regions that have strong haloclines (i.e., the Antarctic and the Subarctic North Pacific (SNP)), because cooling weakens the negative thermal buoyancy of surface waters in those regions and makes the positive salinity buoyancy more dominant. However, overturning increases upon pseudo-cooling in the North Atlantic (NA), where the positive salinity buoyancy is smallest among the Polar Regions. We propose that the total amount of deep water formation is constrained by the energy required to drive the upwelling limb of the overturning, so that the NA behaves as a buffer to ventilation changes that occur in the other polar basins. As expected, the strength of the ACC increases significantly in a pseudo-warm world, as does the equivalent of the Gulf Stream in our model.

References:

Sigman D. M. et al., 2004. Polar ocean stratification in a cold climate. *Nature,* 428, 59-63

Publications:

De Boer, A. M., D. M. Sigman and J. R. Toggweiler. "The effect of global ocean temperature change on deep ocean ventilation". Submitted to Paleoceanography.

Project Report: **The Effect of Winds and Basin Geometry on the Global Overturning Circulation**

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

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

Theme 4: Paleoclimate

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

Objectives: A decade ago, Toggweiler and Samuels (Deep-Sea Res., 1995) proposed that North Atlantic Deep Water (NADW) formation is proportional to the strength of the winds that drive the Antarctic Circumpolar Current (ACC) in the Southern Hemisphere. The idea that Southern Ocean (SO) winds may have a strong influence on NADW formation is now widely accepted but fundamental questions remains. How do the SO winds compete with the heat and freshwater forcing? What is the role of the energy constraint? Is the wind-driven increase in NADW formation due to increased northward Ekman flow at Drake Passage latitude? If so, what determines the distribution of these waters between the Atlantic and the Pacific? How does Antarctic bottom water formation respond to the SO winds and why? The objective of this study is to address these questions.

Methods and Results/Accomplishments:

We have designed three sets of experiments to run using the GFDL MOM4 ocean general circulation model coupled to a sea-ice model and an energy moisture balance model for the atmosphere. We preferred an idealized two-basin geometry above more realistic topography because the study is concerned with basic principles rather than exact predictions. Our initial set of experiments was designed to answer first the basic question of why the Atlantic is preferred above the Pacific as a basin for deep convection. The results show that both the length of the Atlantic and its narrowness are instrumental to its success as a sinking basin while the lengths of the adjacent continents are of minor importance.

The second set of experiments was specifically geared toward understanding the role of the SO winds on convection in all the major polar basins. As we strengthen the winds south of 40 deg. S, we find that the polar haloclines break down one by one so that the overturning in the three polar areas are switched on sequentially (North Atlantic first, Southern Ocean second and North Pacific third). This suggests that there is a threshold for deep-water formation in each area of the ocean that is governed by basin geometry, the local freshwater forcing, and the Southern Ocean winds.

The third set of experiment deals with the effect of the thermal versus haline forcing on the global overturning circulation. We systematically weaken and strengthen the thermal forcing in the model by adjusting the temperature in the calculation of the density (and there only). We find that convection in halocline dominated polar regions (e.g., the Southern Ocean and North Pacific) increase in a thermal regime (high temperatures in the density equation) but that more salty polar ocean basins (e.g., the North Atlantic) behave in the opposite fashion, indicating a constraint in the global sinking rate.

Some additional experiments were performed to test the importance of winds in other regions. The results of all the experiments are synthesized into a global theory for the strength and distribution of the overturning circulation.

References:

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

Publications: Manuscript pending.

Project Report: **The Pliocene Paradox Workshop**

Principal Investigator: S. George H. Philander (Princeton Faculty)

Other Participating Researchers: 20 participants

Theme #4: Paleoclimate

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

Objectives: *The first workshop was held in Princeton on October 21 and 22, 2004 to discuss:* Conditions during the early Pliocene (3 to 5 million years ago approximately) amount to a paradox: the world was much warmer then than it is now even though the same sunlight was incident on essentially the same global geography, and even though the atmospheric concen-tration of carbon dioxide was essentially the same as today. This paradox implies that climatic conditions then, and those of today, are two very different responses to essentially the same external forcing. The critical questions are therefore: What disturbances can cause a transition from one state to the other? Can the current rise in atmospheric CO^2 cause a transition?

