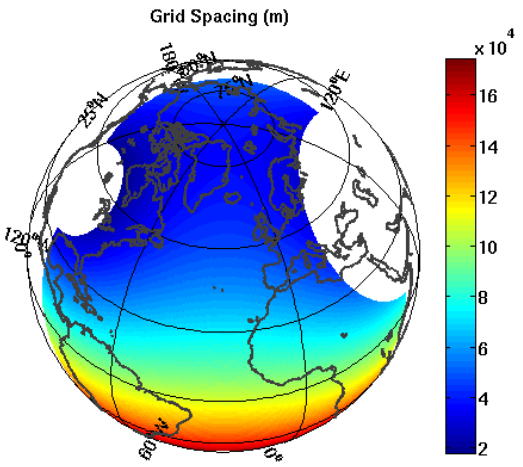
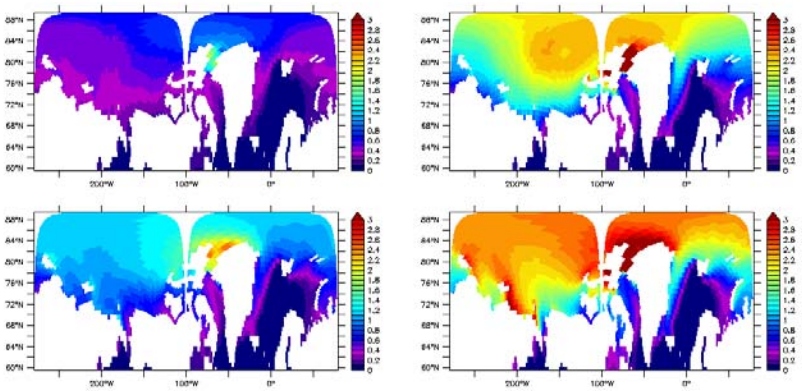


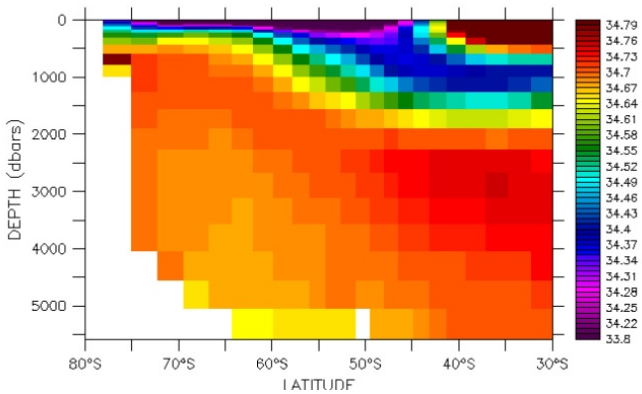
Annual Progress Report
July 1, 2008 – June 30, 2009

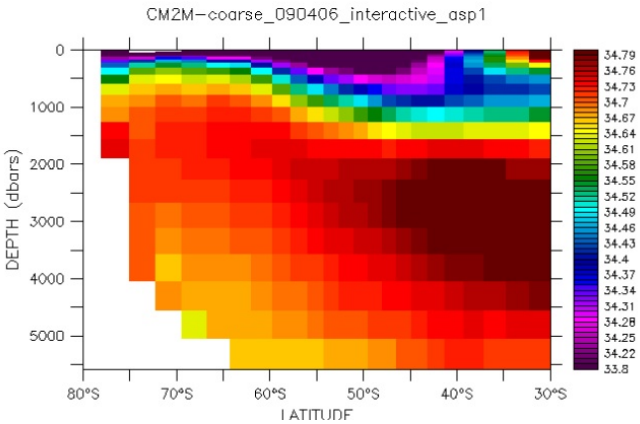
Cooperative Institute for Climate Science
at Princeton University
NOAA Cooperative Agreement NA17RJ2612



CICS

Jorge L. Sarmiento, Director
Geoffrey K. Vallis, Associate Director
Cooperative Institute for Climate Science
Princeton University Forrestal Campus
300 Forrestal Road
Princeton, New Jersey 08540





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Cooperative Institute for Climate Science
Princeton University

Annual Report of Research Progress under Cooperative Agreement NA17RJ2612
During July 1, 2008 – June 30, 2009

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

Introduction

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

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

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

Research Themes Overview

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

(1) **Earth System Studies/Climate Research.** Earth System modeling at GFDL and in CICS has emerged from an intense period of model development during which we have produced fundamentally new atmospheric, oceanic and land models, coupled models, chemistry-radiative forcing models, cloud resolving models with new microphysics, and a non-hydrostatic limited area model. These models are already producing useful products, but new and more sophisticated tools will continually be required for increasingly realistic representation of the processes and interactions in the Earth's climate system.

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

CICS is also continuing to pursue approaches to confronting models with observations in order to diagnose problems and judge reliability. The ability to simulate the observed climate, and its variability, with reasonable accuracy is a *sine qua non* of a sound climate modeling system. That variability arises from and is moderated by a host of factors, including ENSO, volcanic eruptions, the reddening by the ocean of weather variability in the atmosphere, the changes in the radiatively-active short-lived species and their climate forcing, clouds and the hydrologic cycle, soil moisture, interdecadal oceanic variability, and the glacial-interglacial cycles of the Pleistocene. These all represent distinct challenges that must ultimately be addressed simultaneously by a successful Earth System model, and the research presented below describes some of the efforts along these lines.

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

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

(2) **Biogeochemistry**. CICS is contributing to the development of the land and ocean biogeochemistry components of the Earth System model. The new model components are being used to study the causes and variability of land and oceanic carbon sinks and to develop a data

analysis system for carbon that will provide improved estimates of the spatial distribution of carbon fluxes.

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

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

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

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

(4) **Paleoclimate.** The most valuable observational constraints that we have to test our understanding of the response of the Earth System to changes in forcing come from the geological and ice core record. GFDL has a long history of important contributions to our understanding of climate change through the application of climate models. In recent years, Princeton University has attracted several new faculty with active research programs in the empirical and theoretical analyses of paleoclimate. CICS is supporting research on critical issues that Princeton has particular expertise in that are likely to be of importance in determining future climate response. These include the changing response of the climate to solar insolation forcing, the influence of tropical ocean-atmosphere states on climate, and the influence of freshwater fluxes and temperature changes on ocean circulation.

CICS research is closely aligned with the U.S. Climate Change Science Plan (US-CCSP) that was issued in July 2003 and with NOAA's Strategic Plan for FY 2003-2008. The US-CCSP identified five goals: (1) to increase understanding of the past and present climate, including variability and change, (2) to improve the quantification of the forces causing climate change and related changes, (3) to reduce uncertainty in predictions about future climate and related changes, (4) to understand ecosystem responses to climate change, and (5) to develop resources to support policies, planning and adaptive management (decision support). The research that is being carried out under CICS is

obviously central to the first, second, and third of these goals. In addition, our research on improved estimation of carbon source and sinks is directly called for in the US-CCSP document under goal 2. The coastal work and the global ecosystem modeling required in the biogeochemistry section contribute to goal 4, and all of the modeling work supplies tools that aid in decision support (goal 5).

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

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

Education/Outreach

This year, CICS continued its collaboration with a Princeton University professional development institute for New Jersey teachers. This well-established summer program, QUEST, is led by Princeton University's Teacher Preparation Program. A one-week Weather and Climate unit for teachers in fourth through twelfth grades, held this summer, offered a wide range of inquiry-based experiences through which the teachers could develop an understanding of atmospheric processes. In addition to exploring the greenhouse effect and human impacts on climate and global warming, participating teachers evaluated technological solutions including solar energy conversion, fuel cells, and wind energy. They learned new methods to teach about weather and climate change, with an emphasis on earth system modeling and analysis. The unit was developed and taught by Dr. Steven Carson, formerly a scientist and Outreach Coordinator at GFDL, and currently a middle school science teacher in Princeton. Fourteen teachers participated in the Weather and Climate unit, including two former Teacher Preparation Program graduates, one of whom is currently teaching high school physics and one who is now student teaching. Five of the teachers are from either urban or urban rim school districts thus increasing the participation of underrepresented groups in science education.

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:

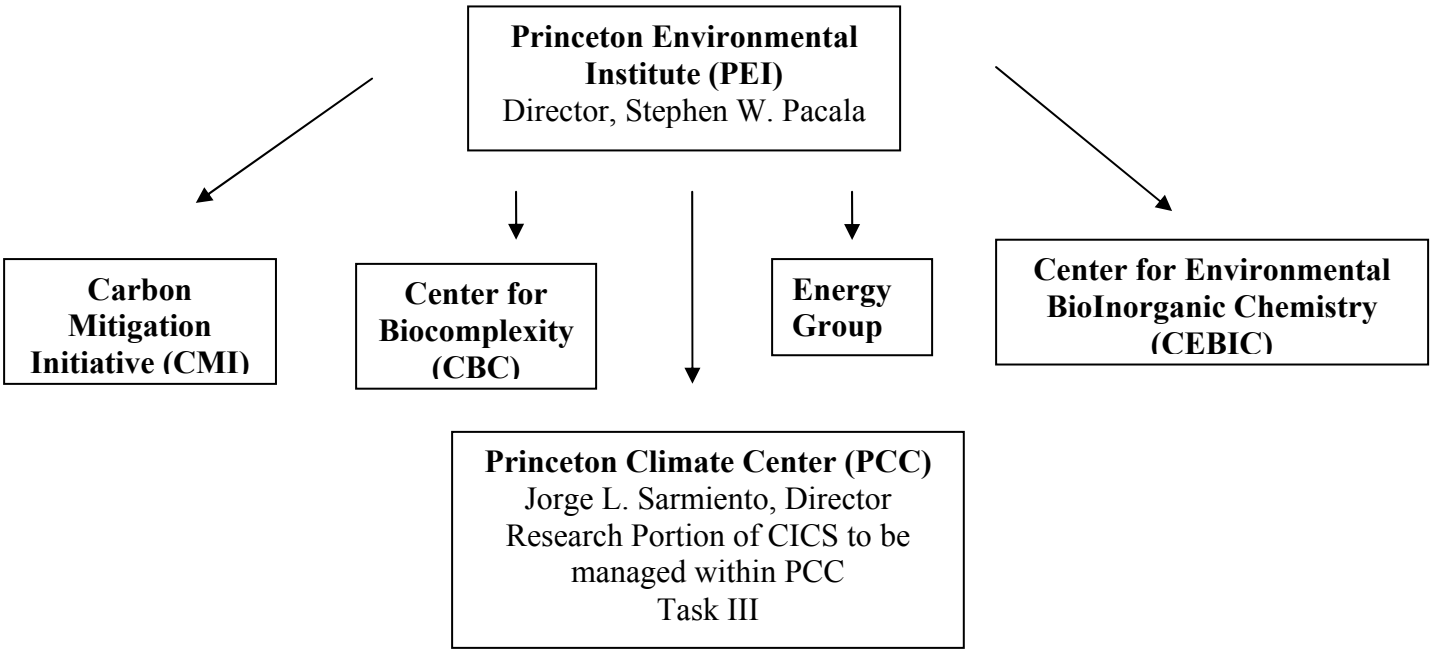
I. Administrative Activities including outreach efforts are carried out jointly by the AOS Program and Princeton Environmental Institute (PEI).

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.

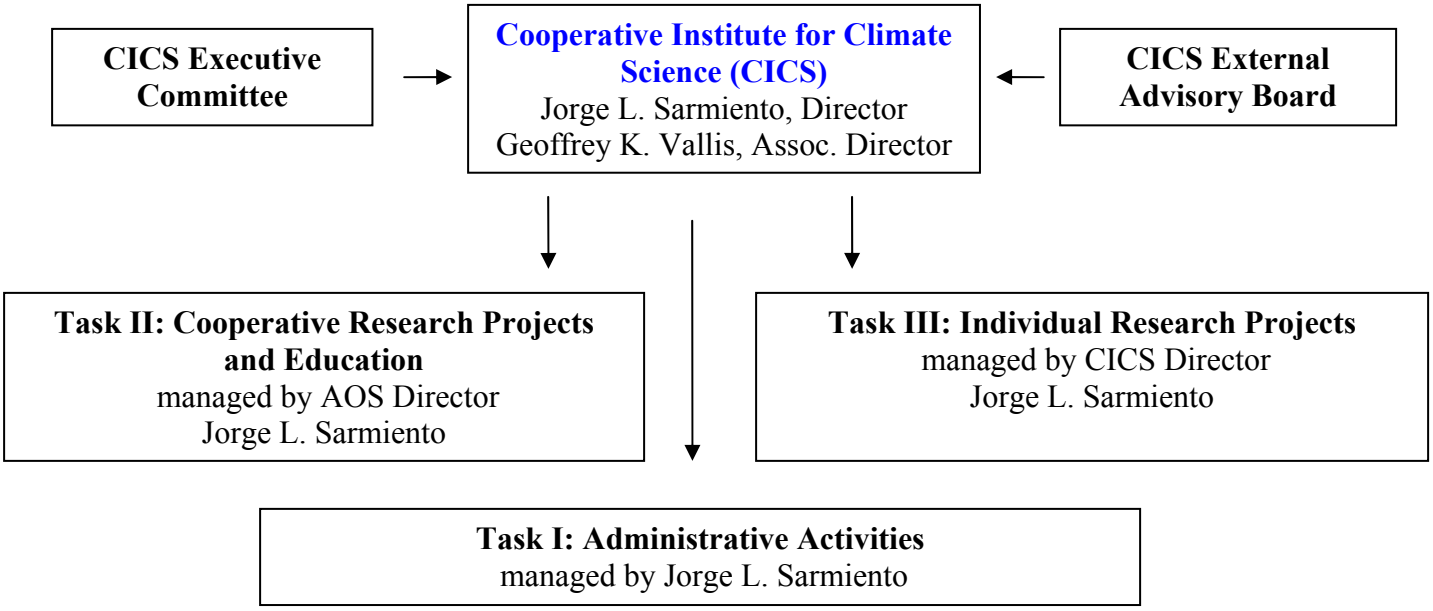
III. Principal Investigator led research projects supported by grants from NOAA that comply with the themes of CICS. These all occur within AOS and the Princeton Environmental Institute (PEI), and may also include subcontracts to research groups at other institutions on an as needed basis.

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 Princeton University associated faculty. The Director is also advised by an External Advisory Board consisting of representatives from NOAA and three senior scientists independent of NOAA and Princeton University.

Princeton Environmental Institute Structure



Cooperative Institute for Climate Science Structure



CICS Committees and Members

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

Executive Committee
Anand Gnanadesikan – GFDL Oceanographer
Isaac Held – GFDL Senior Research Scientist
V. Ramaswamy – Director of GFDL, GFDL Senior Research Scientist
Geoffrey K. Vallis – Associate Director of CICS and Senior Research Oceanographer
Jorge L. Sarmiento – Director of CICS and Professor of Geosciences
Stephen W. Pacala – Director of PEI, Professor of Ecology and Evolutionary Biology
Michael Oppenheimer – Professor Geosciences and Public and International Affairs, WWS
Denise Mauzerall – Associate Professor of Public and International Affairs, WWS

External Advisory Council
Jeffrey T. Kiehl – Senior Scientist, Climate Change Research Section, NCAR
A.R. Ravishankara – Director of NOAA's ESRL Chemical Sciences Division
Dave Schimel – Senior Scientist at NCAR's Terrestrial Sciences Division
Peter Schlosser – Associate Director and Director of Research of the Earth Institute at Columbia University, Vinton Professor of Earth and Environmental Engineering in the School of Engineering and Applied Science, and Professor of Earth and Environmental Sciences at Columbia
Chet Koblinsky – Director of NOAA's Climate Program Office

Research Highlights

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

EARTH SYSTEM STUDIES/CLIMATE RESEARCH

Research in Earth System Studies/Climate Research may be divided into Ocean Dynamics, Large-Scale Atmospheric Dynamics, Chemistry and Radiative Forcing, Climate Variability and Coupled Atmosphere-Ocean Modeling, and Clouds and Moist Convection. Research in all areas involves cooperative activities between the University and GFDL, in particular post-doctoral fellows and research students working with GFDL staff, as well as University researchers and faculty whose activities are funded through CICS. In the sections 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 the fundamental to the 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 whole, so enabling us to build better models of the system and, ultimately, to better predict it. That is, the overall goal of these activities is to provide a better *predictive understanding* of the climate system. In the following few sections we briefly highlight a few of the activities, and this is followed by a more detailed description of the individual projects.

Large-Scale Atmospheric Dynamics

Atmospheric dynamics remains at the core of the large-scale circulation of the atmosphere, and is and will remain an essential activity within climate dynamics. The work in this area varies between fundamental aspects of the large-scale circulation and more applied work in model development and parameterization. One area under investigation is the interaction of the El Niño–Southern Oscillation and the North Atlantic Oscillation. These are probably the two dominant modes of natural variability in the climate system on timescales of seasons to decades, and so it is important to understand any linkages between the two. In fact, a teleconnection between the two phenomena has been found involving the stratosphere: It has been found that in El Nino winters, waves propagate upward into the stratosphere, where they weaken the stratospheric polar vortex. This in turn can lead to a downward propagation into the troposphere after the onset of the stratospheric warmings, which corresponds to a surface pressure pattern resembling the negative phase of the NAO. It is a potentially quite important effect, although its robustness remains to be determined.

Ocean Dynamics and Modeling

For the foreseeable future, ocean climate models will not resolve mesoscale eddies, and so their effects must be parameterized. Current parameterizations are based on a scheme which does not account properly for the turbulent dynamics of such eddies. In an effort to improve this, and in collaboration with GFDL and MIT researchers, we have developed a new parameterization for the effects of mesoscale eddies in ocean models. The parameterization builds on that of Gent and McWilliams (in that it is an advective, or adiabatic, scheme) but it enforces the transport streamfunction to have a low vertical model structure, in accord with our expectations stemming

from the theory of geostrophic turbulence. The parameterization also naturally satisfies boundary conditions at the ocean top and bottom, and does not need any ad hoc tapering scheme. Thus far, numerical implementations have been encouraging, and the scheme is likely to become the default eddy parameterization scheme in the GFDL ocean models.

Chemistry, Aerosols and Radiative Forcings

One important activity in this area is the simulation of biomass burning. Such burning can have a significant effect on the Earth's radiation budget and it is important to model this correctly in our GCMs. Work performed by postdoc Brian Magi has led to a much improved understanding of the causes of errors in our current models, and so of means to correct them. Magi found that there were significant discrepancies in aerosol optical properties in AM2 compared to available observations that spanned a range of spatial and temporal scales, and suggested ways in which this may be corrected. Relatedly, global burned area and carbon released from fire disturbances to the atmosphere were dramatically overestimated by the land model LM3 compared to the general consensus, and using constraints suggested by CICS work, the simulations of fire occurrence in LM3 have been significantly improved.

Coupled Atmosphere-Ocean-Ice Modeling

An important aspect of the coupled climate system is sea ice, and with the onset of global warming and the possibility of open shipping passages in the Arctic Ocean, we are paying increased attention to this. A highlight of our work has been the development of a sea ice ridging scheme that provides an improved dynamical component of sea ice growth.

Why is this effect important and what have we done? A convergent sea ice drift field puts the floes under pressure, which can result in fracturing of the ice. Blocks of broken ice pile up along these fractures or rims of thicker ice floes in so-called ridges. Large parts of the sea ice cover become deformed, and because thicker ice is more resistive against pressure and melt it is clearly important to consider ridging in large-scale sea ice models. To this end, we have implemented a ridging parameterization in the GFDL sea ice model, and this has had potentially very important effects. For example, the opening of the sea ice cover due to ridging enhances the seasonality of the ice. In winter, opening enables an increased heat loss from the ocean accompanied by an enhanced sea ice production. In contrast, the ocean can gain more heat in summer by absorbing short wave radiation resulting in a stronger sea ice retreat. These are key features that must be included in any credible climate model if all-important seasonal effects are to be properly included, a topic of increasing importance in a warming world.

Clouds, Moist Convection and Hurricanes

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. There are many important topics under investigation, but here we will highlight the role of a seemingly technical one, cloud microphysics and its interaction with aerosols.

A new stratiform cloud scheme including a two moment bulk cloud microphysics module, a cloud cover parameterization allowing supersaturation over ice, and an ice nucleation parameterization has been implemented into the latest generation GFDL Atmospheric Model (AM3) as part of an effort to

treat aerosol-cloud-radiation interactions more realistically. In the new scheme clouds are more likely to be either glaciated or liquid. The reduced number of supercooled droplets in the new scheme leads to a very different global frequency distribution of liquid droplet effective radii compared to the original scheme, although the effect on the global radiation balance is not large. Although some of the processes involved are still poorly understood, their investigation and proper representation in GCMs is crucially important in the light of changing anthropogenic aerosol and aerosol precursor emissions.

