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
## Table of Contents

**Introduction** 1

**Research Themes Overview** 2-6

**Structure of the Joint Institute** 7-8

**CICS Committees and Members** 9

**Research Highlights**

*Earth System Modeling and Analysis* 10-11

- *Ice Sheet Modeling*
- *High Resolution Atmospheric Modeling*
- *Ocean Model Development*
- *Software Development*

*Earth System Modeling Applications* 11-12

- *Climate Variability and Change*
- *Large-scale Ocean Circulation and Mixing*
- *Ocean Modeling of the Gulf of Mexico Oil Spill*
- *Impacts of Climate Change on the Earth System*

**NOAA Funding Tables** 13

**Project Titles** 14-16

**Progress Reports** 17-128

**Publications** 129-133

**CICS Administrative Staff** 134

**Personnel Support Information** 135-140

**CICS Project Awards** 141-143
Introduction

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

The mission of CICS is to focus the core scientific competencies of Princeton University into answering key questions related to the sciences of climate change and Earth System Modeling, and so provide an effective bridge between the two institutions.

The overall vision of CICS is to:

*be the world leader in understanding and predicting climate and the environment, integrating physical, chemical, biological, technological, economic and social dimensions, and in educating the next generations to deal with the increasing complexity and importance of these issues.*

CICS is thus built upon the strengths of two outstanding institutions and the ties between them: **Princeton University** in biogeochemistry, physical oceanography, paleoclimate, computer science, hydrology, climate change mitigation technology, economics and policy, and **GFDL** in numerical modeling of the atmosphere, oceans, weather and climate. CICS now proposes research that, when combined with the ongoing activities at GFDL, is intended to produce the best and most comprehensive models of the Earth System, and therefore enable NOAA to deliver a new generation of products to decision makers.

To summarize, the main goals of this cooperative institute are as follows:

1. To aid in the development of GFDL’s Earth system model by providing expertise in its constituent components, particularly in ocean modeling and parameterizations, in ocean biogeochemical cycling and ecology, in land modeling and hydrology, in understanding the interactions within and among the various components of the Earth system, and in the computational infrastructure that binds all the components together in a model.

2. To use the Earth system model and its component parts, to address problems in climate change and variability on decadal and longer timescales. This includes using the model and observational data to assess the state of the Earth system, and to provide projections of the future state of the system.

3. To educate and train future generations of scientists for NOAA and the nation as a whole, by providing access to a graduate degree program and a postdoctoral and visiting scientist program that
provide academic training and a hands-on opportunity to work with NOAA scientists at a NOAA facility.

Research Themes Overview

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

Earth System Modeling and Analysis

Climate modeling at Princeton University and GFDL is continually producing new models, including 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 may, in principle, be appropriately combined to give what might be called an Earth System Model, or ESM. Such models, by definition, seek to simulate all aspects — physical, chemical and biological—of the Earth system in and above the land surface and in the ocean. Thus, an Earth System Model consists of, at least:

1. An atmospheric general circulation model, including a dynamical core for the fundamental fluid dynamics and water vapor, a radiation scheme, a scheme for predicting cloud amounts, a scheme for aerosols, and various parameterization schemes for boundary layer transport, convection and so forth.

2. An oceanic general circulation model, including a dynamical core, various parameterization schemes for boundary layers, convection, tracer transport, and so on.

3. An ice dynamics model, for the modeling and prediction of sea ice.

4. An atmospheric chemistry module, for predicting chemically active constituents such as ozone.

5. A land model, for land hydrology and surface type, and a land ice model.

6. Biogeochemistry modules for both land and ocean. These may be used, for example, to model the carbon cycle through the system.

7. A computational infra-structure to enable all these modules to communicate and work together efficiently.

The goal of Earth System Modeling development at CICS and GFDL is, then, to construct and appropriately integrate and combine the above physical and biogeochemical modules into a single, unified model. Such a model will then be used for decadal to centennial, and possibly longer, studies of climate change and variability (as described primarily in the ‘applications’ section). At present, such a model does not exist in final form, and improvements are needed in two general areas:

1. Improvement on the physical side of the models, in the ocean, atmospheric, sea ice and land components.
2. Further incorporation of biological and chemical effects into the model, and ecosystem modeling.