Methods and Results/Accomplishments:

The workshop's twenty participants discussed conditions during the early Pliocene (3 to 5 million years ago approximately) which amounts to a paradox: the world was much warmer then than it is now even though the same sunlight was incident on essentially the same global geography, and even though the atmospheric concentration of carbon dioxide was essentially the same as today. This paradox implies that climatic conditions then, and those of today, are two very different responses to essentially the same external forcing. The transition from that state (which included perennial El Nino conditions) to the present one involved recurrent Ice Ages induced by Milankovitch forcing. What disturbances can cause a return to the earlier warmer world? Can the current rise in atmospheric CO_2 cause such a transition?

From the observational results it is evident that, in the equatorial Pacific, sea surface temperatures were as warm in the east as the west up to 3 Ma. El Niño was in effect perennial up to that time. The appearance of cold surface waters introduced feedbacks associated with tropical ocean-atmosphere interactions, significantly enhancing climate sensitivity to perturbations such as the Milankovitch forcing. A solution to the Pliocene paradox could be the following important difference between the early Pliocene and today: atmospheric CO_2 has been high for merely a few decades before the present, but had been high for many millennia leading up to 3 Ma. It is entirely possible that the prolonged persistence of high CO_2 levels will cause a return of perennial El Nino conditions.

These results were presented during the final half day of the workshop to a public audience at Princeton University.

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

Principal Investigator: Rong Zhang (Princeton Research Staff)

Other Participating Researchers: Thomas L. Delworth (GFDL)

Theme #4: Paleoclimate

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

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

Methods and Results/Accomplishments:

In this study Zhang and Delworth use a newly developed coupled ocean-atmosphere model (GFDL CM2.0) to investigate the global scale response of the climate system to a sustained addition of fresh water to the model's North Atlantic, such as may have occurred during glacial periods. In response to this forcing, the model's thermohaline circulation weakens substantially, thereby reducing the oceanic meridional heat transport in the Atlantic, with a resultant cooling in the North Atlantic and warming the South Atlantic (Figure 3.1). The associated global response involves the enhanced atmospheric heat transport across the equator, a southward shift of the intertropical convergence zone (ITCZ) over both the Atlantic and Pacific sectors (Figure 3.2), an El Nino like condition (Figure 3.1) and weakened Walker circulation in the southern tropical Pacific, a La Nina like condition (Figure 3.1) and strengthened Walker circulation in the northern tropical Pacific, a dipole subsurface temperature response and more symmetric ocean circulation about the equator in the western tropical Pacific, and weakened Indian and Asian summer monsoons (Figure 3.3). The substantial weakening of the thermohaline circulation leads to a more symmetric annual mean zonally averaged ITCZ and zonally integrated Hadley circulation about the Equator. These responses are consistent with the global-scale synchronization of millennial-scale abrupt climate change as indicated by paleoclimate records (Wang, et al., 2001; Altabet et al., 2002; Stott et al., 2002).