BIOGEOCHEMISTRY

Biogeochemistry Model

One of the key issues regarding the potential of sequestering anthropogenic carbon (C) into the terrestrial biosphere is whether plants would response with increased productivity as atmospheric CO_2 rises. This so called CO_2 fertilization effect can particularly be dampened when the availability of essential nutrients (nitrogen and phosphorus) is limited. Sophisticated modeling tools that capture the coupling of the different elements in the Earth's vegetation (carbon, nitrogen, phosphorus) are critical for modeling this effect. Over the past several years we have developed a coupled terrestrial C-N model within the Princeton-GFDL land model LM3V. The model is innovative on several fronts of C-N interactions (e.g. belowground C-N feedbacks, prognostic handling of biological N fixation) In addition to testing the model with observations at FACE CO_2 enrichment experiments, we have performed a series of global-scale simulation to investigate terrestrial carbon storage over the past 500 years, specifically the coupled effects of land-use, atmospheric CO_2 increase, C-N coupling, anthropogenic N-deposition, and recent climate change. When all factors are considered we obtain a terrestrial net C source of 110 GtC since 1500, and 24 GtC since 1860. Our results agree well with budget estimates which are based on the difference between cumulative anthropogenic emissions, and atmospheric and oceanic inventory changes since 1860. Similarly we obtain decadal scale terrestrial fluxes that are comparable with data-based methods, with a large increase in the modeled sink from 0.5 to 1.5 GtC between the 1980s and 1990s respectively.

Project Titles
Cooperative Institute for Climate Science (CICS)
NOAA Cooperative Agreement NA17RJ2612

- Altimetry Helps to Explain Patchy Changes in Hydrographic Carbon Measurements
- Antarctic Sub-Polar Atmospheric Circulation
- Applying IPCC-Class Models Of Global Warming To Fisheries Prediction (Workshop)
- Atmosphere, Ocean, and Climate Dynamics
- Atmospheric Radiocarbon as a Tracer of Large-Scale Southern Ocean Wind Variations over the Period 950-1950
- Cloud Microphysics and Feedbacks in the GFDL General Circulation Model
- Constraining Oceanic Circulation And Basal Melting Beneath Ice Shelves
- Dust Transport to Antarctica in Present and Past Climates
- Effect of Sea Ice Ridging in a Global Coupled Climate Model
- Flexible Modeling System (FMS)
- GFDL Data Portal
- Global Warming Pattern Formation
- Hurricane Intensity in Dry and Moist Atmospheres
- Hurricane-Climate Interaction
- Hybrid Ocean Model Development
- Influences from Climate and Meteorology on Pollution Transport from/to North America
- Interaction between El Nino-Southern Oscillation and North Atlantic Oscillation - Role of the Stratosphere
- Investigating the Impact of Aerosols on the Climate over South-Asia Using the GFDL General Circulation Model
- Marine Ecosystem Modeling: Applications of the Regional Ocean Modeling System to Coastal Ocean Forecasting and Regional Climate Impact Studies
- Modeling Carbon - Nitrogen Interactions in the Terrestrial Biosphere
- Modeling Land-Use Dynamics in the Earth System
- Modeling Sea Ice-Ocean-Ecosystem Responses to Climate Changes in The Bering-Chukchi-Beaufort Seas with Data Assimilation of RUSALCA Measurements
- Ocean Mixing Processes and Parameterization
- Ocean-Atmosphere Interactions, Climate Variability and Change in a Hierarchy of Models
- Southern Hemisphere Circulation and Storm Tracks in a Changing Climate
- The Contribution of Various Continuum Models in the Longwave and Shortwave
- The Simulation of Biomass Burning
- Topographic Venting of Ganges Valley Pollutants
- Use of Satellite Remote Sensing and GCM Simulation to Study Aerosol-Cloud Interactions
- What Should a Subgridscale Parameterization Look Like?

Progress Reports:

Earth System Studies/Climate Research

Progress Report: **Hybrid Ocean Model Development**

Principal Investigator: Alistair Adcroft (Research Oceanographer)

Other Participating Researchers: Laurent White (Princeton Postdoctal Associate), Torge Martin (Princeton Postdotoral Associate), David Marshall (Oxford, UK)

Theme #1: Earth System Studies/Climate Research

NOAA's Goal #1: Protect, Restore, and Manage the Use of Coastal and Ocean Resources through Ecosystem-based Management (20%)
NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond (75%)
NOAA's Goal #3: Serve Society's Needs for Weather and Water Information (5%)

Objectives: Develop CM2G for IPCC; develop iceberg model for coupled models; develop hybrid coordinate capabilities in GOLD

Methods and Results/Accomplishments:

CM2G and ESM2G: CM2G has been run for thousands of years cumulatively and we are confident that CM2G is both a viable model and the first with a believable level of mixing in the ocean interior (it is the first successful isopycnal coupled model with a decent climate).

Hybrid GOLD: our most recent paper introduces a new concept of continuous isopycnals that enables hybridization without the pitfalls of mixing layered and Eulerian formulations. Attending LOM09 (Layered Ocean Modelling meeting) we learned that we are far ahead of the HyCOM in methods for hybridization and the quality of our solution.

Icebergs: Inclusion of icebergs in ESM2G is complete but the write-up (headed by Martin) is long overdue. We are now planning the next version of iceberg model that will use probabistic representations of calving and broaded parameterizations of erosion.

Eddy parameterization: The concept of using an eddy energy equation has finally made it into a paper where we show that certain parameterizations used in this paradigm satisfy various stability theorems.

Publications:

D. Marshall and A. Adcroft, 2009: Parameterization of ocean eddies: potential vorticity mixing, energetics and Arnold's stability theorem. Ocean Modelling, (subm.)

L. White, A. Adcroft and R. Hallberg, 2009: High-order regridding-remapping schemes for continuous isopycnal and generalized coordinates in ocean models. J. Comp. Phys. (accepted)

R. Hallberg and A. Adcroft, 2009: Reconciling estimates of the free surface height in Lagrangian vertical coordinate models with mode-split time stepping. Ocean Modelling, 29(1), doi:10.1016/j.ocemod.2009.02.008.

Griffies, Stephen, Alistair Adcroft, Ventakramani Balaji, Robert W Hallberg, Sonya Legg, T Martin, and A Pirani, et al., February 2009: Sampling Physical Ocean Field in WCRP CMIP5 Simulations: CLIVAR Working Group on Ocean Model Development (WGOMD) Committee on CMIP5 Ocean Model Output, International CLIVAR Project Office, CLIVAR Publication Series No. 137, 56pp.

T. Martin and A. Adcroft, 2009: Impact of calving and icebergs in a coupled climate model. in prep for J. Clim.

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

Principal Investigator: V. Balaji (Senior Professional Specialist)

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

Theme #1: Earth System Studies/Climate Research

NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond ((75%)
NOAA's Goal #3: Serve Society's Needs for Weather and Water Information (5%)

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

Methods and Results/Accomplishments:

- Development of Flexible Modeling System (FMS) and FMS Runtime Environment (FRE) in support of Earth system modeling activities at PU/GFDL.
- Awarded 24 million hours under DoE INCITE program.
- Design and development of high-resolution climate models (ChiMES Project: http://www.gfdl.noaa.gov/~vb/chimes). ChiMES has received a total of about 100 million CP-hours under INCITE and other awards.
- FMS run on 50,000 cpus at Oakridge National Lab (ORNL) Leadership Computing Facility.
- Formulation of a draft community-wide standard specification of model grids (http://www.gfdl.noaa.gov/~vb/gridstd/gridstd.html) under adoption within the Climate and Forecasting conventions.
  Provided design oversight for Sergey Nikonov (CICS) in design and implementation of the GFDL Curator, which maintains a database of model results delivered to the public from PU/GFDL models for IPCC AR4 and other projects.
- Provided oversight to Yana Malysheva (HPTi) in design of web services for display of model output.
- Joined architecture and design committees of NOAA's National Environmental Modeling System (NEMS) and National Unified Operational Prediction Capability (NUOPC)
- Design of next-generation model and data frameworks (Earth System Curator project) in collaboration with the Earth System Modeling Framework (ESMF), Program for Integrated Earth System Modeling (PRISM), Global Organization of Earth System Science Portals (GO-ESSP) and CF Conventions groups, whose steering committees I serve on.
- METAFOR Project gets EU-FP7 award for building a common information model for climate models following on Curator work. METAFOR renewed for 2009.
- Organized AGU Session IN21B, San Francisco December 2008.
- Key presentation at Working Group on Numerical Experimentation (WGNE), Montreal, November 2008: *An Overview of NOAA Climate Modeling*. More talks listed at website.

References:

Sabine, C.L., R.A. Feely, and R. Wanninkhof (2006), Globl Oceans: Ocean carbon. In stae of the Climate in 2005, K.A. Shein (ed),, Bull. Am. Meteorol. Soc., 87(6), S29-S30.

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

Publications:

Rocky Dunlap, Spencer Rugaber, Leo Mark, V. Balaji, Cecelia DeLuca, 2008: Earth System Curator: Metadata Infrastructure for Climate Modeling. Accepted for publication in *Earth Science Informatics*.

Progress Report: **Southern Hemisphere Circulation and Storm Tracks in a Changing Climate**

Principal Investigator: Andrew Ballinger (Princeton graduate student)

Other Participating Researchers: Gabriel Lau - advisor (GFDL/Princeton), Geoff Vallis (Princeton)

Theme #1: Earth System Studies/Climate Research

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

Objectives: To investigate the response of the Southern Hemisphere circulation and associated storm tracks to higher sea surface temperatures

Methods and Results/Accomplishments:

The geography of the three major Southern Hemisphere continents (aside from Antarctica) is such that the southern-most regions (e.g. Southern Australia, South Africa, Argentina) enjoy a moderate climate with relatively dry summers and wetter winters, supporting important agricultural industries. The climate of these large regions is sensitive to changes in the latitude of the Southern Hemisphere storm tracks and the frequency and intensity of associated cyclones, since their winter rainfall comes predominantly from the passage of these cyclones and the accompanying frontal systems, which are able to penetrate farther northward (over land) during these months.

Using a high-resolution (0.5° x 0.5°) atmospheric global climate model developed at GFDL (AM2.1) the seasonal climatology and secular changes of Southern Hemisphere circulation and associated storm tracks were investigated. Changes in various fields were analyzed by comparing a 20-year "CLIMO" model run (using 1980-2000 average SSTs) with a 20-year "CMIP" run (using SSTs from the CMIP runs around the time of double CO2 doubling). Anthropogenic greenhouse gases (including ozone) were held fixed at 1990 levels in both runs, thus direct radiative effects were not considered in the comparison.

As described by Held & Soden (2006), we find that the major large-scale changes in the Southern Hemisphere precipitation and evaporation fields follow simple Clausius-Clapeyron scaling. That is, wet regions are projected to get wetter, and dry regions become drier. Our results also show an expansion of the Hadley Cell (approximately 0.5°), suggesting that recent trends (Seidel et al., 2007) will continue. A poleward shift in the latitude of the storm track was evident, particularly in austral winter where the shift was approximately 4 degrees. These results were consistent with the multi-model ensemble study of Yin (2005).

References:

Held, I. M., and B. J. Soden, 2006: Robust responses of the hydrological cycle to global warming. J. Climate, 19, 5686–5699

Seidel, D. J., Q. Fu, W. J. Randel, and T. J. Reichler, 2008: Widening of the tropical belt in a changing climate. Nature Geosci., 1, 21–24

Yin, J. H., 2005: A consistent poleward shift of the strom tracks in simulations of 21st century climate. Geophys. Res. Lett., 32(L18701), doi:10.1029/2005GL023684

Progress Report: **Influences from Climate and Meteorology on Pollution Transport from/to North America**

Principal Investigator: Yuanyuan Fang (Princeton graduate student)

Other Participating Researchers: Hiram Levy (GFDL), Larry Horowitz (GFDL), Arlene Fiore (GFDL) and Anand Gnandesikan (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 how climate change and meteorology affect pollution transport from/to the North America

Methods and Results/Accomplishments:

My research in the past year mainly includes two parts. The objective of these studies is to characterize pollution transport and how it is affected by meteorology/climate. The regions I am interested is North America, as a source and a receptor of pollutants.

1) Transport from the United States is affected by synoptic scale meteorology and is considered to be episodic [e.g., Merrill et al., 1996]. We use 15-year summer daily export fluxes of CO across the northeast boundary of the United States simulated by MOZART4 to define high (fluxes above 15-day moving average fluxes + one standard deviation), modest (fluxes above 15-day moving average fluxes but below the one standard deviation) and low (fluxes below 15-day moving average fluxes) export days. Statistical analysis shows that high export days are more likely to correlate with migratory cyclones over Gulf of Saint Lawrence, while low export days likely experience high pressure systems over the same region. Although cyclone passages predominately drive the high export events, export when high pressure systems dominate is also important (which occurs on 50% of all summer days and contributes 35% of export) [Figure 1].

2) Climate change over the next century is predicted to have a direct impact on global circulations and regional meteorology [IPCC, 2007]. Changing climate affects pollution emission, production, transport and sink, therefore, directly influences air quality. We use idealized CO tracer with fixed lifetime simulated the GFDL AM3 model to assess the impact from climate change to transport. By using this tracer and keep the emissions fixed for present and future experiments, we are able to focus on transport pattern shifts itself (by investigating the different source-receptor relations between different regions [HTAP, 2007]) while avoiding the interference of the complexity and uncertainty of changing chemistry and emissions in the Future. Our preliminary results show that North America surface tracer concentration increases in the future due to less ventilation of its local tracer emissions, while its mid-tropospheric concentration is reduced because of both less local tracer ventilated from the boundary layer and less transport from the foreign sources [e.g., EA]. For the same idealized tracer with extra wet depositions, North America experience both higher surface concentration and higher mid-tropospheric pollutant concentrations due to reduced ventilation and reduced precipitations over this region. In general, surface air quality over North America worsens in the future and its local tracers play a more important role, leading to a "climate change penalty" situation in the future [Wu et al., 2008]. Additional reductions of pollutant emissions are needed to reach the same target of air quality in the future.

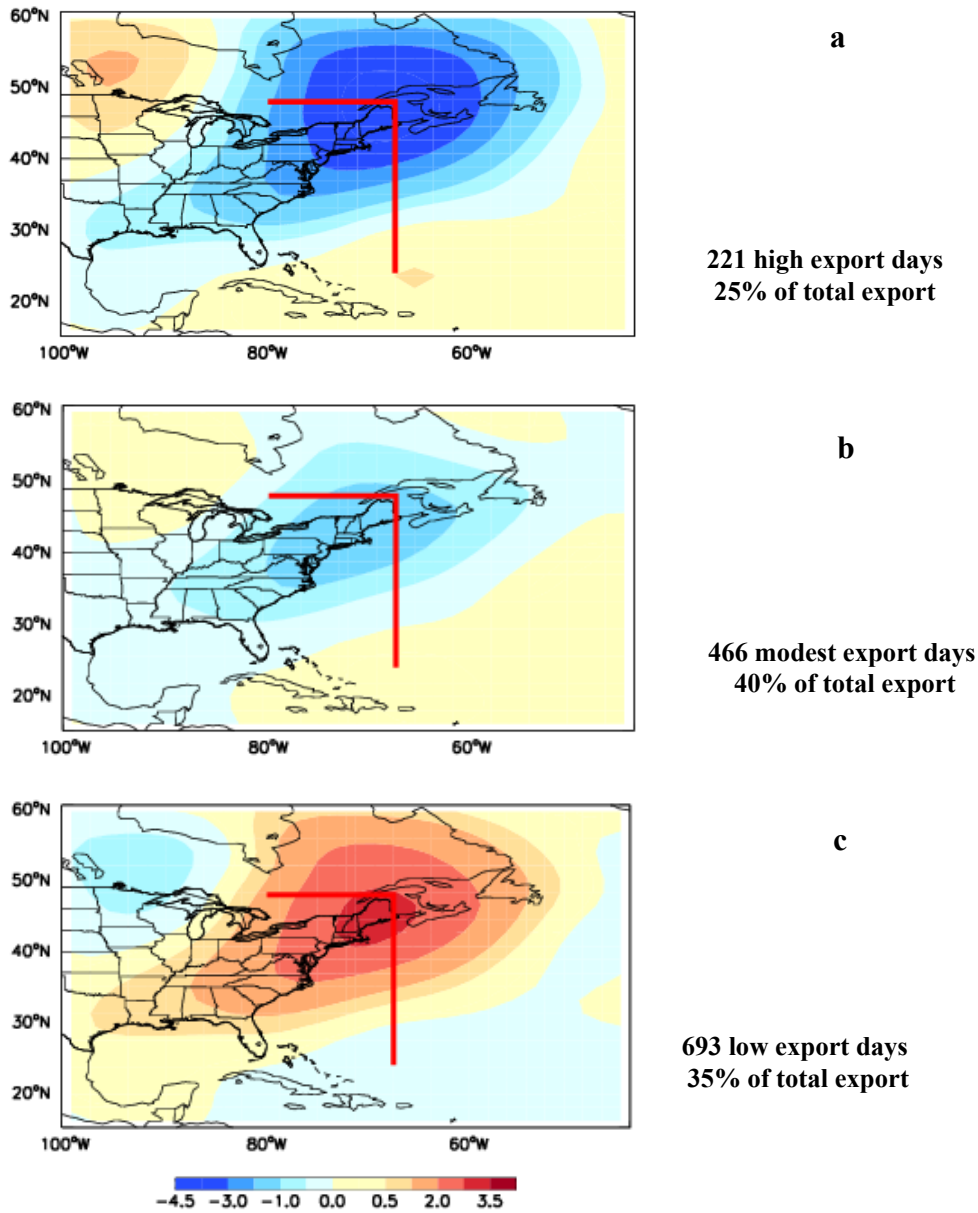


Figure 1. Composite of surface pressure anomalies (hPa) relative to the 15-day moving average "background" values for high (a), modest (b) and low (c) export days, defined as described in Section 5. Red lines show the northeast boundary of the United States. The number of days (from 15 summers of 1990 to 2004) included in each panel are: 221, 466, and 693 days, contributing 25%, 40%, and 35%, respectively, to total summertime export through the northeast boundary.

References:

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HTAP 2007, Hemispheric Transport of Air Pollution 2007, interim report prepared by the Task Force on Hemispheric transport of Air Pollution

Wu, S., L.J. Mickley, D.J. Jacob, D. Rind, and D. Streets (2008), Effects of 2000-2050 changes in climate and emissions on global tropospheric ozone and the policy-relevant background ozone in the United States, Journal of Geophysical Research, 113, D18312, doi:10.1029/2007JD009639

Publications:

Yuanyuan Fang, Arlene, Larry Horowitz, etc., Estimating the contribution of high daily export events to total pollutant export from the United States in summer, JGR, under review, 2009

Yuanyuan Fang, et al., North America as a source and receptor in the Future, in preparation

Progress Report: **Ocean-Atmosphere Interactions, Climate Variability and Change in a Hierarchy of Models**

Principal Investigator: Riccardo Farneti (Princeton Research Associate)

Other Participating Researchers: Geoffrey K. Vallis (Princeton), Thomas L. Delworth (GFDL)

Theme #1: Earth System Studies/Climate Research

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

Objectives: To understand climate variability and change, meridional energy transports and the role of oceanic mesoscale eddies with the help of idealized and high-resolution coupled models.

Methods and Results/Accomplishments:

Climate variability and mid-latitude mechanisms of ocean-atmosphere interactions have been investigated with coupled and uncoupled integrations of a three-dimensional ocean-atmosphere-land-ice climate model of intermediate complexity (ICCM; Farneti and Vallis, 2009a). The model is based on the Geophysical Fluid Dynamics Laboratory (GFDL) Flexible Modelling System (FMS) and is designed to be a powerful tool for the climate modelling community under a variety of possible applications, from local air-sea interactions to the study of climate of extrasolar planets. We have focused on the decadal and interdecadal variability of the system, giving a statistical and dynamical description of its oceanic and atmospheric signatures (Farneti and Vallis, 2009b). We have also examined, both theoretically and numerically, the meridional energy transfer in the coupled atmosphere-ocean system with a focus on the extra-tropics (Vallis and Farneti, 2009c).Finally, the variability and compensation of the heat transport in the system was analyzed and compared to comprehensive CGCMs (Farneti and Vallis, 2009d).