Both of these are continual processes, that can never be said to be complete, although at various stages the development of a component, or a complete model, may be ‘frozen’ to allow numerical experiments to take place in a stable environment.

Developing and testing such ESMs is an enormous task, which demands a significant fraction of the resources of CICS and GFDL. Further, at any given time, model development depends on existing knowledge of how systems behave, but for that development to continue our body of knowledge and understanding must also increase correspondingly, and without that, model development would stagnate. That is to say, one might regard ESM development as both a scientific and engineering enterprise, and proper attention and respect must be paid to both aspects. The contributions and goals of CICS might be divided into the following two general areas:

1. Development of modules (or components) for the Earth System Model (for example, the land model and parts of the ocean model), in collaboration with GFDL scientists. These aspects are described in more detail in the sections below. Note that not all of the modules above involve CICS scientists; rather, CICS complements rather than duplicates GFDL efforts. For example, the dynamical core of the atmospheric model, the ice model, and many of the physical parameterizations of the atmospheric model, have been and will continue to be developed at GFDL itself. This document focuses on those components to which CICS is directly contributing.

2. Seeking improved understanding of the behavior of components of the Earth system, and the interaction of different components, thereby aiding in the long-term development of ESMs. These aspects involve comparisons with observations, use in idealized and realistic situations, and development of new parameterizations and modules, as described in more detail in the sections below. The development of ESMs is a research exercise, and is crucially dependent on continually obtaining a better understanding of the ocean-atmosphere-ice-land system. We begin with the computational framework, into which the other components fit. We then discuss the development of some of the various components, and then return to the problem of understanding and modeling the system as a whole.

Data Assimilation

Data assimilation, also known as state estimation, may be defined as the process of combining a model with observational data to provide an estimate of the state of the system which is better than could be obtained using just the data or the model alone. Such products are necessarily not wholly accurate representations of the system; however, especially in data-sparse regions of the globe and for poorly measured fields, the resulting combined product is likely to be a much more accurate representation of the system than could be achieved using only the raw data alone. (Of course, this in turn means the products contain biases introduced by whatever model is used.) The process of combining data and model has grown increasingly sophisticated over the years, beginning with optimal-interpolation and three-dimensional variational data assimilation (3D-Var). Currently, most centers use 4D-Var (with time as an additional variable) and ensemble Kalman filter methods. All these methods are essentially least-squares methods or variations of least-squares methods, with the final estimate being chosen to minimize the appropriately chosen ‘distance’ between the final estimate, the data and a model prior. The difference between the various methods
lies in the choice of the metric used to measure distance and the corresponding weight given to the observations and the prior estimate, and in the choice of which fields or parameters are allowed to be adjusted in order to produce the final estimate. Modern methods generally allow the error fields to evolve in some fashion, so allowing a dynamic estimation of the error covariances and a better estimate of the appropriate weights. The literature is extensive; see Kalnay (2003) and Wunsch (2006) for reviews.

There is a long history of data assimilation in meteorology, largely associated with weather forecasts: data from satellites, radio-sondes and other sources are combined with a model estimate from a previous forecast, to provide the initial state for a subsequent forecast. Re-analysis products are now available that combine model and data over the last fifty or so years into a single, consistent product. The application of data assimilation methodology in oceanography is more recent, reflecting in part the relative sparsity of data in the ocean and so the likely large errors inherent in any such analysis. However, with the advent of near-routine observations from satellites (e.g., altimeters) and profiler drifters (e.g., the Argo float system), a much higher density of observations is possible and ocean data assimilation has become a practical proposition. This is important because it is the initial state of the ocean, and not the atmosphere, that will largely determine the evolution of the ocean and the climate on the decadal and longer timescales, and so determining the natural variability of the climate. Still more recently, inverse modeling, an optimization technique closely related to data assimilation, has been applied to oceanic and terrestrial biogeochemical fields – for example, CO₂, CH₄, and CO – in an attempt to constrain the carbon budget. Here, the field is still in its infancy, and the term ‘data assimilation’ might imply capabilities that do not yet exist, but that one may hope will exist at the end of the proposal period.