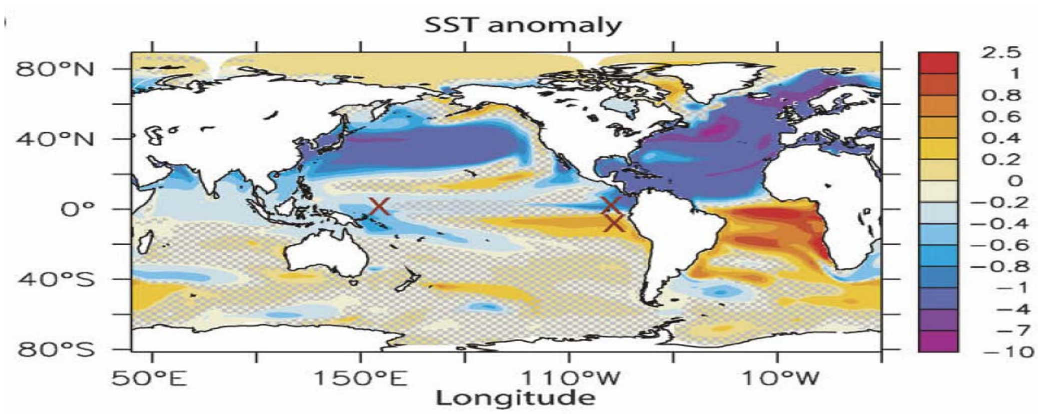

Figure 3.1 Annual mean SST anomaly. The brown crosses mark locations of paleoclimate proxies.

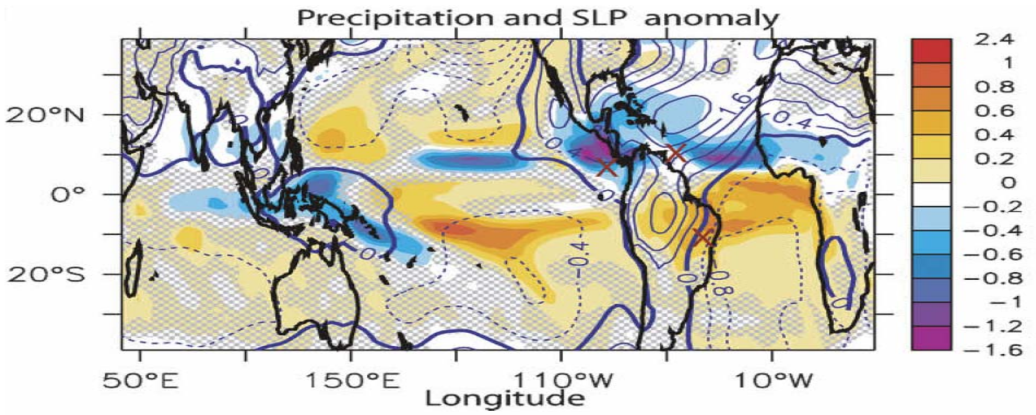

Figure 3.2 Annual mean precipitation anomaly (m/yr). The blue contour is the annual mean SLP anomaly with an interval of 0.4 hPa. The brown crosses mark locations of paleoclimate proxies.

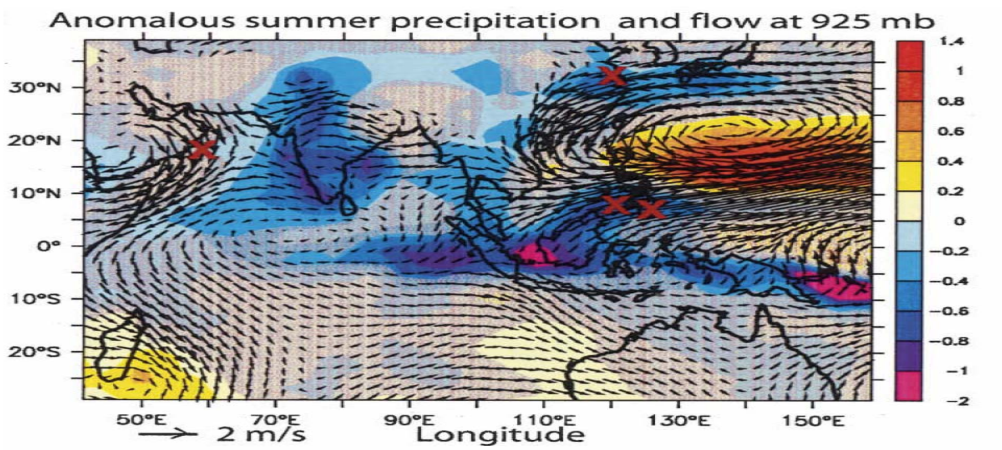

Figure 3.3 Anomalous summer precipitation and flow at 925 hPa. The brown crosses mark locations of paleoclimate proxies. The precipitation anomaly is significant at 95% level in area without shadow, and not significant at 95% level in area with shadow with Student's t-Test.