On a different note, we performed simulations with a high-resolution global coupled model, the GFDL CM2.4, and compared the results with a coarse version of the same model, CM2.1, under idealized climate change scenarios. We focused on the dynamical response of the Southern Ocean, and the role played by mesoscale eddies -- parameterized or permitted -- in setting the residual circulation and meridional density structure (Farneti et al., 2009e). Compared to the case in which eddies are parameterized, and consistent with recent observational (Boning et al, 2008) and idealized modelling studies (Hallberg and Gnanadesikan, 2006), the eddy-permitting integrations of CM2.4 show that eddy activity is greatly energized with increasing mechanical and buoyancy forcings, buffering the ocean to atmospheric changes, and the magnitude of the oceanic circulation response is thus greatly reduced. The presence of active ocean eddy dynamics seems to translate into significant reductions in atmospheric feedbacks. Further, we showed that present numerical approaches for the parameterization of eddy-induced transports are too restrictive, and prevent coarse-resolution models from faithfully representing the eddy response to variability and change in the forcing fields.

We are presently testing a new parameterization of mesoscale eddy transfer in the ICCM model, and comparing the results with standard parameterizations used in most CGCMs. Integrations with the intermediate complexity model will hopefully provide evidence of the ability to better represent eddy fluxes under present and altered climatic conditions using the new eddy scheme. Ultimately, the new parameterization will be implemented in to CM2.1.

References:

Hallberg, R. and A. Gnanadesikan, 2006: The role of eddies in determining the structure and response of the wind-driven Southern Hemisphere overturning: Results from the Modeling Eddies in the Southern Ocean (MESO) project. J. Phys. Oceanogr., 36, 2232–2252.

Boning, C. W., A. Dispert, M. Visbeck, S. R. Rintoul, and F. U. Schwarzkopf, 2008: The response of the Antarctic Circumpolar Current to recent climate change. Nature Geosci., 1 (12), 864–869.

Publications:

Farneti, R., T.L. Delworth, A.J. Rosati, S.M. Griffies, F. Zang (2009e), The role of mesoscale eddies in the rectification of the Southern Ocean response to climate change, J. Phys. Oceanogr., Submitted.

Farneti, R. and G.K. Vallis (2009d), Meridional energy transports in the atmosphere-ocean system: Variability and compensation, Climate Dyn., To be submitted.

Vallis, G.K. and R. Farneti (2009c), Meridional energy transports in the atmosphere-ocean system: Theory and numerical experiments, Q. J. R. Meteorol. Soc., In press.

Farneti, R. and G.K. Vallis (2009b), Mechanisms of interdecadal climate variability and the role of ocean-atmosphere coupling, Climate Dyn., Submitted.

Farneti, R. and G.K. Vallis (2009a), An Intermediate Complexity Climate Model (ICCM) based on the GFDL Flexible Modelling System, Geosci. Model. Dev. Discuss., 2, 1, 341-383.

Progress Report: **Investigating the Impact of Aerosols on the Climate over South-Asia Using the GFDL General Circulation Model**

Principal Investigator: Dilip Ganguly (Princeton Postdoctoral Research Associate)

Other Participating Researchers: V. Ramaswamy (GFDL) and P. Ginoux (GFDL)

Theme #1: Earth System Studies/Climate Research

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

Objectives: Inferring the composition and concentration of aerosols by combining the AERONET, MPLNET and CALIOP data: comparison with in-situ measurements and utilization to evaluate the GCM results.

Methods and Results/Accomplishments:

Over the last one year, the focus of our research has been to evaluate and improve the AM2 simulations of aerosol parameters over South-Asia by examining all major factors, which can influence a realistic assessment of the impacts of aerosols on the climate over the region. Major accomplishments of our work include 1) developing a tool based on minimization method to retrieve the composition and concentration of aerosols using the observations available from AERONET (Aerosol Robotic Network), MPLNET (Micro Pulse Lidar Network) and CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization), which can be used to evaluate model results over worldwide locations. 2) Evaluating the meteorological variables simulated by AM2 over south Asia and creating new 3D fields of relative humidity and temperature by combining the NCEP reanalysis and radiosonde data and using them in AM2 nudged simulations. 3) Evaluating aerosol parameters from AM2 simulations over North America and South-Asia. 4) Carrying out AMIP type simulations using a developing version of AM3 with and without aerosols over South Asia to understand the impacts of aerosols on the climate over the region.

Most GCMs (General Circulation Models) including AM2 fail to reproduce the AOD (aerosol optical depth) peak over the Indo-Gangetic basin (IGB) as noticed through satellite observations [see *http://nansen.ipsl.jussieu.fr/AEROCOM/*]. Insufficient data on aerosol composition makes it difficult to improve GCM results over this source region. In order to overcome this general problem, *Ganguly et al*. [2009a] developed a new method to derive the concentration of aerosol components from the spectral measurements of AOD and single scattering albedo along with their size distribution and extinction profile available from the collocated AERONET and MPLNET stations. The technique was applied over selected sites in three different regions of the United States (West coast, Great Plains, and North-East) and validated using in-situ measurements of aerosol composition from the IMPROVE (Interagency Monitoring of Protected Visual Environments) and EPA (Environmental Protection Agency) network [*Ganguly et al*., 2009a]. Subsequently, *Ganguly et al*. [2009b] used the same technique to retrieve the composition and concentration of aerosols over the IGB region by using the data from AERONET stations and the space borne lidar CALIOP. Figure 1 shows the comparison of observed values of AOD, single scattering albedo, size distribution and extinction profile of aerosols for the month of December 2007 over Kanpur site with their estimated values based on the results of our minimization. Comparison of our results with AM2 simulations reveal that AM2 is largely underestimating organics and black carbon concentrations over this region during all months. Sulfate is also underestimated during most months but there is an overestimation from May to September. Thus there is a compelling need for improving the aerosol inventories and dust sources over the region in order to make realistic assessment of the impacts of aerosols on the south Asian monsoon.

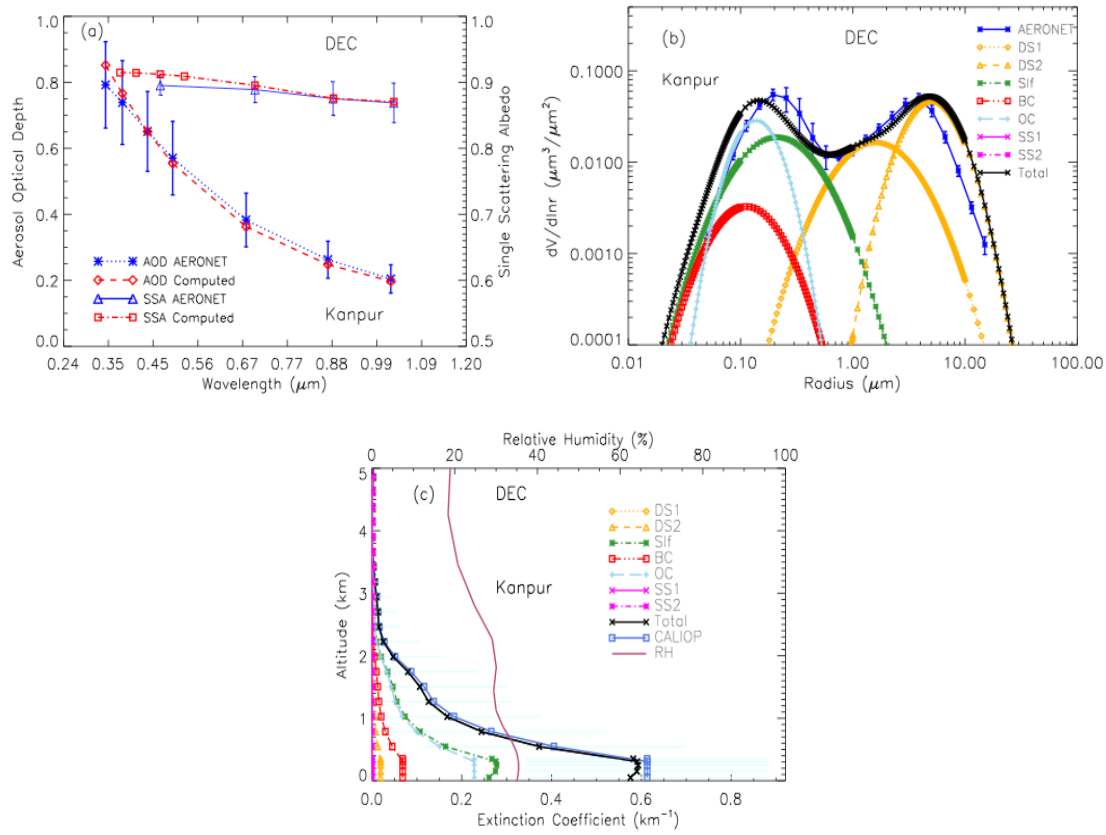

Figure 1: Comparison of AOD, single scattering albedo, and size distribution of aerosols from the AERONET site at Kanpur and the extinction profile from CALIOP with their estimated values based on our retrieval for December 2007. Panels (b) and (c) also show the contribution of individual aerosol components to the total size distribution and extinction profile respectively based on our results.

In to fill this gap of missing emissions over the IGB region, we added extra emissions of BC (Black Carbon), OC (Organic Carbon) and sulfate aerosols over the IGB region to the existing biomass burning inventory used by AM2 such that the area mean AOD over the region matches with those observed from satellite instruments like MODIS (Moderate Resolution Imaging Spectroradiometer) and MISR (Multiangle Imaging Spectroradiometer). Subsequently, we carried out some equilibrium simulations using a developing version of AM3 (am3p5-bugfix1) to investigate the climate response to the anthropogenic emissions of aerosols from Asia. Currently we are analyzing the results of these experiments as well as planning to repeat some of these and new experiments using the final version of AM3 and also with the mixed layer version of AM3 to account for the response of the SSTs to the aerosol forcing.

Publications:

Ganguly, D., P. Ginoux, V. Ramaswamy, O. Dubovik, J. Welton, E. A. Reid and B. N. Holben(2009a), Inferring the composition and concentration of aerosols by combining AERONET and MPLNET data: comparison with other measurements and utilization to evaluate GCM output, *J. Geophys. Res*., doi:10.1029/2009JD011895.

Ganguly, D., P. Ginoux, V. Ramaswamy, D. M. Winker, B. N. Holben, and S. N. Tripathi (2009b), Retrieving the composition and concentration of aerosols over the Indo-Gangetic basin using CALIOP and AERONET data, *Geophys. Res. Lett., 36*, L13806, doi:10.1029/2009GL038315.

Progress Report: **What Should a Subgridscale Parameterization Look Like?**

Principal Investigator: Arno Hammann (Princeton graduate student)

Other Participating Researchers: Anand Gnanadesikan (GFDL)

Theme #1: Earth System Studies/Climate Research

Theme #1: Earth System Modeling and Analysis

NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond (100%)

Objectives: To improve subgridscale parameterizations in the meso- and sub-mesoscale of ocean dynamics.

Methods and Results/Accomplishments:

We approach the problem of finding a subgridscale closure scheme by (1) defining the parameterizable terms in the context of a two-resolution model setup. The fields from an eddy-resolving version of our adiabatic two-layer channel model (cf. Hallberg and Gnanadesikan, 2001) are averaged onto a coarse grid, from which a low-resolution version steps them forward one timestep at a time. Subgridscale forcings are computed as the differences between the fine and coarse fields at every timestep. The method is somewhat similar to that used by Berloff (2005) (2) The step-by-step differences between the two models (the 'subgridscale') are then related to the mean fields by linear regression. The regression uses information from all available model variables in a certain area surrounding each point to be predicted The method has the advantage of (1) not making any a priori assumptions on the functional form of subgridscale terms (e.g. diffusion), and (2) using the correct type of average to define subgridscale terms (as opposed to, for example, zonal or temporal averages).

For a moderate difference in grid resolution between the fine and coarse model, we find that the dominant subgridscale correction corresponds to the lowest order truncation error in the numerical approcimation to certain spatial derivatives. For larger resolution differences, this truncation error decreases in importance relative to corrections arising from the true nonlinear terms in the model equations. While these terms are more directly what we seek to model, they are not well captured by linear regression, and we cannot say at this point if more advanced, nonlinear regression techniques will be more successful.

References:

Pavel S. Berloff. On dynamically consistent eddy fluxes. Dynamics of Atmospheres and Oceans, 38:123–146, 2005.

Peter R. Gent and James C. McWilliams. Isopycnal mixing in ocean circulation models. Journal of Physical Oceanography, 20:150–155, January
1990.

Robert W. Hallberg and Anand Gnanadesikan. An exploration of the role of transient eddies in determining the transport of a zonally reentrant currrent. Journal of Physical Oceanography, 31:3312–3330, 2001.

Publications:

In preparation.

Progress Report: **Use of Satellite Remote Sensing and Gcm Simulation to Study Aerosol-Cloud Interactions**

Principal Investigator: Harshvardhan (Visiting Research Scholar, Purdue University)

Other Participating Researchers: Yi Ming and 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: Model aerosol-cloud interaction for GCM parameterization

Methods and Results/Accomplishments:

MODIS coud optical property data for July for seven years was used to obtain drop concnetration for low level marine clouds. This data base will form the "ground truth" agianst which simulations from the experiemntal version of the GFDL GCM which includes prognostic aerosol and cloud interactions will be compared. In the brief period of the study (8 weeks), we were able to choose a geographical area where the compartison will be made. The regions off Europe and S. America were eliminated because of the complex flow regime in the North Atlantic and the absence of point sources in Chile, respectively. Therefore, we will concentrate on the stratocumulus region off California and the biomass burning region off Namibia. The protocol for this study has been described in Bennartz (2007) and Bennartz and Harshvardhan (2007).

References:

Bennartz, R. (2007), Global assessment of marine boundary layer cloud droplet number concentration from satellite, J. Geophys. Res., 112, D02201, doi:10.1029/2006JD007547.

Bennartz and Harshvardhan (2007), Correction to "Global assessment of marine boundary layer cloud droplet number concentration from satellite," J. Geophys. Res., 112, D16302, doi:10.1029/2007JD008841.

Publications:

Wilcox, E.M., Harshvardhan, and S. Platnick (2009), estimate of the impact of absorbing aerosol over cloud on the MODIS retrievals of cloud optical thickness and effective radius using two independent retrievals of liquid water path, J. Geophys. Res., 114, D05210, doi:10.1029/2008JD010589.

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

Principal Investigator: Yi Huang (Former AOS graduate student (Princeton), presently post doc (Harvard)

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

Methods and Results/Accomplishments:

Using the established method of synthesizing OLR spectrum from GCM simulation and processing the satellite observation [see Huang et al., 2007 and last year's report], we analyze the seasonal variations of Outgoing Longwave Radiation (OLR) accompanying the variations in sea surface temperatures (SST) from satellite observations and model simulations, focusing on the tropical oceans where the two quantities are strikingly anti-correlated. A spectral perspective of this "super-greenhouse effect" is provided, which demonstrates the role of water vapor line and continuum absorptions at different altitudes and the influences due to clouds. A model-satellite comparison indicates that the GFDL General Circulation Model can fairly well represent the total-sky radiative response to SST in the water vapor infrared absorption band despite the significant bias in the mean state, but this comprises compensating water vapor- and cloud-related errors. The analysis reveals that the GCM significantly underestimates the cloud induced radiative responses in the window region which is related to the bias in the mean state. Thus, spectral decomposition proves essential to understand and assess the OLR-SST relationship and the impacts of water vapor and cloud upon this linkage.

We also investigate the variability and change of OLR spectrum by combining the simulation and observation. First, the natural variability in unforced climate is simulated. Then, the change of OLR spectrum in forced changing climate is analyzed both for a continuous 25-year time series and for the difference between two periods 140-year apart. Spectrally resolved radiances have more pronounced and complex changes than broadband fluxes. In some spectral regions, the radiance change is dominated by one controlling factor (e.g. the window region and CO2 band center radiances are controlled by surface and stratospheric temperatures, respectively) and well exceeds the natural variability under climate change. In some other spectral bands, the radiance change is influenced by multiple and often competing factors (e.g. the water vapor band radiance is influenced by both water vapor concentration and temperature) and, although still detectable against natural variability at certain frequencies, puts stringent requirements (spectral resolution no less than 1 cm-1; drift less than 0.1 K / decade) for observational instruments. The difference between clear-sky and all-sky radiances measures the cloud radiative effect, but is subject to temperature lapse rate change (non-cloud radiative effect). These results demonstrate that accurate continuous observation of OLR spectrum can provide an advantageous means for monitoring the climate system and for validating climate models.

Publications:

Huang, Y. and V. Ramaswamy, (2009), Evolution and Trend of Outgoing Longwave Radiation Spectrum, Journal of Climate, 22(17), doi:10.1175/2009JCLI2874.1.

Huang, Y., and V. Ramaswamy (2008), Observed and simulated seasonal co-variations of outgoing longwave radiation spectrum and surface temperature, Geophys. Res. Lett., 35, L17803, doi:10.1029/2008GL034859.

Huang, Y. (2008), Satellite-observed and model-simulated outgoing longwave radiation spectra, Ph.D. thesis, Princeton University, 155pp.

Progress Report: **Ocean Mixing Processes and Parameterization**

Principal Investigator: Sonya Legg (Princeton Research Oceanographer)

Other Participating Researchers: Jody Klymak (Univ of Victoria), Rob Pinkel (SIO), Maxim Nikurashin (Princeton), Jamie Shutta (USCarolina, Hollings scholar), Robert Hallberg (GFDL), Stephen Griffies (GFDL), Alistair Adcroft (Princeton), 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 understand and quantify the mixing in the ocean interior and near the bottom boundary, develop parameterizations of these mixing processes for incorporation in GFDL climate models, and evaluate the impact of mixing on the general circulation of the ocean.

Methods and Results/Accomplishments:

Legg has focused on two aspects of ocean mixing: that generated by tides, and that in oceanic overflows.With regard to tidal mixing, one article has been published in JPO in the past year (Legg and Klymak, 2008) describing the influence of the slope steepness on the establishment of transient internal hydraulic jumps and overturning. Another manuscript (Klymak, Legg and Pinkel, 2009) has recently been accepted for publication in JFM, examining in greater detail the establishment of high vertical wavenumber lee-waves by flow over tall steep ridges, such as the Hawaiian ridge. Both of these manuscripts describe simulations carried out with the nonhydrostatic MITgcm, as well as theoretical predictions for the internal wave field and overturning observed. I am now considering how to best incorporate this localized mixing at tall steep ridges into our tidal mixing parameterizations in the GCMs.

Maxim Nikurashin began work at GFDL as a postdoc under my supervision in January. He is also carrying out simulations of internal tides with MITgcm, but with a focus on the internal tides generated over small-scale rough topography, as opposed to tall isolated ridges. Together we are examining how the results of his simulations can be used to improve the tidal mixing parameterization of Simmons et al 2004.

I am also supervising Jamie Shutta, an undergraduate Hollings intern. She is carrying out a series of idealized simulations using the MITgcm to elucidate the scattering and breaking of internal tides by reflection from bumpy topography. This will help to quantify the final fate of the low mode internal tides which propagate away from their generation region.

With regard to overflows, Legg was the coordinating PI for the recently completed climate process team on gravity current entrainment. A major accomplishment of that CPT was the implementation of several new parameterizations of overflow processes in GFDL's ocean models, in time for the new round of IPCC simulations. The principal achievements of the CPT are described in a recently published paper in the Bulletin of the American Meteorological Society (Legg et al, 2009). Another recently published article describes comparative simulations of idealized overflows with the MITgcm and GOLD (Legg et al, 2008) focusing on the effect of model advection schemes and subgridscale schemes.

A major effort of the past year has been to use the new ocean model GOLD in idealized large-scale configurations to try to understand the impact of the new parameterizations of overflows on the large-scale circulation. While this effort is still ongoing, early results suggest that an overturning circulation driven by overflows from a marginal sea looks quite different from an overturning circulation driven by open ocean convection.

References:

Simmons, H.L., S.R.Jayne, L.C. St Laurent, A. Weaver, 2004: Tidally driven mixing in a numerical model of the ocean general circulation. Ocean Modelling, v6, 245-263.

Publications:

Legg S. and J. Klymak, 2008: Internal hydraulic jumps and overturning generated by tidal flow over a tall steep ridge. J. Phys. Oceanogr. v38, 1949-1964.

Legg S., L. Jackson and R.W. Hallberg, 2008: Eddy-resolving modeling of overflows, in "Ocean modelling in an eddying regime", eds M.W. Hecht and H. Hasumi, AGU Geophysical Monographs, p63-82.

Legg S., B. Briegleg, Y. Chang, E.P. Chassignet, G. Danabasoglu, T. Ezer, A.L. Gordon, S. Griffies, R.W. Hallberg, L. Jackson, W. Large, T.M. Ozgokmen, H. Peters, J. Price, U. Riemenschneider, W. Wu, X. Xu and J. Yang, 2009: Improving oceanic overflow representation in ocean climate models: the gravity current entrainment climate process team. Bull. Am. Met. Soc, doi:10.1175/2008BAMS2667.1

Klymak, J., S. Legg and R. Pinkel, 2009: High-mode stationary waves in stratified flow over large obstacles, J. Fluid Mech, accepted.