In the next few sections we describe the various activities that CICS is involved in, and proposes to be involved in, including data assimilation and inverse modeling. Many of these activities will be conducted in collaboration with GFDL scientists, and in particular activities involving the ocean state estimation and ocean initialization for decadal to centennial predictions (the next subsection) will be carried out largely with postdoctoral research fellows working closely and in collaboration with 28 GFDL scientists. Analogous to the development of ESMs, data assimilation in ESMs has many components, and we propose to focus on a subset of these, as follows.

• Ocean data assimilation in climate models. By estimating the ocean state using all available data (including ARGO, altimetry, and hydrographic sections), the detection and prediction of climate change and variability on decadal timescales is enabled.

• High resolution ocean data assimilation, both to gain experience in this activity for the next generation of ocean climate models and for present-day regional models.

• Ocean tracer inversions for determining water mass properties, pathways, and sources and sinks of biogeochemical tracers, and to evaluate the ocean component of the Earth system model.

• Analyzing satellite observations of ocean color to elucidate ocean ecosystem processes.

• Atmospheric inversions for estimating high-quality, time-dependent flux maps of CO₂, CH₄, and CO to the atmosphere from tracer observations in the atmosphere and oceans, to evaluate the sources of these tracers and elucidate source dynamics.

• Use of terrestrial ecosystem carbon dynamics to evaluate carbon fluxes and help evaluate ESM parameter variability.
The overall goal of this activity is to collaborate with GFDL to create a capability whereby data can be combined with an Earth system model to provide a better assessment of the state of the current Earth system, and that can be used to provide forecasts of the future state of the system. More details on these activities are given in the sections following.

## Earth System Modeling Applications

The development and the use, or the *applications*, of an Earth System model must proceed hand-in-hand, and in this section we focus on how the ESM will be used to address problems of enormous societal import. The problems we propose to focus on involve decadal and centennial timescales, the interaction of natural and anthropogenically-forced variability, and the changes and impacts on the environment that affect society. *The overall goal of this activity is to use the Earth system model, in whole or in part, to investigate problems associated with climate change and its impacts on timescales of a decade or longer.*

The applications may be conveniently, if not fundamentally, divided into three general areas:

1. Applications involving one or two individual components of the ESM — for example, integrations of the ocean general circulation model to better understand the large-scale circulation, and how it might respond to global climate change, or integrations involving the ocean circulation and the biogeochemical tracers within it.

2. Applications involving the physical components of climate system; coupled ocean-atmosphere-land-ice models. These are the traditional ‘climate models’, and will remain of singular importance over the lifetime of this proposal.

3. Applications involving the ESM as a whole. Typically, these involve the biological and biogeochemical components of the model, for these depend also on the physical aspects of the model and therefore require many model components.

In all of the above areas both idealized and realistic model integrations will be performed: the former to better understand the behavior of the models and the interactions between their components, and the latter to give the best quantitative estimates of the present and future behavior of the Earth system. As with the other themes, CICS seeks to complement GFDL activities by providing expertise in distinct areas, typically those that are concerned with the dynamics of subsystem (e.g., the ocean circulation and its biogeochemistry, the land) where CICS has particular expertise, or that are concerned with understanding the interactions between systems. Applications involving integrations of the comprehensive, state-of-the art ESM that are aimed at providing quantitative measures of the present and future state of the Earth system, for example for future IPCC assessments, will only be carried out as part of a close collaboration with GFDL.
Education/Outreach

Summer Institute in Weather and Climate

CICS continued its collaboration with a Princeton University professional development institute for New Jersey teachers, once again this year. This well-established summer program, QUEST, is led by Princeton University’s Teacher Preparation Program. A one-week Weather and Climate unit for teachers of students in second through eighth grades, held this summer, offered a wide range of inquiry-based experiences through which the teachers explored the fundamentals of weather, the Earth’s climate, and the interaction of land, ocean, and atmosphere. Inquiry-based investigations included air pressure, temperature, seasons, the greenhouse effect, humidity, clouds, wind, the Coriolis effect, storms, and colors in the sky. In addition to exploring the greenhouse effect and human impacts on climate and global warming, participating teachers participated in discussions that considered public misconceptions and avenues of communication to improve public understanding of climate change. Additionally, models were introduced to aid in the teachers’ understanding of weather conditions and weather prediction. 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. The instructional team also included Travis Merritt, a middle school teacher in Lawrence, New Jersey. Ten teachers participated in the Weather and Climate unit, representing seven different school districts. Teachers serving underrepresented students in urban districts comprised 40 percent of the participating districts.