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Publications:

Zhang, R. and T. L. Delworth, 2005. Simulated Tropical Response to a Substantial Weakening of the Atlantic Thermohaline Circulation. Letter in *Journal of Climate*, 18, 1853-1860.

2004-2005 CICS Publications

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

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.

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

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

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

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

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

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

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

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Task I: Administrative Activities and Outreach Supported Personnel

Name	Rank	Advisor
Carson, Steve	Chemistry Teacher at Princeton Regional Schools	-

Task II: Cooperative Research Projects and Education Supported Personnel

Name	Rank	Advisor
Adcroft, Alistair	Research Oceanographer	Leetmaa
Balaji, Venkatramani	Prof. Technical Staff	Leetmaa
Chen, Gang	Graduate Student	Held
Fiore-Field, Arlene	Research Associate	Levy
Frierson, Dargan	Graduate Student	Vallis
Fučkar, Neven S.	Graduate Student	Vallis
Gebbie, Geoffrey (Harvard)	Research Associate	Tziperman
Gerber, Edwin	Graduate Student	Vallis
Haine, Thomas (JHU)	John Hopkins Faculty	-
Hammann, Arno	Graduate Student	Philander
Huang, Xianglei	Research Associate	Ramaswamy
Huang, Yi	Graduate Student	Ramaswamy
Jackson, Laura	Research Associate	Hallberg
Jia, Limin	Graduate Student	Singh
Jiang, Xianan	Research Associate	Lau
Kang, Sarah	Graduate Student	Held
Khare, Shree	Graduate Student	Anderson
Kim, Byung-Gon	Research Associate	Ramaswamy
Lee, Seoung-soo	Graduate Student	Donner
Legg, Sonya	Research Oceanographer	Leetmaa
Pauluis, Olivier	Research Staff	Held
Phillips, Vaughan	Research Staff	Ramaswamy
Ramachandran, S.	Visiting Research Staff	Ramaswamy
Randles, Cynthia	Graduate Student	Ramaswamy
Riviere, Gwendal	Research Associate	Orlanski
Russell, Joellen	Research Staff	Toggweiler
Smith-Mrowiec, Agnieszka	Graduate Student	Garner
Song, Qian	Research Associate	Rosati
Tziperman, Eli (Harvard)	Harvard Faculty	-
Vallis, Geoffrey	Research Oceanographer	Leetmaa
West, James	Research Staff	Ramaswamy
Xia, Youlong	Research Staff	Milly
Yang, Huiyan	Graduate Student	Levy
Yin, Jianjun	Research Associate	Stouffer
Zhang, Rong	Research Staff	Vallis
Zhao, Ming	Research Associate	Held
Zhao, Rongrong	Research Associate	Vallis

Task III: Individual Projects Supported Personnel

Name	Rank	Advisor
Altevogt, Andrew	Research Staff	Hedin/Oppenheimer
Barreiro, Marcelo	Research Associate	Philander
Crevoisier, Cyril	Research Associate	Sarmiento
DeBoer, Agatha	Research Associate	Sigman
Déry , Stephen	Research Associate	Wood
Donner, Simon	Research Associate	Oppenheimer
Frolking, Geoffrey (UNH)	Research Associate	Hurtt
Gerber, Stefan	Research Associate	Hedin/Oppenheimer
Gloaguen, Erwan	Research Associate	Sarmiento
Gloor, Emanuel	Research Scholar	Sarmiento
Hurtt, George (UNH)	UNH Faculty	-
Jacobson, Andrew	Research Staff	Sarmiento
Key, Robert	Research Oceanographer	Sarmiento
Luo, Lifeng Luo	Research Staff	Wood
Malyshev, Sergey	Research Staff	Pacala
Manfreda, Salvatore	Research Associate	Rodriquez-Iturbe
Rodriguez-Iturbe, Ignacio	Princeton Faculty	-
Sarmiento, Jorge L.	Princeton Faculty	-
Sharif, Hatim	Research Staff	Wood
Shevliakova, Elena	Research Staff	Pacala
Simeon, Jennifer	Prof. Technical Staff	Sarmiento
Slater, Richard	Prof. Technical Staff	Sarmiento
Sweeney, Colm	Research Staff	Sarmiento
Wojcik, Rafal	Research Staff	Wood
Wood, Eric F.	Princeton Faculty	-