Progress Report: **Dust Transport to Antarctica in Present and Past Climates**

Principal Investigator: Fuyu Li (Princeton Graduate student)

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

Theme #1: Earth System Studies/Climate Research

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

Objectives: To understand the mechanisms of dust transport to Antarctica and its implications for long-term climate change.

Methods and Results/Accomplishments:

I am working with V. Ramaswamy and Paul Ginoux to study the transport of dust to Antarctica ice cores and its implications for long-term climate change. In the last year, I have finished the investigation on the mechanisms of dust transport to Antarctica, and have started to investigate how the land properties and meteorological factors affect the transport in the past, specifically during the Last Glacial Maximum (LGM). The study is motivated by the observational evidence that, during LGM, dust concentration in the Antarctic ice cores were 10-100 times higher than present climate. We primarily use the GFDL Climate Model, including the runs for present and LGM conditions, NOAA HYSPLIT trajectory model, and ice core records. It serves as a continuation of my previous work, and helps to better understand the variability of dust records in Antarctica ice cores as well as the long-term climate change.

Among the many processes which could cause the observed high dust depositions in LGM, we first performed sensitivity tests regarding to the LGM dust source expansion due to (a) lower sea level and (b) the reduced vegetation cover. The results show that the global dust source area in LGM was 2 -3 times of present source area. It results in 6 – 7 fold of deposition, burden, and dust optical depth in Antarctica. Specifically, at the Antarctic ice cores (Vostok, Dome C, Byrd Station, and Taylor Dome), the lower sea level in LGM contribute to more of the dust concentration increase compared with reduced vegetation cover, and they two combined (e.g. the total source expansion) can explain most of the increase. In addition to the source expansion, other factors such as increased winds and reduced precipitation in LGM were also investigated. Although the LGM surface wind intensities appeared to be stronger globally, they were weaker at the major South Hemisphere dust sources (the main contributors to the Antarctica dust) and caused less dust emission in these regions. The low level wind speed increased by ~ 30% over the Southern Ocean in LGM. The increase of dust concentration is 20 – 30 % in the ice cores due to the LGM weaker precipitation. Therefore, the strong wind intensities and reduced precipitation during LGM are not likely to be the main factors for the 10 – 100 times higher dust concentration in Antarctica ice cores.

Publications:

Fuyu Li, Paul Ginoux, V. Ramaswamy, Transport of South American Dust to East Antarctica, submitted to J. Geophys. Res., 2009

Progress Report: **Interaction between El Nino-Southern Oscillation and North Atlantic Oscillation - Role of the Stratosphere**

Principal Investigator: Ying Li (Princeton graduate student)

Other Participating Researchers: Gabriel Lau (GFDL/Princeton)

Theme #1: Earth System Studies/Climate Research

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

Objectives: To understand the dynamical process of the stratosphere-troposphere coupling responsible for the wintertime teleconnection between ENSO and NAO

Methods and Results/Accomplishments:

The GFDL Climate Model CM3, which has 48 vertical levels, has been used to study the stratospheric-troposphere coupling in the teleconnection between El Nino-Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO).

It has been found that the in the El Nino winters, wave number 1 component of the wave activities increase in the extratropics and propagate upward into the stratosphere, where it weakens the stratospheric polar vortex. The increase of the Wave 1 is mainly related to the deepening of the wintertime Aleutian low via the ENSO-induced tropospheric extratropical pattern such as Pacific-North America pattern (PNA). Suppressed upward propagation of the wave activities is found in the La Nina winters. Thus increased occurrence of stratospheric sudden warmings (SSWs) is expected during El Nino. On the other hand, it is also found that both the zonal mean zonal wind anomalies at the 60N and the positive anomalies of geopotential height over the polar cap associated with weak polar vortex during the SSWs propagate downward to the troposphere after the onset of the SSWs, which corresponds to a surface pressure pattern resembling the negative phase of the NAO.

Meanwhile, another dynamical mechanism for the teleconnection between ENSO and NAO by the role of transient eddies was and still needs further explored by using the daily data in the 2000-yr 1860 control run CM2.1. Timescales of the processes, i.e. how does the low-frequency pattern generates the changes of the storm track variability, and how does the induced changes of the synoptic eddies further feedback onto the low-frequency pattern, needs to be further examined.

References:

Ineson, S. and A. A. Scaife, 2008: The role of the stratosphere in the European climate response to El Nino. Nature Geosciences, doi:10.1038/ngeo381

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

Principal Investigator: Christopher Little (Princeton Ph.D. Student)

Other Participating Researchers: Anand Gnandesikan (GFDL), Michael Oppenheimer (Princeton)

Theme #1: Earth System Studies/Climate Research

NOAA's Goal #1: Protect, Restore, and Manage the Use of Coastal and Ocean Resources through Ecosystem-based Management (20%)
NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond (80%)

Objectives: The melting of ice shelves from beneath constitutes a loss of ice from the cryosphere and a source of freshwater to the ocean; it also influences ice sheet dynamics. My overarching goals are to understand the physical processes that control the location and rate of basal melting, as well as its sensitivity to changed oceanic conditions, and its influence on ice shelf/sheet stability, oceanic freshwater balance, and global climate. I currently employ idealized ice shelf configurations to isolate the mechanisms -- sub-shelf thermodynamic and dynamic controls -- by which heat drives basal melting. These idealized simulations may also be used to examine sensitivity to changes in model formulation and parameterizations, improving our confidence as we look develop realistic, coupled models of ocean-ice shelf interaction.

Methods and Results/Accomplishments:

To date, I have used a numerical ocean model (the Hallberg Isopycnal Model) to describe the transport and mixing of water masses and heat undernearth ice shelves. I have modified this model to incluede a thermodynamically active ice interface. In the past few months, I have updated the ice shelf code to the newest release of GOLD, one of two ocean models incorporated in the GFDL coupled climate model framework.

Antarctic ice shelves can be roughly segregated into two regimes ("warm" and "cold"), characterized by dramatic differences in spatial extent, basal melting rates, and sub-shelf oceanographic conditions. In my thesis research, I have focused on the distinct mechanisms by which cavity shape influences heat transport within these regimes. This year, I've had a paper accepted by JGR-Oceans highlighting the role of ice shelf shape in determining basal melting rates, particularly in steep regions near the grounding line in "warm" regimes (similar to those in the Amundsen Sea). The dynamics of the ice-ocean boundary layer -- and its model representation -- are found to be critical. Ice shelf shape (including large scale gradients and smaller-scale roughness) strongly influence near ice velocity and temperature profiles, and thus the distribution of melting in the cavity.

In January and February, I participated in a 2 month long research cruise to the Amundsen Sea. I will use the data collected at and near Amundsen Sea ice shelves (from cruises in 2007 and 2009) for validation of model results in the next few years. In collaboration with other GFDL oceanographers and recently hired glaciologists, I am pursuing more realistic studies of the sensitivity of specific ice shelves to changes in regional oceanic circulation.

Publications:

Little, C. M., Gnanadesikan, A., Oppenheimer, M. How ice shelf morphology controls basal melting. Accepted for publication in Journal of Geophysical Research.

Griffies, S.M. et al. Problems and prospects in large-scale ocean circulation models. Conference white paper for OceanObs 2009.

Progress Report: **Hurricane-Climate Interaction**

Principal Investigator: Ian Lloyd (Princeton graduate student)

Other Participating Researchers: Gabriel Vecchi (GFDL/NOAA), Gabriel Lau (AOS faculty advisor)

Theme #1: Earth System Studies/Climate Research

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

Objectives: To investigate the oceanic controls on hurricane activity using observational analysis from recent satellite data.

Methods and Results/Accomplishments:

The influence of oceanic changes on tropical cyclone activity was investigated using observations from the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) satellite and the IBTRACS tropical cyclone dataset over the period 1998-2007. We examined Sea Surface Temperature (SST) conditions before, during, and after the passage of tropical cyclones, by using Lagrangian composites along cyclone tracks across all ocean basins. We found that tropical cyclones induce a cooling of SST as they pass over a location, and that the cooling becomes larger as cyclone intensity increases, up to approximately category 3 storms; this result follows expectations of stronger cyclones driving larger cooling. For the very strongest tropical cyclones, however, the average SST cooling is weaker as the intensity of the cyclone increases - a somewhat counter-intuitive result. We argue that the reduced cooling under extreme tropical cyclones is the manifestation of an ocean feedback on the ability of cyclones to intensify.

Publications:

Lloyd, I. D. and G. A. Vecchi, 2009: "Oceanic control on hurricane intensity". To be submitted to GRL.

Lloyd I. D., and G. A. Vecchi, 2009: "Submonthly Indian Ocean cooling events and their interaction with large-scale conditions". Submitted to J. Clim., in revision.

Progress Report: **The Simulation of Biomass Burning**

Principal Investigator: Brian I. Magi (Princeton Research Associate)

Other Participating Researchers: Paul Ginoux (GFDL), Elena Shevliakova (Princeton), Yi Ming (GFDL), 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:
1. To better understand the simulation of the biomass burning contribution to the global aerosol in the GFDL Atmospheric Model.
2. To improve the simulation of biomass burning in the carbon cycle simulated by the GFDL Land Model.

Methods and Results/Accomplishments:

My research continued to focus on aerosol properties in regions impacted by biomass burning. I finished a detailed analysis of Southern Hemisphere African aerosol optical properties simulated by the GFDL Atmospheric Model Version 2 (AM2p14, updated to include interactive/online aerosols and internal mixing, which are features of AM3) and we discussed our findings in Magi et al. (2009). In the paper, we concluded that there were significant discrepancies in aerosol optical properties in AM2 compared to available observations that spanned a range of spatial and temporal scales. The observations included aircraft-based measurements and retrieved aerosol optical properties from the NASA Aerosol Robotic Network (AERONET) and the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) on the Terra satellite.

We discussed the discrepancies in aerosol optical depth (AOD) and single scattering albedo (SSA), and showed that AM2 AOD was biased low by 30-40% in the tropics and 0-20% in the extratropics of southern Africa (Figure 1). AM2 SSA was biased high by 3-8% throughout southern Africa (Figure 2), noting that the bias increased during the biomass burning season (red points in Figure 2). We estimated that radiative forcing is overestimated by ~8% at the top of the atmosphere, while surface radiative forcing is underestimated by ~20% throughout the year over southern Africa. Uncertainty in SSA accounts for well over half of the uncertainty in southern African aerosol radiative forcing, both at the top of the atmosphere and at the surface. We are currently examining comparisons of the simulated biomass burning aerosol in AM3 using techniques discussed in Magi et al. (2009). This should provide a powerful evaluation of model performance with respect to aerosols.

In addition to the work with the GFDL Atmospheric Model, I worked with the Version 3 of the GFDL Land Model (LM3, E. Shevliakova) to better constrain the fire model. Prior to this collaboration, global burned area and carbon released from fire disturbances to the atmosphere were dramatically overestimated by LM3 compared to the consensus suggested by published studies that focused solely on simulating fire. Using constraints based on my work, we were able to tune down the fire occurrence in LM3. We are currently working on developing better regional fire simulations in LM3, as well as developing a seasonal fire model.

Finally, in Magi (2009) we discuss results based on measurements that are relevant to modeling the southern African aerosol. We apportioned aerosol mass among major contributing species, as well as deriving values of the impact of these species of the scattering and absorption of solar radiation. We showed that the primary aerosol species found over southern Africa are carbonaceous in nature and that although tropical and extratropical aerosol species contributions differ, their innate radiative properties are consistent. We also showed that although black carbon aerosol accounts for the majority of aerosol

absorption as expected, organic carbon aerosol accounts for over a quarter of the absorption (Figure 3). This is an important result that can help constrain assumptions about biomass burning aerosol properties in the GFDL GCM.

Publications:

Refereed Publications

Magi, B.I. (2009), Chemical apportionment of southern African aerosol mass and optical depth, Atmos. Chem. Phys. Discuss., 9, 13439-13474.

Magi, B.I., P. Ginoux, Y. Ming, and V. Ramaswamy (2009), Evaluation of tropical and extratropical Southern Hemisphere African aerosol properties simulated by a climate model, J. Geophys. Res., 114, D14204, doi:10.1029/2008JD011128.

Non-Refereed Publications

Magi, B.I., P. Ginoux, Y. Ming, and V. Ramaswamy, The Reality of Simulating the Biomass Burning Aerosol over Southern Africa, Poster presentation, NOAA GFDL Laboratory Review, June 2009.

Magi, B.I., Emissions, Seminar presentation, GFDL-NCAR Atmospheric GCM Meeting, April 2009.

Magi, B.I., Historical aerosol emissions comparisons, Informal seminar presentation, NOAA Geophysical Fluid Dynamics Laboratory, March 2009.

Magi, B.I., Biomass burning inventories, Informal seminar presentation, NOAA Geophysical Fluid Dynamics Laboratory, February 2009.

Magi, B.I., The reality of simulating biomass burning in southern Africa, Seminar presentation, NOAA Earth System Research Laboratory, February 2009.

Magi, B., M. Coughlan, A. Edwards, M. Hurteau, A. Petty, F. Seijo, and C. Wiedimyer (2008), Meeting Report from AIMES (Analysis, Integration and Modeling of the Earth System) Young Scholar's Network Workshop on Cultural Uses and Impacts of Fire: Past, Present, and Future, Eos, 89(40), doi:10.1029/2008ES002414.

Schmid, B., H. Guan, M. Kuzmanoski, P. Pilewskie, A. Bucholtz, A. McComiskey, S. McFarlane, and B. Magi, The Sensitivity of Shortwave Radiative Forcing and Heating Rates to the Aerosol Vertical Profile, International Radiation Symposium, August 2008.

Magi, B.I., M. Tosca, S. Ravi, A. Konare, and V. Jauss, Fires in the Current Climate, AIMES (Analysis, Integration and Modeling of the Earth System) Young Scholar's Network 4th Workshop on Cultural Uses and Impacts of Fire: Past, Present and Future, Oral Presentation, July 2008.

Magi, B.I., P. Ginoux, Y. Ming, and V. Ramaswamy, The reality of simulating the biomass burning aerosol over southern Africa, AIMES (Analysis, Integration and Modeling of the Earth System) Young Scholar's Network 4th Workshop on Cultural Uses and Impacts of Fire: Past, Present and Future, July 2008.

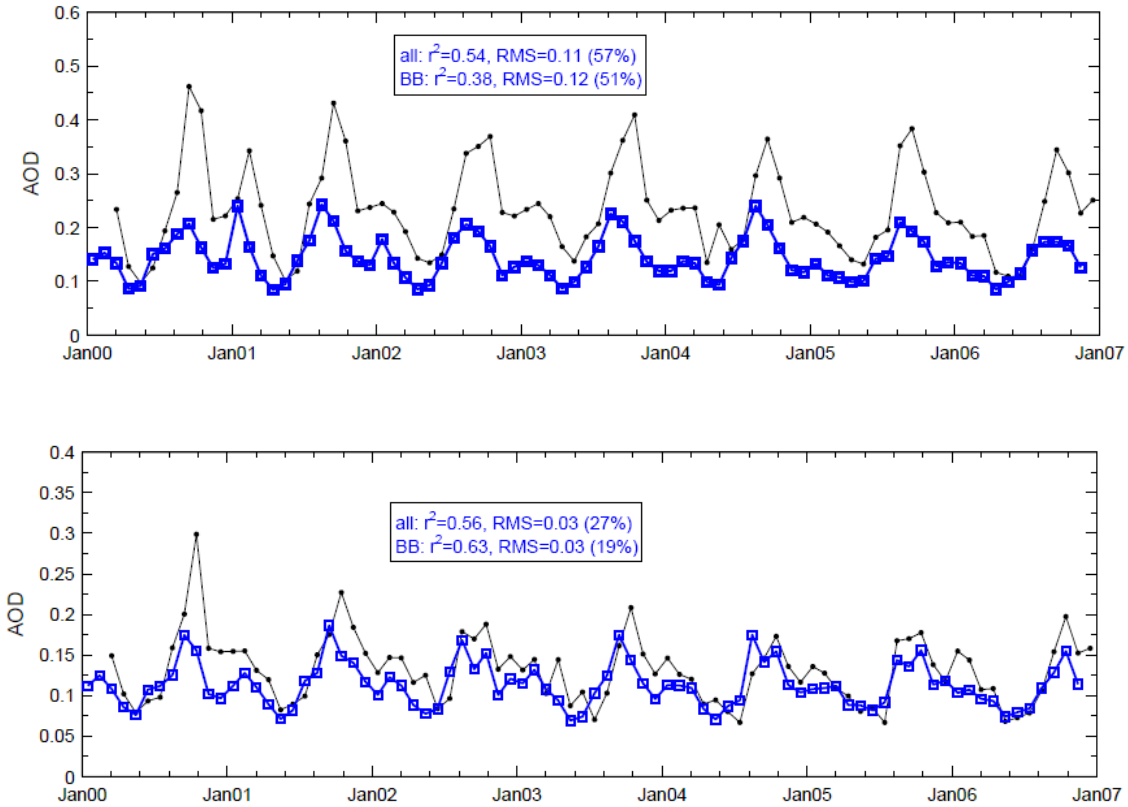

Figure 1. Comparison of monthly averaged aerosol optical depth (AOD) derived from AM2 output (blue) with AOD retrieved from MODIS satellite measurements (black) over (top plot) tropical southern Africa and (bottom plot) extratropical southern Africa. AOD is averaged only over land surfaces. (From Magi et al., 2009)

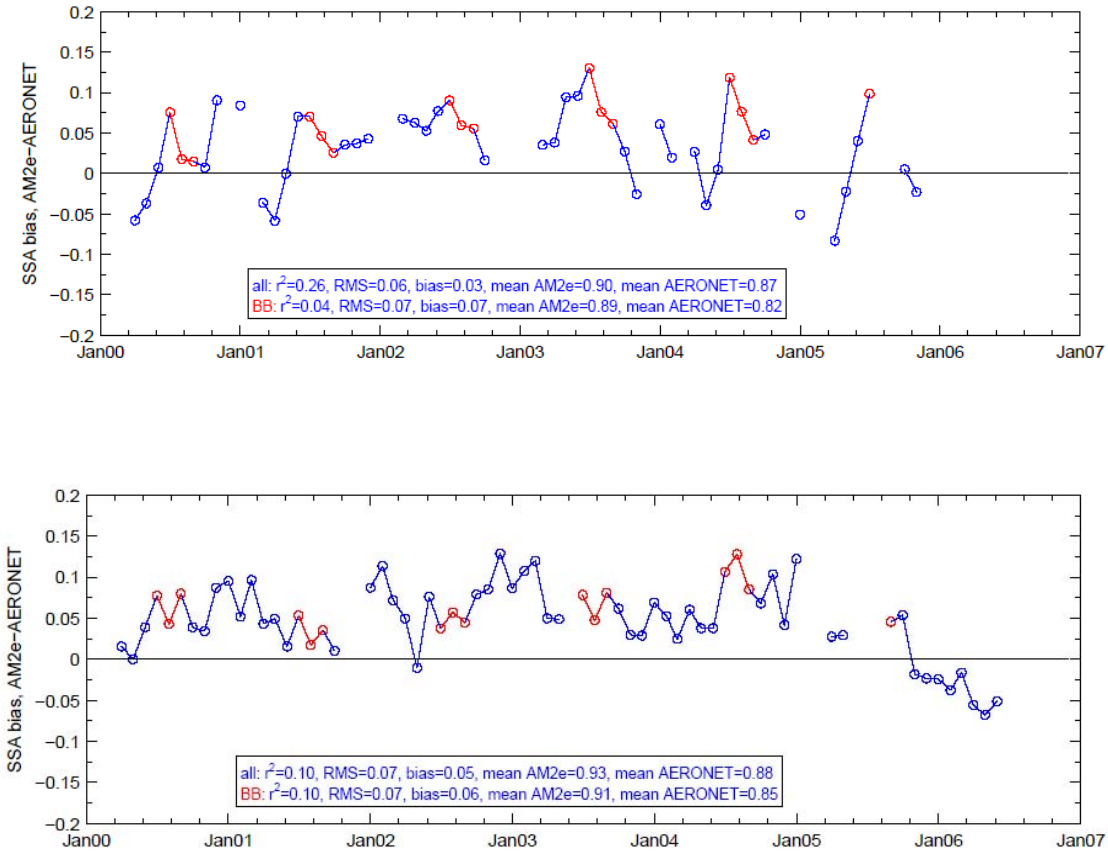

Figure 2. Comparison of monthly averaged single scattering albedo (SSA) output from AM2 (AM2 with external mixing) with SSA derived from Aerosol Robotic Network (AERONET) measurements in (top plot) Mongu, Zambia (latitude 15.25ºS, longitude 23.15ºE, elevation 1107 m) and (bottom plot) Skukuza, South Africa (latitude 24.99ºS, longitude 31.59ºE, elevation 150 m). Red circles and lines are during the biomass burning season (July, August, September). Blue circles and lines are during the remainder of the year. (From Magi et al., 2009)