Coral Workshop

Through CICS, the NOAA Coral Reef Conservation Program sponsored a “Coral Vulnerability Workshop” from August 30-September 1, 2010 at Princeton University. Quantifying the impacts of climate change and ocean acidification on coral reefs under different future scenarios is critical to making proactive decisions about both the need to mitigate greenhouse gas emissions and the actions that may be required to promote adaptation to climate change. The ultimate products of this project will be a globally extensive suite of downscaled reef-level projections of the effects of climate change and acidification that will help identify coral reefs and regions that may be more susceptible/resistant and vulnerable/resilient to climate change and acidification. This effort will supply a key consideration in the design and management of marine protected areas. Locally, the forecasted range of likely climate change impacts will help managers optimize actions and plans to protect reefs. From an outreach perspective, another goal of the workshop was to identify scientific meetings that would appropriately link the resultant model findings with reef managers who can make use of this information for conservation efforts. Dr. Logan has since presented preliminary model findings in the “Decision Support Tools for Coral Reef Managers” session at AGU-San Francisco in December 2010. She will also be presenting on this work at the International Marine Conservation Conference in Victoria in May 2011. In addition, we plan to submit all peer-reviewed scientific articles resulting from this project to the IPCC 5th Assessment Working Group II: Impacts, Adaptation and Vulnerability. We plan to continue these outreach efforts as the project matures and the analyses are complete.
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 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.
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

*The Executive Committee met on July 2, 2010.
Six CICS administrative staff meetings were held during the academic year.
Executive Summary of Important Research Activities

There is so much fascinating and important work going on in CICS that it is impossible to highlight just a few in a fair fashion. The following selection should be therefore regarded primarily as a small representative selection of ongoing research in the major research and education areas; space does not permit us to do more. We organize these highlights by the major themes of the cooperative institute.

EARTH SYSTEM MODELING AND ANALYSIS

In the paragraphs below we summarize and highlight some of the activities going on in the area of Earth System Modeling. There is an entire spectrum of fascinating and important activities, from fundamental to quite applied; the Earth System, as complex as it is, demands such a wide range of activities. However, these activities also provide the essential building blocks for understanding the system and come together in a coherent whole, so enabling us to build better models of the system and, ultimately, to better predict it.

Ice Sheet Modeling

Climate models in the past have traditionally included the atmosphere, the ocean and sea ice. One of the most uncertain aspects of the climate system is the behavior of ice over land, for if this were to melt sea level would go up catastrophically. The report by O. Sergienko describes how CICS is now developing an ice sheet model in order to better understand land ice behavior and its interaction of with other components of the climate system. The model is capable of capturing major known processes governing behavior of ice sheets. The model is capable of running in a stand-alone configuration, and produces the present day configuration of the Antarctic Ice Sheet fairly well. As part of this development, and in collaboration with CICS postdoc Daniel Goldberg, an inverse model has been developed for the robust estimation of physical parameters in the model. The complete incorporation of an ice sheet model into the coupled climate model is some time away, but this development is a crucial first step, involving the interplay of basic science and model development.

High Resolution Atmospheric Modeling

CICS has participated in some exciting recent developments associated with regional models and hurricane models. In particular, a prototype two-way nested model with a fixed nested grid has been developed and is currently being tested in hydrostatic, dry simulations of lengths ranging from days to years, as described in the report by Lucas Harris. The model will primarily be used for hurricane forecasting but may also be used for regional climate simulation and pollution transport. The development of a nested model requires that substantial technical hurdles be overcome. The nesting scheme that has been developed here produces very little noise at the boundary of the nested grid and, importantly, does not degrade the large-scale flow. It is an important technical accomplishment that we expect will lead to significant scientific advances in hurricane prediction in the years to come.

Ocean Model Development

Ocean modeling is in an exciting phase at CICS and GFDL. A climate model with an isopycnal ocean component has been developed and integrated to quasi-equilibrium in ESM2G, as described in
the report by A. Adcroft. Much effort was focused on the abyssal mixing, yielding a very good match of Indo-Pacific overturning with observational estimates. Isopycnal models are important because they are able to conserve water mass properties much better than z-coordinate models, especially in an eddying regime and when integrations of decades or longer are required, as is the case in climate modeling of anthropogenic global warming and climate variability. CICS/GFDL is now the only center to have ‘IPCC-class’ climate models with either z-coordinate models (as in the traditional MOM ocean model) or an isopycnal model (the GOLD model), so uniquely enabling the robustness of the results to be better determined.