Departures - Task II and Task III:

Stephen Déry - 7/1/05 Assistant Professor University of Northern British Columbia
Arlene Fiore-Field - 8/24/04 Research Scientist GFDL
Byung-Gon Kim - 3/1/05 Researcher Kangnung National University, Korea
Olivier Pauluis - 8/31/04 Assistant Professor New York University
Colm Sweeney - 4/1/05 Researcher CIRES

Ph.D. Defense - Task II: November 18, 2004
Student: Shree Khare *Advisor:* Jeffrey Anderson
Dissertation: Observing Network Design for Improved Prediction of Geophysical Fluid Flows-Analysis of Ensemble Methods

Personnel				
Category	Number	B.S.	M.S.	Ph.D.
Research Scientist	5			5
Visiting Scientist	1			1
Postdoctoral Fellow (Research Associate)	16			16
Professional Technical Staff	3		2	1
Research Staff	11			11
Administrative *	0			
Total (≥ 50% support)	**36**	**0**	**2**	**34**
Graduate Students	13	12		1
Employees that receive < 50% NOAA funding (not including graduate students)	14			14
Located at the Lab (include name of lab)	34-GFDL	8		26
Obtained NOAA employment within the last year	**1-GFDL			

*Administrative Staff: Jorge L. Sarmiento, Director, Laura Rossi and Stacey Christian, Financial and Administrative Support, devote significant time to Joint Institute work but receive total support from Princeton University for this work.

**Arlene Fiore Field, Physical Scientist
NOAA-Geophysical Fluid Dynamics Laboratory
Start Date: August 25, 2004

CICS FY'05 List of Awards

Amount	PI	Project Title
$ 268,523	Jorge L. Sarmiento	Determination of Carbon Source & Sink Distributions (Task III)
$ 155,200	Jorge L. Sarmiento	Ocean and Atmospheric Inverse Modeling for Global Carbon Flux Determinations (OGP-Task III)
$ 207,476	Stephen W. Pacala	Development of Carbon Sink Models (Task III)
$ 179,576	Sarmiento/Pacala	Biogeochemical Cycles and Climate (Task III)
$ 41,713	Lars Hedin	Modeling Terrestrial Nutrient Cycling (Task III)
$ 41,713	M. Oppenheimer	Modeling Terrestrial Nutrient Cycling (Task III)
$ 84,340	Eric Wood	Land Surface Predictability Studies at GFDL (OGP-Task III)
$ 50,000	Emanuel Gloor	Carbon Observing System (Task III)
$ 50,000	S. George Philander	Study of Paleo-Climates (Task III)
$ 50,000	Daniel Sigman	Study of Paleo-Climates (Task III)
$ 141,790	Robert M. Key	CO_2/CLIVAR Repeat Hydrography Program CO_2 Synthesis Science Team (OCO-Task III)
$ 9,874	Colm Sweeney	Atmosphere and Coastal Ocean CO_2 Measurement Platform-SABSOON (OGP-Task III)
$ 99,433	Eric F. Wood	A Hydrologic Ensemble Seasonal Forecast System Over the Eastern U.S. (OGP-Task III)
$ 11,000	Steve Carson	QUEST (Task I)
$2,540,000	S. George Philander	Cooperative Research Projects and Education (Task II)