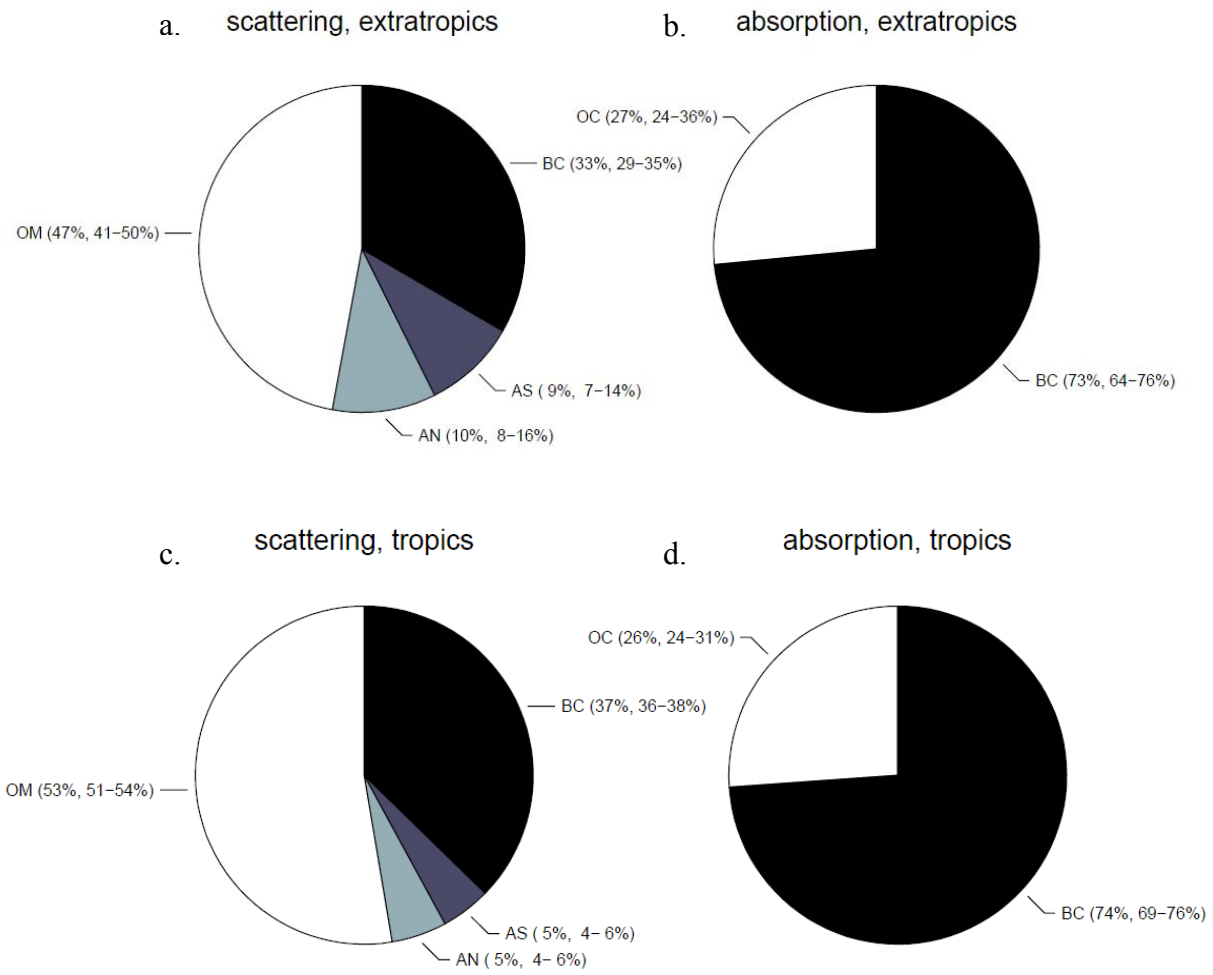

Figure 3. Apportionment.of scattering (a and c) and absorption (b and d) at a wavelength of 550 nm in extratropical (a and b) and tropical (c and d) southern Africa. Shown are the median percent contributions (with the interquartile range) of organic matter (OM), black carbon (BC), ammonium nitrate (AN), and ammonium sulfate (AS). (From Magi, 2009)

Progress Report: **Effect of Sea Ice Ridging in a Global Coupled Climate Model**

Principal Investigator: Torge Martin (Princeton, Postdoctoral Research Associate)

Other Participating Researchers: Mike Winton (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: Introducing a numerical sea ice ridging scheme to the sea ice model component of GFDL's coupled climate model in order to account for dynamic sea ice growth.

Methods and Results/Accomplishments:

Growth and melt of sea ice are thermodynamic processes. However, sea ice thickness can also increase due to dynamic effects. A convergent sea ice drift field puts the floes under pressure, which can result in fracturing of the ice. Blocks of broken ice pile up along these fractures or rims of thicker ice floes in so-called ridges. Ridges are more common for Arctic sea ice than Antarctic. Large parts of the Arctic sea ice cover are deformed, and because thicker ice is more resistive against pressure and melt it is important to consider ridging in large-scale sea ice models. Furthermore, ridging leads to an opening of the sea ice cover affecting the heat exchange between ocean and atmosphere. As global coupled climate models have horizontal resolutions of 10^2 km the ridging process needs to be parameterized.

Fundamental ideas on sea ice ridging parameterizations date back to the 1970s (e.g. Rothrock, 1975). A more recent work of Lipscomb et al. (2007) presents an improved, numerically stable algorithm for the use in large-scale simulations. We apply this algorithm, which describes ridging based on the available energy depending on the state of sea ice motion as well as ice thickness and fractional coverage, to the Sea Ice System (SIS) of GFDL's model suite. This allows us to test the impact of ridging in a global coupled climate model set up, which includes the atmosphere and land models AM2 and LM2, respectively, and the ocean model MOM4.1.

We ran the coupled model with ridging (experiments RDG) and without (CTRL) and with low (DARK) and high surface albedo values for snow and ice (BRIGHT). We used albedo values 0.58 and 0.68 for ice and 0.80 and 0.88 for snow. The dark case without ridging is comparable to the CM2.1 simulations, a former GFDL coupled model setting used for IPCC AR4 runs. However, in order to better resolve deformed ice, we have increased the number of ice thickness categories from 5 to 10 adding more classes for thick sea ice.

A comparison of the four different simulations described above reveals that ridging increases the sea ice mass and makes the ice cover more sensitive to climate feedbacks. Ridging increases the sea ice thickness by about 0.5 m in the central Arctic or locally by more than 1 m in coastal areas (Figure 1). The increased albedo in the BRIGHT runs helps to emphasize the results of ridging. In general, the impact of a brighter albedo exceeds the effect of ridging. However, ridging importantly changes the spatial distribution of ice thickness. In the experiment CTRL_BRIGHT there is a dominant north-south gradient visible with a maximum at the North Pole. This pattern is typical for purely thermodynamic sea ice models because it reflects the strong seasonality of solar radiation in these high latitudes. This is different in the RDG_BRIGHT run where dynamic sea ice processes are able to affect the sea ice thickness and its distribution is more realistic.

The opening of the sea ice cover due to ridging enhances the seasonality of the ice. In winter opening enables an increased heat loss from the ocean accompanied by an enhanced sea ice production. In contrast, the ocean can gain more heat in summer by absorbing short wave radiation resulting in a stronger sea ice retreat.

References:

Holland, M.M., C.M. Bitz, E.C. Hunke, W.H. Lipscomb, and J.L. Schramm, 2006, Influence of the Sea Ice Thickness Distribution on Polar Climate in CCSM3, J.Clim, 19, 2398-2414.

Lipscomb, W.H., E.C. Hunke, W. Maslowski, and J. Jakacki, 2007, Ridging, strength, and stability in a high-resolution sea ice model, JGR, 112, C03S91, doi:10.1029/2005JC003355.

Rothrock, D.A., 1975, The Energetics of the Plastic Deformation of Pack Ice by Ridging, JGR, 80(33), 4514-4519.

Publications:

Martin, T., and M. Winton, Revisiting the effect of sea ice ridging in a coupled climate model, in preparation.

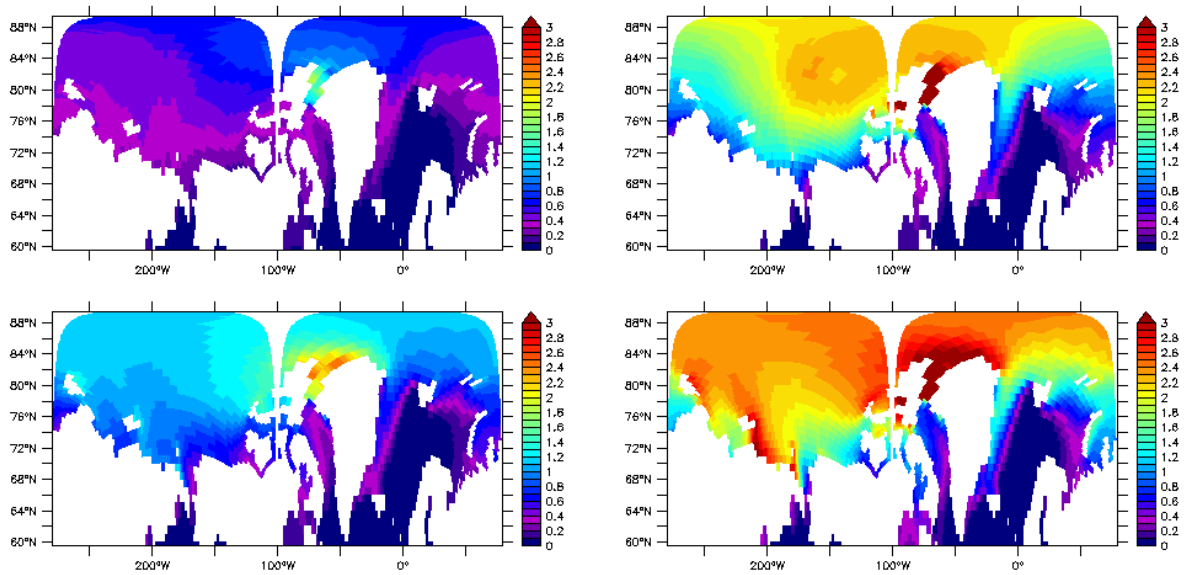

Figure 1 Five year average of mean sea ice thickness in the Arctic for experiments CTRL_DARK (upper left), RDG_DARK (lower left), CTRL_BRIGHT (upper right) and RDG_BRIGHT (lower right).

Progress Report: **GFDL Data Portal**

Principal Investigator: Serguei Nikonov (Princeton Earth System Modeler)

Other Participating Researchers: V. Balaji (Princeton)

Theme #1: Earth System Studies/Climate Research

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

Objectives: Design and development GFDL Data Portal software system for publishing, discovery, navigation and access data for forthcoming IPCC AR5 model simulations

Methods and Results/Accomplishments:

- Design relational DB Curator and XML-RDBMS mapping algorithms incorporated in FMS Runtime Environment System (FRE) for supporting modelling framework and supplying simulation data with model metadata on Data Portal.
- Design and development Data Portal publishing system for populating Data Portal with simulation data and model metadata complied with IPCC AR5 adopted standards.
- Provided design oversight Yana Malysheva (HPTi) in development Curator DB-oriented CMOR-enabled package for IPCC AR5 and model development web interface.
- Provided design oversight Chris Rehbein (HPTi) in development of the components for new generation of FRE (XML canonicalizer), IPCC AR5 Publisher (Commander Metadata).

References:

http://nomads.gfdl.noaa.gov/CM2.X/
http://cobweb:8080/extmdbCW/

Progress Report: **Modeling Sea Ice-Ocean-Ecosystem Responses to Climate Changes in The Bering-Chukchi-Beaufort Seas with Data Assimilation of Rusalca Measurements**

Principal Investigator: Leo Oey (Princeton Research Scholar)

Theme #1: Earth System Studies/Climate Research

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

Objectives: To understand the role of the Arctic Ocean to climate.

Methods and Results/Accomplishments:

A numerical ocean circulation model with realistic topography, but with an idealized forcing that includes only lateral transports is used to study the role of the Alaskan Stream (AS) in modulating the Bering Sea (BS) variability. Sensitivity experiments, each one with a different (but time-independent) AS transport reveal a non-linear BS response. For example, an increase of AS transport from 10 to 25 Sv causes a warming (~0.25 ºC mean, ~0.5 ºC maximum) and sea level rise in the BS shelf due to increase transports of warmer Pacific waters through the eastern passages of the Aleutian Islands, but an increase of AS transport from 25 to 40 Sv had an opposite impact on the BS shelf with a slight cooling (~0.1 ºC mean, ~0.5 ºC maximum). As the AS transport increases, flows through passages farther downstream in the western Aleutian Islands are being affected and the variability in the entire BS is reduced. Transport variability (~0.1Sv) in the Bering Strait flow toward the Arctic Ocean found to be correlated with meso-scale variations of the AS and associated transport variations in the Aleutian Islands passages. It is estimated that potential long-term changes in the mean transport of the AS may contribute to changes in transports across the Aleutian Islands that are about 20-30% of the contribution from meso-scale variability. These results have important implications for understanding the observed variations in the Bering Strait and potential future climate variations in the Arctic Ocean.

Progress Report: **Antarctic Sub-Polar Atmospheric Circulation**

Principal Investigator: Isidoro Orlanski (Princeton Senior Researcher)

Other Participating Researchers: Dr. Silvina Solman Center for Atmospheric and Ocean Research, Buenos Aires 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 (80%)
NOAA's Goal #3: Serve Society's Needs for Weather and Water Information (20%)

Objectives: To understand the role of the sub-polar quasi-stationary atmospheric circulation and its impact over South America weather and climate.

Methods and Results/Accomplishments:

Sub-polar high anomaly preconditioning precipitation over South America

The mechanisms associated with the intraseasonal variability of precipitation over South America during the spring season are investigated with emphasis on the influence of a quasi-stationary anomalous circulation over the southeastern South Pacific Ocean.

The main pattern of precipitation variability on intraseasonal time-scales is characterized by the well-known dipole structure with centers of action centered over the South Atlantic Convergence Zone (SACZ) region and the La Plata Basin (LPB) region (Nogues et al 2000). Time-series of daily precipitation anomalies were built for these two regions in order to explore the dominant time-scales of variability. A spectral analysis performed to these time-series revealed several peaks corresponding to periods of roughly 40 days, 23 days, 14-16 days and 10 days, being the lower-frequency peaks more prevalent for SACZ and the high-frequency peaks more prevalent for LPB.

The large-scale circulation patterns preconditioning precipitation variability over LPB and over SACZ were explored by means of a regression analysis performed using the daily 500 hPa geopotential anomaly field provided by the daily NCEP/NCAR reanalysis data set. The most prominent feature of the regression fields is the presence of a quasi-stationary anomalous anticyclonic (cyclonic) circulation over the southeastern South Pacific Ocean (SEP) associated with positive rainfall anomalies over LPB (SACZ) and emanating from that high (low) system, an external Rossby wave propagating northeastwards, towards the South American continent.

The synoptic scale activity, quantified in terms of a frontal activity index, showed a strong influence on precipitation over LPB and to a lesser extent over SACZ. However, it has been argued that the high-frequency activity that certainly triggers precipitation events over LPB is actually modulated by the circulation variability at lower frequencies, in particular, by the anomalous high over the SEP region.

The connection between this anomalous high and the rest of the variability of the circulation over the Pacific Ocean could have different origins (the PSA, the Indian dipole, among others). However, the behavior of this circulation anomaly may be supported by the interaction with surface conditions by a positive feedback mechanism which can enhance the response of the high anomaly itself which in turns reinforces the Rossby wave train propagating towards the South American continent.

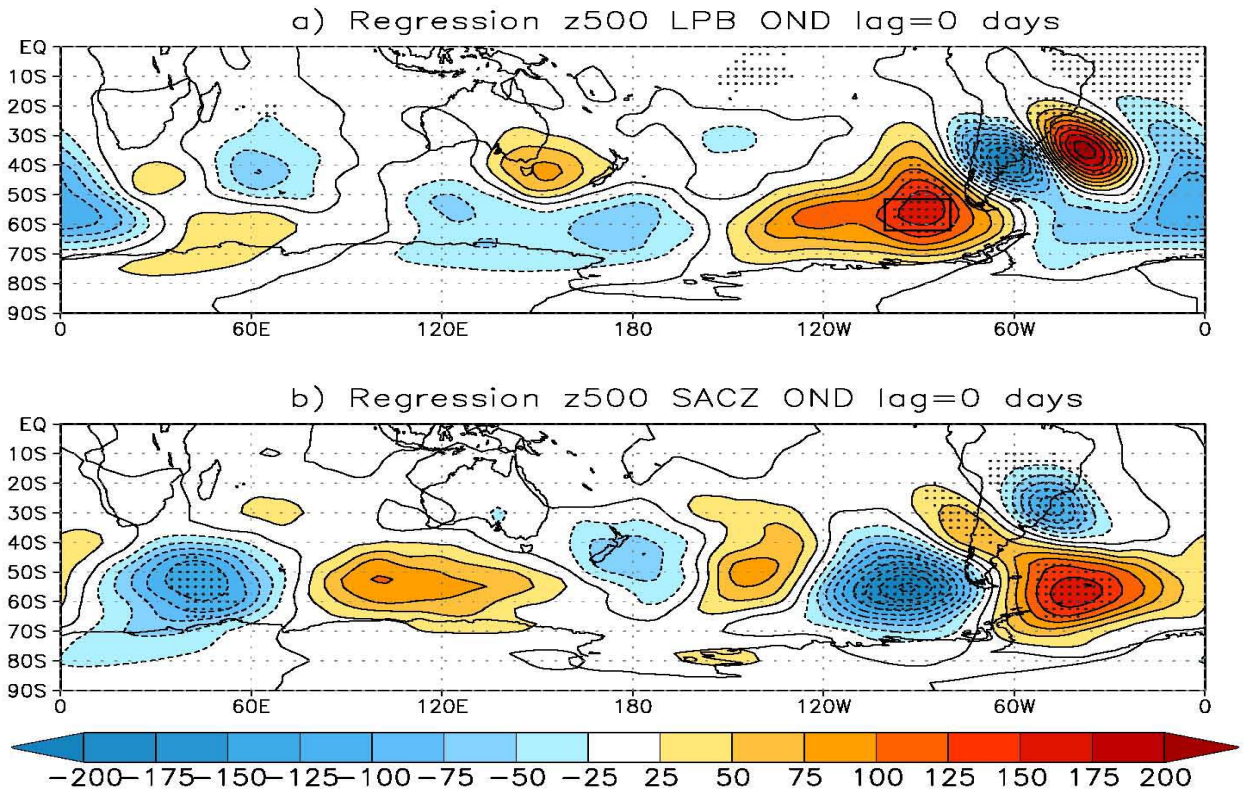

Figure 1: Regression of the 500 hPa geopotential height field with the precipitation time-series corresponding to LPB (a) and SACZ (b), respectively. Contours are drawn every 25 m2 s-2. Blue (orange) shading and dashed (solid) lines corresponds to negative (positive) values. Stippled areas indicate where the correlation between the two variables is significant at the 95% confidence level, based upon the F-statistic. The box in (a) defines the SEP area, where the anomalies of 500 hPa heights were averaged to define the SEPz time-series.

References:

Nogués-Paegle J., L.A. Byerlee and K. C. Mo, 2000: Intraseasonal modulation of South American summer precipitation. Mon. Wea. Rev.,128, 837-850.

Publications:

Orlanski I. and S. Solman, 2009: The mutual interaction between external Rossby waves and thermal forcing: The sub-polar regions. (in preparation).

S. Solman and I.Orlanski. 2009: Sub-polar high anomaly preconditioning precipitation over South America, in preparation.

Progress Report: **Topographic Venting of Ganges Valley Pollutants**

Principal Investigator: Arnico K. Panday (Princeton Postdoctoral Research Associate)

Other Participating Researchers: Larry Horowitz (GFDL), Hiram Levy (GFDL), Eri Saikawa (Princeton), Vaishali Naik (GFDL), Masayuki Takigawa (JAMSTEC, Yokohama), Paolo Bonasoni (ISAC-CNR, Bologna), Paolo Cristofanelli (ISAC-CNR, Bologna), Jayanta Kar (U. of Toronto & NASA Langley), Maheswar Rupakheti (UNEP RRCAP, Bangkok), Bidya Banmali Pradhan (ICIMOD, Kathmandu)

Theme #1: Earth System Studies/Climate Research

NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond (80%)
NOAA's Goal #3: Serve Society's Needs for Weather and Water Information (20%)

Objectives: To use high resolution model runs to study the mechanisms by which air pollutants from the Ganges Valley are lifted and exported by wind systems in the Himalaya; to study the downwind consequences of this pollution transport; and to identify and design future field measurements in the Himalaya.