Software Development

An often unheralded but vital component of Earth System models is the development of the underlying software, and this year we highlight it in our report. CICS has taken the lead in the development of the ‘Flexible Modeling System’ that forms the basis for all the Earth System Models that are developed at GFDL and CICS, as described by V. Balaji. In the past year, the development of the FMS Runtime Environment was accomplished as a distributed workflow system spanning several sites. This enables the porting of Earth System Models to remote computer systems to be accomplished more readily. Thus, the porting of the Earth System models to the new supercomputer center in Oak Ridge was accomplished, as well as the integration of the models at other DoE sites. In addition, development of the GFDL Curator system has taken place. Among other things, this system is used in the international climate model intercomparison project CMIP5, which in turn is used as part of the physical science basis for the IPCC AR5.

EARTH SYSTEM MODELING APPLICATIONS

Climate Variability and Change

Understanding interaction of anthropogenic climate change with natural variability is an important topic in climate research, and a central aspect of CICS. One such project in this area is described in this report by G. Vallis. The goal of Vallis’s project is to understand climate sensitivity, namely the amount that the climate (and in particular the average surface temperature) will warm by if carbon dioxide levels continue to increase. In a project with GFDL scientists Isaac Held and Mike Winton, it was noted that the response of the climate system occurs on two disparate timescales, a relatively short timescale governed in part by the mixed layer depth and a longer timescale involving the deep circulation. Building on this knowledge, Vallis, with graduate student Lauren Padilla and Mechanical Engineering faculty Clarence Rowley, were able to make an estimate for the transient climate sensitivity based on observed 20th century warming. Their estimate is for the warming that will occur on the relatively short term (i.e., the decadal timescale) and includes the effects of natural variability and an explicit estimate of the errors in the estimate; that is to say, the investigators provide a probability distribution function for the expected warming.

Large-scale Ocean Circulation and Mixing

A long-standing problem in ocean circulation is the maintenance of deep stratification and the meridional overturning circulation. A notable advance in our understanding of this is detailed in the report by M. Nikurashin. He describes the development and testing of a novel theory for the deep
stratification and overturning circulation of the ocean. The theory and simulations show that, in the limit of weak mixing typical for the present mid-depth ocean, the deep stratification throughout the ocean is set by wind and eddies in the circumpolar channel and the rate of the overturning circulation is set by mixing acting across the deep stratification in the ocean basins away from the channel. Notably, and in contrast to long-standing classical theories by Munk and Wunsch, a deep stratification can be maintained even as the diapycnal diffusivity tends to zero. This is an important result with many implications both for the general circulation itself and our representation of it in general circulation models.

Ocean mixing is nevertheless important for the maintenance of the meridional overturning circulation and the report by S. Legg describes how mixing is generated by tides and by oceanic overflows. The scales of motion at which waves break is far less than the grid scale of climate models and so such processes much be parameterized in models for the foreseeable future, and to this end a parameterization has been developed for use in ocean general circulation models that represents tidal mixing at tall steep ridges. The related problem of tidal mixing generated by tidal flow over smaller scale, rough topography has also been studied.

**Ocean Modeling of the Gulf of Mexico Oil Spill**

A significant effort was made to assist in NOAA’s efforts responding to the Deep Water Horizon oil spill. In response to suggestions that there might be impacts of the spill on the east coast of the USA and possibly even on Europe, CICS researchers, led by Alistair Adcroft, showed that 1) biological decay had to be taken into account when projecting the far field extent of this deep spill and 2) there was very little chance that measurable quantities of oil would, in fact, leave the Gulf of Mexico. Projections of surface and deep oil evolution match the observed evolution quite well; decay near the surface was indeed quite rapid though for more reasons than just biological decay. Decay at depth has been much slower and delayed, both due to rate limiting processes that were not considered in their simple representation of biological decay of hydrocarbons.