Methods and Results/Accomplishments:

I have continued the work from last year with a multi-pronged approach:

1. I have set up nested runs of the WRF-ARW model at 2 km resolution in the region around Mt. Everest, and have started testing the model runs against a small field dataset collected by Bonasoni and Cristofanelli and Nepal Climate Observatory - Pyramid (5079 meters above sea level).
2. Using a combination of WRF model runs, MODIS satellite imagery, photography from commercial flights, and MOPITT carbon monoxide data provided by Jayanta Kar, I have explored a possible vertical transport mechanism involving clouds that form daily over Himalayan foothill peaks.
3. Working with Eri Saikawa, Masayuki Takigawa, and Vaishali Naik, I have worked on WRF-Chem runs nested within the Mozart global model to simulate the impacts of Ganges Valley emissions on measurements near Mt. Everest and to simulate the longterm impacts of increased emissions.
4. Working with the Atmospheric Brown Cloud Science Team, The UNEP RRCAP office in Bangkok, and the International Centre for Integrated Mountain Development in Kathmandu, I have worked on identifying suitable sites on the south sides of the Himalaya for long term monitoring stations and for field campaigns aimed at studying processes and producing data sets to validate model runs. Setting up of the field measurements will commence after I start a faculty position at the Department of Environmental Sciences at the University of Virginia.
5. I have brought to completion the publication of two JGR papers about prior work that focused on local air pollution in the Kathmandu Valley, Nepal.

Publications:

Panday, Arnico K., and Ronald G. Prinn. 2009. "The diurnal cycle of air pollution in the Kathmandu Valley, Nepal: Observations." Journal of Geophysical Research - Atmospheres. 114, D09305, doi: 10.1029: 2008JD009777.

Panday, Arnico Ronald Prinn, and Christoph Schär. 2009. "The diurnal cycle of air pollution in the Kathmandu Valley, Nepal: Modeling results" Journal of Geophysical Research – Atmospheres. doi:10.1029/ 2008JD009808. [accepted for publication]

Publications from the ongoing work (1-4) will be submitted to a special issue of Atmospheric Chemistry and Physics in early Fall 2009.

Progress Report: **The Contribution of Various Continuum Models in the Longwave and Shortwave**

Principal Investigator: David Paynter (Princeton Postdoctoral Research Associate)

Other Participating Researchers: V. Ramaswamy

Theme #1: Earth System Studies/Climate Research

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

Objectives: To better understand the contribution of the water vapor continuum in both the longwave and shortwave by using line by line codes radiation codes.

Methods and Results/Accomplishments:

The main aim has been to investigate the contribution of the water vapor continuum in both the longwave and shortwave by performing line by line radiative transfer calculations using model standard atmospheres. This has allowed a detailed comparison to be made between CKD, MT_CKD and the recent measurements conducted by *Paynter et al.* [2007,2009] and Baranov [*Baranov et al.*, 2008], which we call the PB continuum. The PB continuum covers the whole 1200-8000 cm^{-1} spectral region for the self continuum and the major band centers of the same region for the foreign continuum. It has been possible to use the experimental uncertainties associated with these measurements to produce an upper and lower estimate of the continuum contribution within these spectral regions (called PB upper and PB lower continuum respectively). To our knowledge while some previous work has compared CKD to the older RSB [*Roberts et al.*, 1976] continuum in the longwave [e.g. *Huang et al.*, 2007] and investigated the effect of the CKD continuum model in the shortwave [e.g. *Collins et al.*, 2006a] a detailed comparison between the CKD and MT_CKD models or new experimental data has not been previously made in either the longwave or shortwave.

Originally we performed this analysis using the GFDL line by line code. However, we switched to using the RFM [*Dudhia*, 2005] code, as this was easier to adjust to use the latest HITRAN 2006 parameters. We wrote a simple clear sky longwave radiation code based upon Clough et al. [1992] that makes use of these line by line calculations. We also wrote a shortwave radiation code, which uses the DISORT [*Stamnes et al.*, 1988] code that can take into account scattering and cloud cover. Although all calculation discussed here are for clear-sky conditions. We have tested these codes to reproduces numerous results in the literature.

The contribution of the water vapor lines from the three most recent versions of HITRAN (2001, 2004, 2006) was compared. It was found that in the longwave all three versions gave a similar top of the atmosphere radiation (TOA) for each of the three standard atmospheres (MLS, TRO, SAW) investigated. However, while the shortwave absorption by water vapor obtained using HITRAN 2006 and HITRAN 2004 is very similar, HITRAN 2001 predicts about 2% less absorption. Panel A of Figure 1 shows the absorption per a wavenumber analysis of this result for the TRO atmosphere.

In the Longwave each of the continuum models also gave similar results. However, in the shortwave a significant difference was observed between the models. For all three standard atmospheres the total shortwave absorption due to water vapor between 1000 and 18000 cm^{-1} is about 3 % greater when the CKD model is used compared to when MT_CKD is used. This is mainly because of differences in the foreign continuum. This can be seen in the spectral analysis of the foreign continuum contribution to the shortwave absorption for both SAW and TRO atmospheres which is shown in Figure 1 panels B and C respectively.

In the shortwave the PB continuum was found to give a slight increase in absorption compared to MT_CKD. What was perhaps most interesting was the large difference between the absorption predicted

by the lower and upper estimates of the PB continuum. For example in the TRO atmosphere assuming a zenith angle of 30° the impact of the continuum ranges from a lower value of 4 Wm^{-2} to an upper value of 12 Wm^{-2} (see Panel D of Figure 1). This difference is mainly because in the regions between the bands, where the self continuum is most important, no accurate measurements have been made yet. In addition, for the bands beyond 5000 cm^{-1} there is still considerable uncertainty in the foreign continuum. All of this work is currently being written up into a paper that will be submitted soon.

We have also started to use ERA-40 data to perform shortwave and longwave line by line calculations on a global level. So far calculations have been carried using 10 degree grid size for a certain month using different formations of the continuum. An example of the output from this analysis is shown in Figure 2. Panel A gives the percentage contribution of the CKD foreign continuum to the total clear-sky shortwave absorption, while Panel B shows the same but for the upper estimate of the PB self continuum. This highlights how the self and foreign continua are important in different geographical regions.

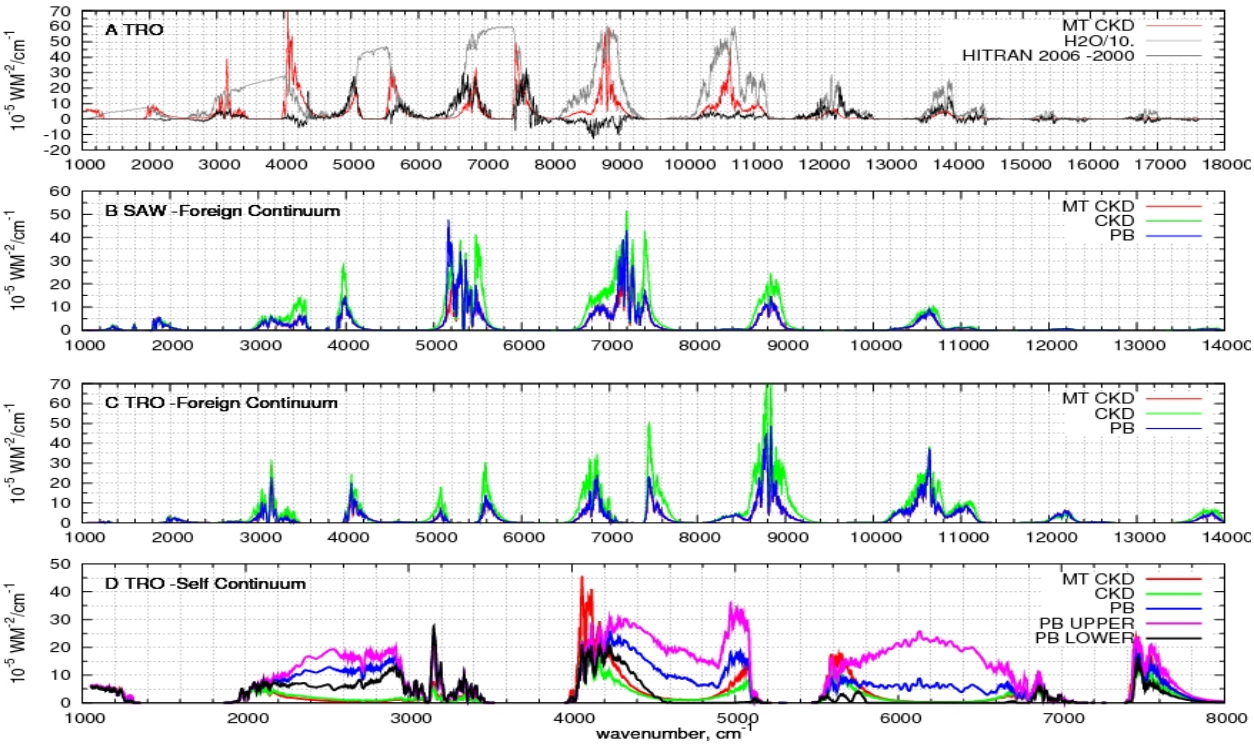

Figure 1: The absorbed shortwave radiation as a function of wavenumber. Panel A: The contribution of MT_CKD and H_2O vapor lines (divided by 10) to the absorbed shortwave radiation for the tropical standard atmosphere (TRO). The difference in absorbed radiation between obtained using HITRAN 2006 compared to HITRAN 2001 is also shown. Panel B: The contribution of the MT_CKD, CKD and PB foreign continuum in the SAW atmosphere. Take note that where no data exists for the PB foreign continuum the MT_CKD continuum data is used; hence quite often the blue PB line is the same as the red MT_CKD line. Panel C: The same as B, but for the TRO atmosphere. Panel D, the same as C, but for the self continuum. The upper and lower estimates of the PB self continuum are also included. Only 1200-8000 cm^{-1} region is shown, as the PB self continuum currently only covers this spectral region.

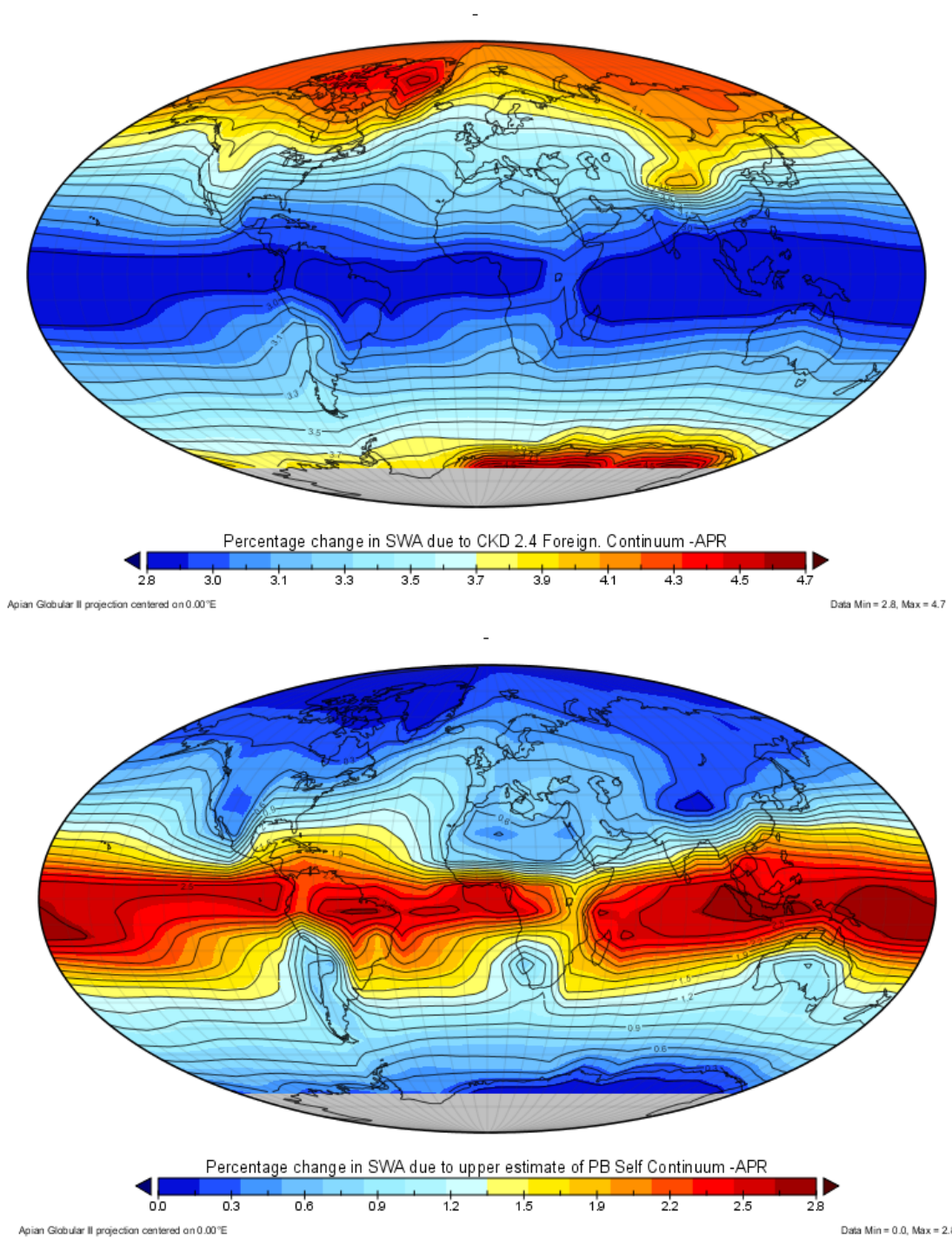

Figure 2: Panel A: The percentage difference in the daily average shortwave absorption due to including the CKD Foreign continuum. Calculated using ERA 40 data for the month of April at a spectral resolution of $1cm^{-1}$ and a 10 degree grid size. Panel B: same as A, but the contribution of the upper limit of the PB self continuum.

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Progress Report: **Cloud Microphysics and Feedbacks in the GFDL General Circulation Model**

Principal Investigator: Marc Salzmann (Princeton Postdoctoral Research Associate)

Other Participating Researchers: Leo Donner (GFDL)

Theme # 1: Earth System Studies/Climate Research

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

Objectives: Reduce uncertainties related to the cloud microphysics parameterization in the GFDL general circulation model and study cloud-climate feedbacks.

Methods and Results/Accomplishments:

A new stratiform cloud scheme including a two moment bulk cloud microphysics module (Morrison and Gettelman, 2008), a cloud cover parameterization allowing supersaturation over ice (Tompkins et al., 2007), and an ice nucleation parameterization (Liu and Penner, 2005) has been implemented into the latest generation GFDL Atmospheric Model (AM3) as part of an effort to treat aerosol-cloud-radiation interactions more realistically. Since homogeneous ice nucleation sometimes requires super-saturations with respect to ice in excess of 140%, the original cloud cover parameterization based on Tiedtke (1993) has been modified to allow for supersaturation over ice following Tompkins et al. (2007). Freezing of deliquescent sulfate aerosols and soot immersion are taken into account based on the parameterization by Liu and Penner (2005), and a modified version of Meyers' formula (Meyers et al., 1992), which depends on dust concentrations, is used to calculate the rate of deposition/condensation freezing on dust. Droplet activation is calculated based on Ming et al., 2006, 2007.

In the new scheme clouds are more likely to be either glaciated or liquid due to the Bergeron Findeisen process, which is in qualitative agreement with observations by Korlev at al. (2003). The reduced number of supercooled droplets in the new scheme leads to a very different global frequency distribution of liquid droplet effective radii compared to the original scheme. This has, however, only a moderate effect on radiation. The super-saturations over ice computed by the new scheme are in qualitative agreement with observations, as well as the temperature dependent frequency distribution of ice number concentrations, which has been compared to a recently published compilation of observations from several aircraft campaigns (Krämer et al., 2009). Unlike the new scheme, the original scheme does not permit super-saturation over ice. Effective ice radii, which are important for determining the influence of cloud ice in the radiative transfer calculations, are determined based on a temperature dependent lookup table in the original scheme. This procedure does not explicitly take into account variations in ice nuclei concentrations, while in the new scheme, the effective ice radii are diagnosed from the prognostic ice number concentration. Simulated ice water content agrees fairly well with CloudSat retrievals (Waliser et al., 2009) for the new scheme and for the original scheme.

The new cloud parameterization includes an improved representation of mixed phase clouds and allows us to start investigating questions regarding ice-aerosol couplings and influences of aerosols on mixed-phase clouds. While some of the processes involved are still poorly understood, these questions are especially important in the light of changing anthropogenic aerosol and aerosol precursor emissions (Andreae et al., 2005) and the relatively short atmospheric residence time of aerosols. A paper describing the implementation of the new scheme and presenting a detailed evaluation with observations is currently in preparation.

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Ming, Y., Ramaswamy V., Donner L. J., Phillips, V. T. J., Kelin, S. A., Ginoux. P. A., Horowitz, L. W.: Modeling the interactions between aerosols and liquid water clouds with a self-consistent cloud scheme in a general circulation model, J. Atmos. Sci., 64, 1189-1209, 2007.

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Progress Report: **Hurricane Intensity in Dry and Moist Atmospheres**

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

Other Participating Researchers: Stephen Garner (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 hurricane intensity in dry and moist thermodynamics systems, and its connetction to boundary layer dynamics.

Methods and Results/Accomplishments:

Hurricane intensity is an issue of great importance and broad public interest. At the same time it is an enormously complex problem and we cannot yet accurately predict the maximum intensity a developing hurricane will attain. In order to improve our insight into the mechanisms that control hurricane intensity, this thesis proposes a simplified theoretical and numerical model, based on a dry thermodynamic framework.

The motivation for this approach stems from the axisymmetric hurricane intensity theory of Emanuel (1986). Hurricanes are sustained by the energy flux supplied from the ocean to the atmosphere, and in a moist environment this flux is a combination of latent and sensible heat fluxes. Emanuel's hurricane intensity theory includes the latent heating due to moisture implicitly, within the definition of entropy. Thus if the sensible heat flux is enhanced to compensate for the missing latent heat source, the same theoretical considerations are valid for a dry framework. Using a non-hydrostatic, axisymmetric numerical model, it is demonstrated here that, indeed, moisture is not necessary to produce hurricane-like storms, either numerically and theoretically.

The mechanisms that control intensity are investigated by performing a large number of experiments for both dry and moist conditions. In both environments, simulated storms are morphologically similar, but always exceed the theoretical intensity limit of Emanuel. It is shown here that if the crude theoretical estimate of the boundary layer entropy budget is replaced with its numerically diagnosed structure, including eddy flux terms, the modified intermediate theory successfully predicts storm intensity in all cases. Therefore, a complete theory of hurricane intensity should follow from a sufficiently accurate theory for the boundary layer entropy budget. Finally, the dry framework should prove useful for the study of polar lows, dust devils and hurricanes in a cold Earth scenario.

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Progress Report: **Atmosphere, Ocean, and Climate Dynamics**

Principal Investigator: Geoffrey Vallis (Princeton faculty)

Other Participating Researchers: R. Farneti (AOS), P. Zurita-Gotor (Madrid), J, Mitchell (IAS, Princeton), S. Griffies (GFDL), R. Ferrarri (MIT)

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 and the interactions between the atmosphere and ocean, and in particular to understand the mechanisms giving rise to natural climate variability, the meridional transport of energy in the ocean-atmosphere system, the stratification of the atmosphere, and the effects of mesoscale eddies on the ocean circulation.

Methods and Results/Accomplishments:

Vallis has been engaged in a variety of research topics over the past year, as follows.

In a continuing study with R. Farneti, we have used an idealized coupled climate model to explore the compensation of energy transport between the atmosphere and ocean. The decadal variability of the climate system stems from variability in the ocean, and this can lead to fluctuations in the meridional energy transport. We have studied the compensation by the atmosphere, and how the partitioning between atmosphere and ocean might change due to natural variabiility, and how it might change under global warming. Vallis also wrote an invited review article on climate variability from months to decades.

In a collaboration with S. Griffies and R. Ferrari, we have developed a new parameterization for the effects of mesoscale eddies in ocean models. The parameterization build on that of Gent and McWilliams (in that it is and advective, or adiabatic, scheme) but it enforces the transport streamfunction to have a low vertical model structure. The parameterization also naturally satisfies boundary conditions at the ocean top and bottom, and does not need any ad hoc tapering scheme.

In work with J. Mitchell, we have explorted the dynamics of superrotation and how this is related to the instability of the Hadley Cell.

In work with P. Zurita-Gotor we are exploring the factors determining the height of the tropopause. the height is determined by a combination of dynamical and thermodynamical factors, and although the so-called radiative constraint hold is useful, the application of specific dynamical theories (baroclinic adjustment, marginal supercriticality, theories of baroclinic turbulence) is ambiguous, with no single theory providing a useful guide.

Publications:

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Zhao, R. and Vallis, G. K. 2008. Parameterizing Mesoscale Eddies with Residual and Eulerian Schemes and a Comparison with Eddy Permitting Models. Ocean Modelling, 23, 1-12.

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Farneti, R. and Vallis, G.K. 2009. An intermediate complexity climate model (ICCM) based on the GFDL Flexible Modeling System. Geosci. Model. Dev. Disc., 2, 341--383

Mitchell, J. and Vallis, G. K. 2009. The transition to superrotation in terrestrial atmospheres. submitted to Geophys. Res. Lett.

Progress Report: **Global Warming Pattern Formation**

Principal Investigator: Shang-Ping Xie (Princeton visiting scientist, Professor, University of Hawaii)

Other Participating Researchers: Gabe Vecchi and Andrew Wittenberg (GFDL)

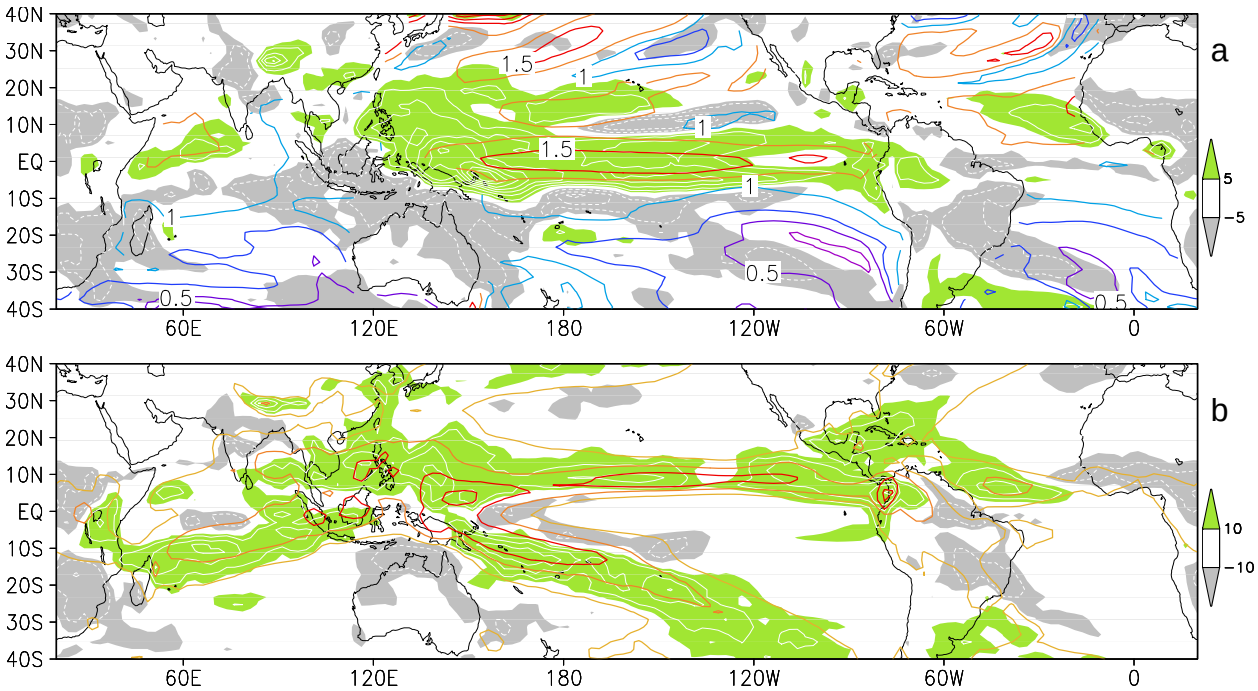
Theme #1: Earth System Studies/Climate Research

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

Objectives: To map spatial variations in sea surface temperature changes under global warming, and investigate their effect on precipitation.

Methods and Results/Accomplishments:

We have investigated spatial variations in sea surface temperature (SST) and rainfall changes over the tropics using ensemble simulations for the first half of the 21st century under the greenhouse gas (GHG) emission scenario A1B with coupled ocean-atmosphere general circulation model of the Geophysical Fluid Dynamics Laboratory (GFDL) and National Center for Atmospheric Research (NCAR). Despite a GHG increase that is spatially uniform, pronounced patterns emerge in both SST and precipitation. Regional differences in SST warming can be as large as the tropical mean. A diagnostic method based on the ocean mixed layer heat budget is developed to investigate mechanisms for SST pattern formation.Our results show that precipitation changes are positively correlated with spatial deviations of SST warming from the tropical mean. The gross moist instability follows closely relative SST change as equatorial wave adjustments flatten upper tropospheric warming. Implications for global and regional response of tropical cyclones are discussed.



In the coupled ocean-atmosphere model simulation, tropical rainfall change follows to first order sea surface temperature variations in space (a), in contrast to a wet-get-wetter response of precipitation to

spatially uniform sea surface warming (b). Annual-mean precipitation change (green/gray shade and white contours mm/month): (a) GFDL CM2.1 A1B ensemble simulation along with SST change (color contours in oC), and (b) AM2.1 simulation in response a uniform 2K sea surface warming along with mean precipitation (black contours at 100, 200, and 300 mm/month). Contour intervals for precipitation are 10 mm/month in (a), and 20 mm/month in (b).

Publications:

Xie, S.-P., C. Deser, G.A. Vecchi, J. Ma, H. Teng, and A..T Wittenberg, 2010: Global warming pattern formation: Sea surface temperature and rainfall. J. Climate, to be submitted.

Progress Reports:

Biogeochemistry

Progress Report: **Modeling Carbon - Nitrogen Interactions In The Terrestrial Biosphere**

Principal Investigator: Lars O. Hedin (Princeton Faculty), Elena Shevliakova (Princeton Research Associate), Stephen W. Pacala (Princeton Faculty)

Other Participating Researchers: Stefan Gerber (Princeton), E. N. Jack Brookshire (Princeton), Sonja G. Keel (Princeton), Michael Oppenheimer (Princeton), Ronald Stouffer (GFDL)

Theme #2: Biogeochemistry

NOAA's Goal #1: Protect, Restore, and Manage the Use of Coastal and Ocean Resources through Ecosystem-based Management (10%)
NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond (90%)

Objectives: One of the key issues regarding the potential of sequestering anthropogenic carbon (C) into the terrestrial biosphere is whether plants would response with increased productivity as atmospheric CO2 rises. This so called CO2 fertilization effect can particularly be dampened when the availability of essential nutrients (nitrogen and phosphorus) is limited. Moreover, humans have not only tapped into fossil fuels to modify the Earth's carbon cycle, they also increased nitrogen (N, a major nutrient) supply to the terrestrial plants by planting N fixing crops (plants that are able to get available N from the vast reservoir of N2 in the atmosphere), by applying N-containing fertilizers, and by fossil fuel burning, resulting in production, transport, and deposition of plant available N. Knowing the consequences and the extent of the anthropogenic modifications of the Earth's biogeochemical cycles is vital. Terrestrial carbon and nutrient cycling is tightly coupled with climate and also linked to the functioning of a range of ecosystems (terrestrial, freshwater, estuarine systems). Sophisticated modeling tools that capture the coupling of the different elements in the Earth's vegetation (carbon, nitrogen, phosphorus) are critical for this task.

Methods and Results/Accomplishments:

Over the past several years we have developed a coupled terrestrial C-N model within the Princeton-GFDL land model LM3V, and a manuscript describing the essential features is currently in press. The model is innovative on several fronts of C-N interactions (e.g. belowground C-N feedbacks, prognostic handling of biological N fixation) and is the most complete representation of biogeochemistry within the complexity and range of a global land surface model. In the past year we have explored the model in several ways.

1) We forced the model with a step change in atmospheric CO2, and compared the results to free air CO2 enrichment (FACE) experiments (Norby et al., 2005), where temperate forests have been subjected to elevated levels of CO2 (Figure 1). The results agree well when we evaluate the model at the FACE sites; we see a similar increase in net primary production. At the Duke FACE site, scientists have explored the N-dependence of the CO2 fertilization effect by adding N fertilizer. We can approximate this in our model by removing N restriction during primary productivity and obtain a stronger response. Both model and FACE experiments show a similar response under N sufficiency. Thus, our model captures the nutrient interactions that ultimately determine, how terrestrial carbon exchange responds to rising levels of atmospheric CO2.

2) We performed a series of global-scale simulation to investigate terrestrial carbon storage over the past 500 years, specifically we tested effects of land-use, atmospheric CO2 increase, C-N coupling, anthropogenic N-deposition, and recent climate change (Figure 2). When all factors are considered we obtain a terrestrial net C source of 110 GtC since 1500, and 24 GtC since 1860. Our results agree well with budget estimates which are based on the difference between cumulative anthropogenic emissions,

and atmospheric and oceanic inventory changes since 1860. Similarly we obtain decadal scale terrestrial fluxes that are comparable with data-based methods, with a modeled sink of 0.5 and 1.5 GtC for the 1980ies and 1990ies respectively (estimates based on data are 0.3 +/- 0.9, 1.0 +/- 0.6, Denman et al., 2007). In contrast, disallowing C-N interactions, or also neglecting the increasing anthropogenic N deposition rates on terrestrial systems change the modeled carbon uptake considerably. Overall we find that the consideration of nutrient interactions is critical to understand changes in the terrestrial carbon budgets over the anthropocene.

3) A major advantage of our approach is that it combines model development with field-based observations and state-of-the-art knowledge unique to Hedin's research group, of how N and other element cycles vary across the terrestrial biosphere. Jack Brookshire has over the past year worked closely with Stefan Gerber and Lars Hedin in abstracting regionally and globally relevant dataset and experimental information, such that it can be used to challenge our emerging LM3V coupled C-N model. Such model-empirical data analysis is only rarely done in traditional Earth system models, and typically to a much lesser conceptual degree than afforded in the Hedin lab group. This means that the LM3V C-N model is currently being shaped as one of the most realistic and most critically benchmarked dynamic C-N models in existence.

4) Of particular concern is if external N inputs from BNF are sufficient to account for observed high hydrologic loss rates of plant available nitrate from tropical forests vs. temperate forests. In combination with results from ongoing field measures in neotropical forests, carried out by Jack Brookshire, our modeling efforts suggest that such cross-biome differences in nitrate loss rates cannot result from differences in climate alone but require a sustained external input. While such high loss rates of nitrate suggest that many tropical forests worldwide are not limited by N, it remains unclear how these losses are maintained over time.

Over the next few months we will continue to make use of the model to investigate the difference in response of CO2 fertilization in tropical vs. temperate forests. Empirical data suggests that legumes in tropical forests are equipped to balance the needs for N by adjusting BNF, and thus may respond stronger to CO2 fertilization as temperate forests. Currently, our N model cannot adequately reproduce such high loss rates of nitrate from tropical forests. Ongoing efforts seek to improve this aspect of the N model. We also will further develop the model to include a prognostic phosphorus cycle. We also intend to integrate the code of the N-dynamics in GFDL's LM3 that combines LM3V with LM3W (i.e. dynamic vegetation and state of the art hydrology, respectively).

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Gerber, S., L.O. Hedin, E. Shevliakova, S.W. Pacala, M. Oppenheimer. 2009. Anthropogenic change and carbon-nitrogen feedbacks in the terrestrial biosphere. Abstract for 8th international Carbon Dioxide Conference, Jena, Germany

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Hedin, L.O., S. Keel, S. Gerber, E. Shevliakova, et al. Resolution of land ecosystem response to increased atmospheric carbon dioxide. *In preparation.*

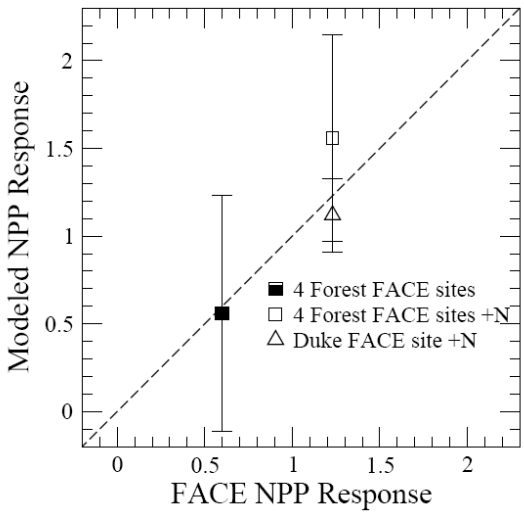

Figure 1: Short term NPP response of the model to a step change in atmospheric CO2 by 200 ppm expressed as biotic growth factor (β formulation). The modeled response is evaluated at the locations of the forest free air CO2 enrichment (FACE) sites summarized in [Norby et al., 2005]. The filled rectangle denotes the realization with the coupled C-N model. We mimicked fertilizer application in the model by shutting off N restriction in plants in all FACE locations (open rectangle: Forest +N), and for the Duke site only (open triangle, Duke+N). Vertical bars represent 1 standard deviation of the model's β factor obtained from annual NPP across 6 years and across the different sites.

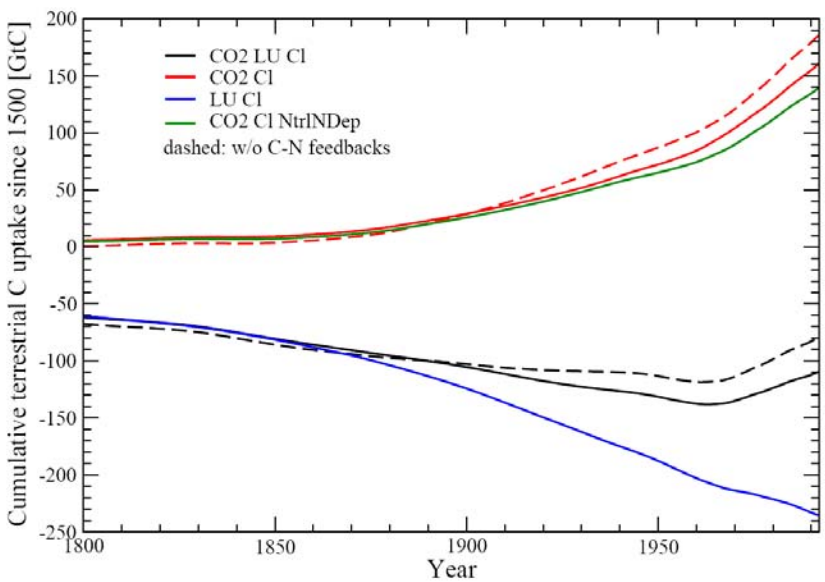

Figure 2: Cumulative terrestrial carbon uptake since year 1500 for different scenarios that include C-N feedback (solid lines) and not (dashed lines). The scenarios include a combination of several effects, as indicated in the legend: increasing atmospheric CO2 (CO2), landuse (LU), recent climate change (Cl), and anthropogenic N deposition (by prescribing pre-industrial values of N deposition, NtrlNDep).

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

Principal Investigator: George Hurtt (Associate Professor UNH)

Other Participating Researchers: S. Frolking (UNH), L. Chini (UNH), B. Moore (UNH), E. Shevliakova (Princeton/GFDL), S. Malyshev (Princeton/GFDL), S. 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 influence of land-use activities on Earth System dynamics

Methods and Results/Accomplishments:

For 2008-2009 we completed remaining activites proposed in our 2007-2008 proposal, as our proposal for 2008-2009 was not supported. In 2007-2008 we proposed to continue our current global landuse modeling efforts, revise our existing products, and concentrate on the development of projections of future land-use activities. Over the past year, we have made substantial progress on each of these proposed activities.

1) In 2008-2009 we continued our efforts to study the effects of historical land-use on the carbon/climate system. Our research directly contributed to and was a defining feature of the new LM3V study published in 2009 (Shevliakova et al. 2009).

2) In 2008-2009, work we initiated in 2007-2008 progressed with core NASA support into an international collaboration among Earth System Modeling teams (including the Princeton GFDL Team) and Integrated Assessment Modeling teams to "harmonize" landuse data based on historical reconstruction of the past and on the IPCC Representative Concentration Pathways (RCPs) for the future in preparation for the next IPCC Assessment. The resulting data products provide the first global consistent set of land-use data (1500-2100) and are widely being adopted by the scientific community for use in AR5. Hurtt et al leads the collaboration, and has presented on this work in numerous scientific forums includng IGBP-iLEAPS (FR), AGU (US), NCAR (US), Max Planc (GR), and is scheduled for plenary oral presentation at the upcoming 8th International CO2 conference (GR). A summary of the work can be found in Hurtt et al. 2009.

3) In 2008-2009, we also investigated the effects of patterns of distributed harvest and consumption of wood and crop biomass on local carbon sources and sinks using the Geophysical Fluid Dynamics Laboratory (GFDL) land model, LM3V, land-use reconstructions from the Global Land-use Model (GLM), and historic population estimates. LM3V vegetation dynamics were forced by the GLM scenarios of land-use transitions between natural and secondary vegetation, croplands and pasture. We developed an algorithm to distribute predicted harvested biomass based on population, socioeconomic status indicators and regional trade estimates and have incorporated the algorithm into LM3v to be used within the coupled earth system model. Work is underway to integrate the algorithm into the newer LM3 model. Results of our analysis were presented at AGU Fall Meeting 2008 (Fisk et al 2008). At half degree resolution, the total absolute difference in flux caused by harvest redistribution is ~4 Pg C annually. Quantifying and capturing this pattern is essential for connecting models to upcoming gridded satellite based CO¬2 observations. We also found significant zonal effects with harvest redistribution creating an apparent carbon sink near the equator and source in the mid latitudes of the northern hemisphere.

Publications:

Fisk J, Shevliakova, E, Hurtt GC, Frolking S (2008), Changes in distribution of carbon sources and sinks due to spatial patterns of harvesting and human consumption, Eos Trans. AGU, 89(53), Fall Meet. Suppl., Abstract B41B-0380.

Hurtt GC, Chini LP, Frolking S, Betts R, Feedema J, Fischer G, Klein Goldewijk K, Hibbard K, Janetos A, Jones C, Kindermann G, Kinoshita T, Riahi K, Shevliakova E, Smith S, Stehfest E, Thomson A, Thorton P, van Vuuren D, Wang Y (2009) Harmonization of Global Land-Use Scenarios for the Period 1500-2100 for IPCC-AR5. Integrated Land Ecosystem-Atmosphere Processes Study (iLEAPS) Newsletter 7:6-8.

Shevliakova E, Pacala SW, Malyshev S, Hurtt GC, Milly PCD, Caspersen JP, Sentman L, Fisk J, Wirth C, Crevoisier C (2009) Carbon Cycling Under 300 Years of Land-use Changes in the Dynamic Land Model LM3V. Global Biogeochemical Cycles 23 GB2022: 1-16.

Progress Report: **Altimetry Helps to Explain Patchy Changes in Hydrographic Carbon Measurements**

Principal Investigator: Keith Rodgers (Princeton Research Staff)

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

Theme #2: Biogeochemistry

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

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

Methods and Results/Accomplishments:

Ocean observations and ocean models were used to identify mechanisms driving large seasonal to interannual variations in dissolved inorganic carbon (DIC) and dissolved oxygen (O2) in the upper ocean. The work started from observations linking variations in upper ocean DIC and O2 inventories with changes in the physical state of the ocean. Models were subsequently used to address the extent to which the relationships derived from short-timescale (six months to two years) repeat measurements are representative of variations over larger spatial and temporal scales.

The main new result here is that convergence and divergence (column stretching) attributed to baroclinic Rossby waves can make a first-order contribution to DIC and O2 variability in the upper ocean. This results in a close correspondence between natural variations in DIC and O2 column inventory variations and sea surface height (SSH) variations over much of the ocean. Oceanic Rossby wave activity is an intrinsic part of the natural variability in the climate system and is elevated even in the absence of significant interannual variability in climate mode indices.

The close correspondence between SSH and both DIC and O2 column inventories for many regions suggests that SSH changes (inferred from satellite altimetry) may prove useful in reducing uncertainty in separating natural and anthropogenic DIC signals (using measurements from CLIVAR's CO2/Repeat Hydrography program).

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Sabine, C.L., R.A. Feely, and R. Wanninkhof (2006), Globl Oceans: Ocean carbon. In stae of the Climate in 2005, K.A. Shein (ed),, Bull. Am. Meteorol. Soc., 87(6), S29-S30.