**Impacts of Climate Change on the Earth System**

The new GFDL Earth System models including both the land biogeochemistry modeling component LM3 and the ocean biogeochemistry component TOPAZ are now functioning and simulations are being carried out as part of the GFDL contribution to the Fifth Assessment of the Intergovernmental Panel on Climate Change. CICS has made crucial contributions to the development of both the land and ocean biogeochemistry components over time. The results of climate model simulations such as these are now being used by CICS scientists in a wide range of applications including assessments of the impact of future climate change on the ocean and terrestrial carbon sinks, as well as phenomena such as coral bleaching and the nesting and oceanic populations of the endangered Pacific leatherback turtle; and, for the leatherbacks, how conservation measures might mitigate the negative impacts of future climate change.
Task I – Administration and Outreach
This task covers the administrative activities of the Cooperative Institute and support of its educational outreach activities. Administrative funding included minimal support of the CICS Director and the part-time administrative assistant. Educational outreach activities included funding for QUEST, a well-established summer program held at Princeton University for elementary and middle school teachers in New Jersey. Princeton University matching funds also supported the Coral Workshop.

Research funds will be carried over to the next fiscal year because NOAA provided prefunding of future years in certain areas of research, and also because we were unable to hire a sufficient number of high quality scientists this year. It is then prudent to carry funds forward to future years, given the volatile nature and unknown level of funding in the future, to ensure continuity in the scientific effort.
Project Titles
Cooperative Institute for Climate Science (CICS)
NOAA Cooperative Award NA08OAR4320752

Task I Projects

- CICS Professional Development Summer Institute in Weather and Climate (Anne Catena)
- Coral Workshop (John Dunne)

Task II Projects

- Arctic (Extreme) Weather And Climate Variability In The GFDL High-Resolution Global Climate Simulations (Thomas Spengler)
- Assessing the Decadal Variability and Predictability of Climate in the GFDL Coupled Models (Rym Msadek)
- Background Ozone Variability and Trends over the Western United States (Meiyun Lin)
- Decoupling the Nitrogen Cycling in an Ocean Biogeochemical Model (John Paul Reid)
- Deep Stratification, Overturning Circulation, and Mixing in the Ocean (Maxim Nikurashin)
- Development of an Ice-Sheet Model (Olga Sergienko)
- Diagnostics Comparing Sea Surface Temperature Feedbacks from Operational Hurricane Forecasts to Observations (Ian Lloyd)
- Dynamical Mechanisms for the Late Winter Teleconnection between ENSO and NAO (Ying Li)
- Dynamics of the Poleward Shift of the Mid-latitude Jet Stream (Joe Kidston)
- El Nino, Radiation & Precipitation: Global and Regional Analysis (Claire Radley)
- Flexible Modeling System (FMS) (V. Balaji)
- Global Land-Atmosphere Coupling Experiment: Soil Moisture Contributions to Subseasonal Forecast Skill (Sergey Malyshev)
- GFDL Data Portal IPCC AR5 Infrastructure (Serguei Nikonov)
- High Resolution Climate Model Simulations over the South Pacific (Kevin Wash-University of Melbourne)
- Hybrid Ocean Model Development (Alistair Adcroft)
- Impact of the Atlantic Meridional Overturning Circulation Variability on Arctic Climate (Salil Mahajan)
- Implementing a Fully Coupled Land Ice Model in GOLD (Daniel Goldberg)
- Improving Simulations of Black Carbon and Secondary Organic Aerosols (SOA) in GFDL AM3 (Junfeng Liu)
- Improving the Representation of Well Mixed Greenhouse Gases in the GFDL Radiation Code (David Paynter)
- Improving Understanding of the Terrestrial Carbon Cycle Dynamics (Elena Shevliakova)
- Influence of Small Scale Processes in the Ocean on the Large-Scale Circulation (Mehmet Ilicak)
- Interactions of the Deep Western Boundary Current (DWBC) with Topography and the North Atlantic Current (NAC) (Yu Zhang)
- Investigating Tropical Cyclogenesis on an Aquaplanet (Andrew Ballinger)
Task II Projects continued