Publications:

Rodgers, K.B., R.M. Key, A. Gnanadesikan, J.L. Sarmiento, O. Aumont, L. Bopp, S.C. Doney, J.P. Dunne, D.M. Glover, A. Ishid, M. Ishii, A.R. Jacobson, C. Lo Monco, E. Maier-Reimer, H. Mercier, N. Metzl, F.F. Pérez, A.F. Rios, R. Wanninkhof, P. Wetzel, C.D. Winn, and Y. Yamanaka (2009), Using altimetry to help explain patchy changes in hydrographic carbon measurements, J. Geophys. Res., 114, C09013, doi:10.1029/2008JC005183.

Progress Report: **Atmospheric Radiocarbon As A Tracer Of Large-Scale Southern Ocean Wind Variations Over The Period 950-1950**

Principal Investigator: Keith Rodgers (Princeton Research Staff)

Other Participating Researchers: Jorge Sarmiento (Princeton), Anand Gnanadesikan (GFDL), Eric Galbraith (Princeton), Sara Mikaloff-Fletcher (Princeton), Rick Slater (Princeton)

Theme #2: Biogeochemistry

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

Objectives: NOAA observations indicate that there have been significant variations in the latitudinal gradient in atmospheric radiocarbon over the last several decades, and that this may be useful for constraining the anthropogenic transient in CO2 concentrations. As a step towards understanding the relative roles of emissions of radiocarbon-depleted fossil fuels in the Northern Hemisphere and the tendency of the Southern Ocean to act as a sink of atmospheric radiocarbon, we have initiated a modeling study to understand the mechanisms controlling uptake of 14CO2 (relative to 12CO2) over the Southern Ocean.

Methods and Results/Accomplishments:

The MOM3 ocean circulation model is used in conjunction with an atmospheric transport model (ATM) to test the hypothesis that dynamical perturbations to the Southern Ocean can drive first-order changes in the delta-c14 of atmospheric CO2. In particular, it is shown that only relatively modest perturbations to the winds over the Southern Ocean can drive significant perturbations to the interhemispheric gradient in atmospheric delta-c14 over decadal timescales. The model results are evaluated against tree ring records of variations in the interhemishperic delta-c14 over the last millennium, and it is shown that the amplitude of variability in the observations can be accounted for by relatively modest perturbations over the Southern Ocean. The model results are used to argue that the reduction in the interhemispheric gradient in atmospheric delta-c14 recorded by tree rings in approximately 1350 AD, between the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA), may have resulted from a weakening of the surface winds over the Southern Ocean at that time.

Publications:

Rodgers, K.B., S. Mikaloff-Fletcher, E. Galbraith, A. Gnanadesikan, T. Naegler, J.L. Sarmiento, and R.D. Slater (2009), manuscript in preparation for Nature Geosciences.

Progress Report: **Applying IPCC-Class Models of Global Warming To Fisheries Prediction (Workshop)**

Principal Investigator: Charles Stock (Princeton Research Oceanographer)

Other Participating Researchers: John Dunne, Anand Gnanadesikan, Kelly Kearney, Jorge Sarmiento

Theme #2: Biogeochemistry

NOAA's Goal #1: Protect, Restore, and Manage the Use of Coastal and Ocean Resources through Ecosystem-based Management (80%)
NOAA's Goal #2: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond (20%)

Objectives: Hold workshop to: 1) develop new and innovative applications of existing IPCC-class models to problems in living marine resource (LMR) science and management; 2) assess the utility of IPCC-class models for these problems; 3) identify the primary factors limiting model utility; and 4) develop plans to overcome these limitations.

Methods and Results/Accomplishments:

The workshop "Applying IPCC-class Models of Global Warming to Fisheries Prediction" was held at Princeton University from June 15-17, 2009. The workshop was sponsored by the Cooperative Institute for Climate Sciences (CICS) and was attended by approximately 50 scientists from Princeton, GFDL, the Earth Systems Research Laboratory, the National Marine Fisheries Service, and other US and international academic institutions. A detailed agenda and workshop materials can be found at: http://www.gfdl.gov/fisheries-and-climate-workshop. Observations suggest strong responses to climate variability for prominent US and global fisheries and are suggestive of strong responses to longer-term forced changes. It was acknowledged that making highly quantitative and highly mechanistic predictions for the response of LMRs to climate requires models capable of capturing patterns arising from interactions between physical, biological, and human factors over a very broad range of space and time scales. However, efforts to develop such advanced models must co-exist with an immediate need to begin integrating existing climate information into simpler models used in fisheries stock assessments.

In order to be viable tools for LMR prediction, IPCC-class climate models must provide information on climate-induced changes and processes thought to be important for explaining fisheries variability and change. Changes in temperature, oxygen, pH, biological productivity, stratification, and seasonal patterns were identified as critical properties of the climate system that need to be accurately modeled. Critical processes and phenomena identified included the primary modes of climate variability, exchange processes between ocean basins and shelves, and coastal ocean dynamics (e.g., coastal upwelling). There is a need for information on these properties and phenomena at regional spatial scales (100-1000 km) and inter-annual to century time scales. Fisheries management interests are focused on inter-annual to decadal time scales, though stock rebuilding plans stretch to multi-decadal scales.

It was agreed that present IPCC-class models sufficiently resolve some of the dynamics listed above, but that utility of AR4 simulations for fisheries applications is limited by several simulation characteristics. The coarse oceanic (~1 degree) and atmospheric grids (~2 degree) have very limited representation of coastal processes and basin-shelf exchange processes. Inter-model spread, model biases, and climate variability generally become more prominent at regional scales. Climate variability can mask the "forced" climate signal and, since AR4 simulations are not "initial value" simulations, this variability will not generally match particular historical or future periods. Lastly, the AR4 archive does not include biological variables.

Statistical and dynamical downscaling are two potential ways to overcome some limitations of AR4 simulations. However, statistical downscaling is empirically-based and dependent on the degree to which large-scale phenomena captured by climate models contain information about small-scale processes. Experience with hurricane prediction at GFDL suggests that predictions can be highly sensitive to slight differences in predictor variables and to regional model biases. This sensitivity may increase as the complexity of the relationship between simulated phenomena and the inferred responses increases. Dynamical downscaling (i.e., embedded high-resolution regional models) has been applied with some success and could allow simulation of the response of highly resolved regional ecosystems to climate forcing. However, downscaled simulations are sensitive to regional climate model biases and coupling has proven difficult in regions bordered by highly energetic currents (i.e., western ocean boundaries) where dynamics are not well resolved by coarse AR4 climate models. Increased atmospheric and oceanic resolution at global scales may be necessary before robust nesting is possible in such situations.

Six case studies were presented during the second day of the workshop. Information from IPCC models was used in a wide variety of ways and the need for guidance regarding "best practices" was recognized. Examples involving global-scale fisheries patterns or highly migratory species (e.g., tuna) have scales that are more amenable to the direct application of present climate models. However, coastal applications have been developed and the overall dominance of coastal regions in global fisheries yields highlights the need to increase climate model effectiveness for these regions.

The final day of the workshop addressed some medium-term horizons in climate modeling, marine ecosystem modeling, and fisheries observations. Decadal-scale climate prediction experiments will be included in AR5 and some experiments will be run at higher resolutions. However, the extent of predictability in the climate system at decadal time scales (and the extent to which current observations and models allow this predictability to be realized) is highly uncertain at this time. Advanced marine ecosystem models that are under development may allow highly mechanistic connections to be drawn between the climate system, fisheries, and human activities but the feasibility of applying some of the techniques used at global scales is not yet clear. Fisheries observations are focused on maintaining the time series of scientific and commercial surveys while adapting new technologies to reduce gaps between biological and physical measurements. A need to facilitate access to this data and provide guidance in their use was identified.

Several workshop products and "next-steps" were identified. A synthesis paper distilling the workshop discussion and findings will be produced. This will provide a more complete consensus view of the material summarized in this document. It will include guidance from climate scientists on best practices for climate model applications to LMR prediction and guidance from fisheries scientists regarding the use of fisheries observations and models. A website (http://www.gfdl.gov/fisheries-and-climate-workshop) has been developed to archive workshop material and facilitate collaborations initiated during the workshop. The need for follow-up workshops on key topics such as statistical and dynamical downscaling was identified, as was the need for continued interactions between the climate and LMR communities. Shared postdocs and/or visiting scientists were suggested as possible ways to achieve this.

The workshop also identified specific areas where improvements to current climate and earth system models may significantly increase the utility of these models for LMR prediction: 1) improved resolution and representation of coastal-scale processes, 2) inter-annual to decadal scale predictions of physical and biological variables, 3) improved resolution of marine foodweb dynamics, 4) improved regional-scale climate predictions (i.e., less inter-model spread), and 5) a robust capacity for global climate simulations to drive regional nested simulations. Many of these improvements overlap strongly with current (AR5) research and model development activities and they will be further integrated with research and model development initiatives presently being composed.

Progress Reports:

Coastal Processes

Progress Report: **Marine Ecosystem Modeling: Applications of the Regional Ocean Modeling System to Coastal Ocean Forecasting and Regional Climate Impact Studies**

Principal Investigator: Dale Haidvogel (Professor, Rutgers University)

Other Participating Researchers: S. Henson (Princeton University), C. Stock and J. Dunne (GFDL), E. Curchitser (Rutgers University)

Theme #3: Coastal Processes

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

Objectives: The objectives of this activity are: to develop, to evaluate, and to apply coupled physical-ecological modeling systems suitable for both short-term and longer-term (e.g., climate-scale) applications; to transition these capabilities to operational use within the NOAA National Ocean Service for coastal ocean prediction; and finally, to study the regional impacts of (e.g.) higher resolution and alternate model formulation on marine environmental response in the context of global climate variability and change.

Methods and Results/Accomplishments:

The modeling conducted in this activity uses the Regional Ocean Modeling System (ROMS), a state-of-the-art regional modeling system encompassing multiple options for marine biogeochemical and ecosystem processes (http://www.myroms.org/). With an international user community now numbering in the many hundreds, the ROMS system is now a central modeling tool in several large marine ecosystem science programs (e.g., U.S. GLOBEC, BEST-BESIERP, CAMEO, etc.).

Two accomplishments are noteworthy this year. First, our partnership with the NOAA National Ocean Service has reached an advanced state. NOS is now employing ROMS for an increasingly large set of Operational Forecast Systems (OFS) and three such OFSs (Chesapeake Bay, Tampa Bay and Delaware Bay) are due to become fully operational in the next 12 months. Second, we (the PI and the other participating researchers noted above) have coupled the GFDL TOPAZ biogeochemical model to ROMS, and have implemented a fine-resolution (40 km) North Atlantic / Arctic Ocean basin-scale model in preparation for studies of interannual variability in primary productivity. Specific results in this latter activity are summarized in an accompanying annual report "**Bloom Dynamics In The North Atlantic: Model Evaluation And Effects Of Spatial Resolution And Formulation** ". These results lay the groundwork for potential participation in future North Atlantic science programs such as BASIN, as well as model inter-comparison studies across the suite of ROMS-supported environmental sub-models.

Education/Outreach

Progress Report: **Cooperative Institute for Climate Science Professional Development Summer Institute in Weather and Climate July 14-18, 2008**

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

Other Participating Researchers: Andrew Bocarsly, Chemistry, Princeton University, Dr. Steven Carson, formerly for the Geophysical Fluid Dynamics Laboratory and currently a middle school teacher in Princeton Township, NJ with the assistance of Anne Catena, Program in Teacher Preparation, Princeton University

Theme #1: Earth System Studies/Climate Research

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

Objectives: In support of the Cooperative Institute for Climate Science's (CICS) intent to educate society about the increasing complexity of understanding and predicting climate and environmental consequences, we designed and delivered professional development for teachers in New Jersey to improve their students' understanding of earth system modeling. This work is a collaboration of Professor Andrew Bocarsly, Chemistry, Princeton University, with Dr. Steven Carson, formerly of the Geophysical Fluids Dynamics Laboratory and currently a middle school science teacher in Princeton Township, New Jersey and Anne Catena, Program in Teacher Preparation at Princeton University.

Methods and Results/Accomplishments:
The July 14-18, 2008 program, offered inquiry-based experiences through which the grade 4-12 teachers developed an understanding of atmospheric physics and chemistry. They explored fundamental content regarding the Earth's climate including the greenhouse effect, human impacts on climate and global warming, as well as consequences of climate change. The teachers evaluated technological and social solutions that allow control over man's impact on climate, including solar energy conversion, fuel cells and wind energy. They learned new methods to teach about weather and climate change to promote an understanding of Earth system modeling and analysis.

Fourteen teachers participated in the professional development, including one former Teacher Preparation Program graduate who is now teaching high school physics and one Teacher Preparation Program student who will be student teaching in the fall of 2008. Five of the teachers are from either urban or urban rim school districts. This outreach effort increases educators' and students' understanding of data, information and research programs resulting in more informed decisions, and increases the participation of underrepresented groups in science education.

Feedback from teachers:

"I feel like I changed my understanding of not just the subject matter, but of myself, my teaching and my understanding of learning."

"I think the content knowledge that can be gained is far superior to other professional development offered to elementary school teachers."

"The climate change class clarified many misconceptions and gave a good foundation for understanding all sorts of energy sources."

"I was able to strengthen knowledge I already had, introduce new information and raise questions for further exploration of concepts. I drew from philosophies, experiences and knowledge from all the people involved."

"I feel more informed about global warming and how I can make a difference."

"QUEST is a unique opportunity to work with professionals in the science field."

"I have gained a better understanding of the science behind climate change and now I feel prepared to educate my students on the topic. The chemistry activities will be utilized in other areas as well."

2008-2009 CICS Publications

Peer Reviewed:

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Ganguly, D., P. Ginoux, V. Ramaswamy, D. M. Winker, B. N. Holben, and S. N. Tripathi (2009b), Retrieving the composition and concentration of aerosols over the Indo-Gangetic basin using CALIOP and AERONET data, *Geophys. Res. Lett., **36***, L13806, doi:10.1029/2009GL038315.

Gerber, E. and **Vallis, G. K.,** 2009. On the zonal structure of the NAO and annular modes. J. Atmos. Sci., **66**, 332-352.

Gruber, N., M. Gloor, **S. E. Mikaloff Fletcher**, S. C. Doney, S. Dutkiewicz, M. J. Follows, M. Gerber, A. R. Jacobson, F. Joos, K. Lindsay, D. Menemenlis, A. Mouchet, S. A. Müller, **J. L. Sarmiento**, and T. Takahashi (2009), Oceanic sources, sinks, and transport of atmospheric CO2, Global Biogeochemical Cycles, **23**, GB1005, doi:10.1029/2008GB003349.

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Legg S. and J. Klymak, 2008: Internal hydraulic jumps and overturning generated by tidal flow over a tall steep ridge. J. Phys. Oceanogr. v**38**, 1949-1964.

Magi, B.I., P. Ginoux, Y. Ming, and V. Ramaswamy (2009), Evaluation of tropical and extratropical Southern Hemisphere African aerosol properties simulated by a climate model, J. Geophys. Res., **114**, D14204, doi:10.1029/2008JD011128.

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Panday, Arnico K ., and Ronald G. Prinn. 2009. "The diurnal cycle of air pollution in the Kathmandu Valley, Nepal: Observations." Journal of Geophysical Research - Atmospheres. **114**, D09305, doi: 10.1029: 2008JD009777.

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Shevliakova E, Pacala SW**, Malyshev S, Hurtt GC**, Milly PCD, Caspersen JP, Sentman L,
Fisk J, Wirth C, Crevoisier C (2009) Carbon Cycling Under 300 Years of Land-use Changes in the Dynamic Land Model LM3V. Global Biogeochemical Cycles **23** GB2022: 1-16.

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Griffies, S.M., **A.J. Adcroft,** A. Gnanadesikan, R.W. Hallberg, M.J. Harrison, **S.A. Legg, C.M. Little**, **M. Nikurashin,** A. Pirani, B.L. Samuels, J.R. Toggweiler, **G.K. Vallis**, L. White, Problems and prospects in large-scale ocean circulation models. Conference white paper for OceanObs 2009.

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	JI Lead Author							**NOAA Lead Author**							**Other Lead Author**						
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Peer-reviewed	**4**	**12**	**30**	**26**	**15**	**17**	**14**	**1**		**3**	**5**	**2**	**4**	**2**	**1**	**10**	**14**	**22**	**18**	**7**	**4**
Non Peer-reviewed	**2**	**4**	**6**	**3**	**6**	**15**	**12**					**1**	**1**	**2**			**2**		**2**	**7**	**2**
Chapters in books		**2**				**2**	**1**						**1**				**3**	**1**			
Ph.D. Thesis		**1**	**1**	**3**	**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.

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

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

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

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

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

Jorge L. Sarmiento, George J. Magee Professor of Geosciences and Geological Engineering, 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.

ADMINISTRATIVE STAFF

CICS Director
Jorge L. Sarmiento
Professor of Geosciences
Princeton University
Phone: 609-258-6585
Fax: 609-258-2850
jls@princeton.edu

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

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

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

CICS Administrative Assistant
Joanne Curcio
Administrative Assistant, CICS
Phone: 609-258-6047
Fax: 609-258-2850
jcurcio@princeton.edu

Task I: Administrative Activities and Outreach Supported Personnel

Name	**Rank**	**Advisor**
Curcio, Joanne	Administrative Assistant	Sarmiento
Sarmiento, Jorge L.	CICS Director	Sarmiento

Departures - Task II:

Ph.D. Defenses

Student: Yi Huang *Advisor:* V. Ramaswamy - August 29, 2008
Dissertation: Satellite-Observed and Model-Simulated Outgoing Longwave Radiation Spectra
Harvard University - Postdoctoral Research Fellow

Task II: Cooperative Research Projects and Education Supported Personnel

Name	Rank	Advisor
Adcroft, Alistair	Research Oceanographer	Ramaswamy
Balaji, Venkatramani	Sr. Prof. Technical Specialist	Ramaswamy
Ballinger, Andrew	Graduate Student	Lau
Fang, Yuanyuan	Graduate Student	Vallis
Farneti, Riccardo	Associate Research Scholar	Vallis
Ganguly, Dilip	Postdoctoral Research Associate	Ramaswamy
Hammann, Arno	Graduate Student	Gnanadesikan
Harshvardhan	Visiting Research Scientist	Ramaswamy
Huang, Yi	Graduate Student	Ramaswamy
Legg, Sonya	Research Oceanographer	Ramaswamy
Li, Fuyu	Graduate Student	Ramaswamy
Li, Ying	Graduate Student	Lau
Little, Christopher	Graduate Student	Gnanadesikan
Lloyd, Ian	Graduate Student	Lau/Vecchi
Magi, Brian	Postdoctoral Research Associate	Ramaswamy
Martin, Torge	Postdoctoral Research Associate	Winton
Nikonov, Serguei	Prof. Technical Specialist	Balaji
Orlanski, Isidoro	Sr. Research Meteorologist	Ramaswamy
Panday, Arnico	Postdoctoral Research Associate	Levy/Horowitz
Paynter, David	Postdoctoral Research Associate	Ramaswamy
Salzmann, Marc	Postdoctoral Research Associate	Donner
Smith-Mrowiec, Agnieszka	Graduate Student	Garner
Vallis, Geoffrey	Sr. Research Oceanographer	Ramaswamy
Xie, Shang-Ping	Visiting Research Scientist	Ramaswamy

Task III: Individual Projects Supported Personnel

Name	Rank	Advisor
Brookshire, Jack	Postdoctoral Research Associate	Hedin/Oppenheimer
Curchitser, Enrique	Assoc. Research Professor	Haidvogel
Gerber, Stefan	Associate Research Scholar	Hedin/Oppenheimer
Haidvogel, Dale	Professor	-
Levin, Julia	Asst. Research Professor	Haidvogel
Oey, Lie-Yauw	Research Oceanographer	Sarmiento
Rodgers, Keith	Associate Research Scholar	Sarmiento
Wolheim, Widred	Research Assistant Professor	Hurtt

Personnel				
Category	Number	B.S.	M.S.	Ph.D.
Faculty	5			5
Research Scientist	5			5
Visiting Scientist	2			2
Postdoctoral Research Associate	7			7
Professional Technical Staff	2			2
Associate Research Scholar	3			3
Administrative	1	1		
Total (≥ 50% support)	**15**	**1**		**14**
Graduate Students	9		8	1
Employees that receive < 50% NOAA funding (not including graduate students)	10			10
Located at the Lab (include name of lab)	20-GFDL		6	14
Obtained NOAA employment within the last year				

Student: Yi Huang *Advisor:* V. Ramaswamy - August 29, 2008
Dissertation: Satellite-Observed and Model-Simulated Outgoing Longwave Radiation Spectra
Harvard University - Postdoctoral Research Fellow

CICS FY'09 List of Funding Amendments for NA17RJ2612

Amount	PI	Project Title
$ 26,887	Lie-Yauw Oey	Collaborative Research: Modeling sea ice-ocean-ecosystem responses to climate changes in the Bering-Chukchi-Beaufort Seas with data assimilation of RUSALCA measurements

Amendment # 25