- Mechanisms of Jet Interaction and Climate Variability (Amanda O'Rourke)
- Modeling the Effects of Rising Sea Surface Temperatures on Global Coral Reefs (Cheryl Logan)
- Ocean Mixing Processes and Parameterization (Sonya Legg)
- Offsetting and Complimentary Characteristics of Sulfate and Soot Direct Radiative Forcings (Ilissa Ocko)
- Predictability of Tropical Cyclone Inter-annual Variability with 25-km GFDL High-Resolution Atmospheric Model (HiRAM) (Jan-Huey Chen)
- Projecting the Response of an Endangered Marine Vertebrate to Climate Change: The Eastern Pacific Leatherback Turtle Population Model (Vincent Saba)
- Regional-Global Two-Way Nesting in the High-Resolution Atmosphere Model (HiRAM) (Lucas Harris)
- Seasonal Phase-locking of the Year-to-Year Variation of SST in the Atlantic Hurricane Main Developing Region and its Climate Change Response (Takeshi Doi)
- Self-aggregation in a Cloud Resolving Model (Caroline Muller)
- Sensitivity of Isoprene Emission Changes to Future Climate and Air Quality (Jingqiu Mao)
- Sensitivity of the Remote Response of ENSO to SST Extra-tropical Anomalies (Isidoro Orlanski)
- Superrotation and Tropical Variability in Dry Atmospheres (Samuel Potter)
- The Effect of Surface Gravity Waves on Short Term Tropical Cyclone Forecasts (Yalin Fan)
- Understanding Aerosol-Induced Regional Circulation and Hydroclimate Changes with Climate Model Simulations and Observations (Massimo Bollasina)
- Understanding Climate Sensitivity in the Presence of Uncertainty and Natural Variability (Geoffrey Vallis)
- Variability of Nordic Seas Overflows (He Wang)
- Warmer Wetter Climate, More Soluble Pollutants (Yuanyuan Fang)

Task III Projects

- Analyzing Links Between Changing Biogeochemistry and Ecosystem Shifts Using an End-To-End Ecosystem Model (Kelly Kearney)
- Combining Atmospheric Observations, Land and Ocean Models to Understand the Global Carbon Cycle (Jorge Sarmiento)
- Cross-shelf Exchange Processes in the Bering Sea: Downscaling Climate Models and Ecosystem Implications (Enrique Curchitser-Rutgers)
- Data Comparison for Phytoplankton Community Composition Input to Topaz (Bess Ward)
- Detection and Attribution of Shifts in the Carbon System (Claudie Beaulieu)
- Developing Methods for Fast Spin-up of Ocean Biogeochemical Models (Joe Majkut)
- Estimate of Anthropogenic Carbon Inventory Changes between the WOCE and CLIVAR Decades (Keith Rodgers)
- Global Carbon Data Management and Synthesis Project (Bob Key)
- Improved Hurricane Risk Assessment with Links to Earth System Models (Erik Vanmarcke)
- Modeling Sea Ice-Ocean-Ecosystem Responses to Climate Changes in the Bering-Chukchi-Beaufort Seas with Data Assimilation of RUSALCA Measurements (Leo Oey)
Task III Projects continued

- Quantifying the Role of Bacterial Extracellular Enzymes in Marine Remineralization Processes for Oxygen Minimum Zone Regions (K. Allison Smith)
- Regional Climate Studies Using the Weather Research and Forecasting Model (James Smith)
- Seasonal Variability in Forest Leaf Area and its Consequences for Terrestrial Carbon Budgets and Ecosystem Structure (David Medvigy)
- Seasonality in CO₂ Fluxes with Earth System Model (Keith Rodgers)
- Terrestrial Carbon-Nutrient Interactions in the Earth System (Lars Hedin)
- Top-down Controls on Marine Microbial Diversity and its Effects on Primary Productivity in the Oceans (Simon Levin)
- Water Mass Formation Processes and their Evolution under Warming Scenarios in Coupled Climate Models (Jaime Palter)

Shadow Awards – NA08OAR4320915

- Development of an Experimental National Hydrologic Prediction System (Eric Wood)
- Ensemble Hydrologic Forecasts over the Southeast in Support of the NIDIS Pilot (Eric Wood)
- Improving Climate Predictions by Reducing Uncertainties about CO₂ Fertilization in the Terrestrial Biosphere (Lars Hedin)
Progress Reports:

Earth System Modeling and Analysis
Progress Report Title: Hybrid Ocean Model Development

Principal Investigator: Alistair Adcroft (Princeton Research Oceanographer)

CICS/GFDL Collaborator: Mehmet Ilicak (Princeton)

Other Participating Researchers: David Marshall (Oxford), Robert Hallberg (GFDL), John Dunne (GFDL)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Ecosystem Goal: Protect, Restore, and Manage the Use of Coastal and Ocean Resources through Ecosystem Approach to Management (20%)
Climate Goal: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond (75%)
Weather & Water Goal: 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:

The first credible isopycnal coupled model has been run out to ocean equilibrium in ESM2G. Much effort was focused on the abyssal mixing (yielding a near perfect match of Indo-Pacific overturning with observational estimates).

Significant time was diverted to examine assist in NOAA’s efforts responding to the Deep Water Horizon oil spill. In response to media-hype asserting east coast and European impacts of the spill (fueled by inappropriate press releases by other agencies), we presented peer-reviewed work showing that 1) biological decay had to be taken into account when projecting the far field extent of this deep spill and 2) there was very little chance that measurable quantities of oil would leave the Gulf of Mexico. Out projections of surface and deep oil evolution happen to match the actual evolution quite well; decay near the surface was indeed quite rapid though for more reasons other than biological decay. Decay at depth has been much slower and delayed, both due to rate limiting processes that were not considered in our simple representation of biological decay of hydrocarbons. To my knowledge, the work was the first peer-review paper to appear from NOAA authors.

Publications:


Martin, T, and Alistair Adcroft, July 2010: Parameterizing the fresh-water flux from land ice to ocean with interactive icebergs in a coupled climate model. Ocean Modelling, 34(3-4), doi:10.1016/j.ocemod.2010.05.001.

Fig. 1: The distribution in two simulations of near-surface [mixed layer] “oil” on July 4th for a hypothetical deep spill of 10,000 barrels per day, highlighting the role of biological decay (consumption of hydrocarbons). Top panel shows distribution of a decaying “oil” while the bottom panel shows distribution of a non-decaying “oil”. The latter (bottom) is not realistic. The former (top) is [coincidentally] close to the observed distributions.
Progress Report Title: Flexible Modeling System (FMS)

Principal Investigator: V. Balaji (Princeton Senior Professional Specialist)

CICS/GFDL Collaborator: Alistair Adcroft (Princeton), Isaac Held (GFDL), Keith Dixon (GFDL), Tony Rosati (GFDL), Jorge Sarmiento (Princeton), S-J Lin (GFDL)

Other Participating Researchers: Karl Taylor (DoE/PCMDI), Max Suarez (NASA/GMAO), Steve Hankin (NOAA/PMEL), George Philander (Princeton), Steve Pacala (Princeton)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Goal: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond (50%)
Weather & Water Goal: Serve Society’s Needs for Weather and Water Information (50%)

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

Methods and Results/Accomplishments:

During the past year, we accomplished the following: development of Flexible Modeling System (FMS) and FMS Runtime Environment (FRE) in support of Earth system modeling activities at PU/GFDL; development of FRE (FMS Runtime Environment) as a distributed workflow system spanning multiple sites (NCCS, NCRC, GFDL); 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; design and development of publication system for climate model output in the GFDL Curator. This system is operationally used for CMIP5; and formulation of data distribution design for CMIP5 (physical science basis for IPCC AR5) in conjunction with Karl Taylor (Director, PCMDI) and others. A novel element I have proposed for this is a method of data citations, which allows journals and other ratings indices to assign credit for model development.

In addition, I 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. This system has now become operational for CMIP5. In collaboration with Sergey Nikonov and Yana Malyshev, (Hpti) web services for analysis and display of model output were developed. This includes being able to provide statistical downscaling and bias correction of climate model output based on the work of Hayhoe and collaborators. This work was presented at the GO-ESSP Meeting in Hamburg, Germany, in October 2009.

Other notable developments include: joined architecture and design committees of NOAA's National Environmental Modeling System (NEMS) and National Unified Operational Prediction Capability (NUOPC). NUOPC is now a funded operational NOAA activity; 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, with a particular focus on CMIP5. We were awarded NSF Grants for the COG (software governance) and ExArch (exascale archives) projects. Additionally, we were awarded a Siebel Energy Grand Challenge grant to promote use of climate data and models in the developing world, with a
particular focus on South Africa and 20 million cpu-hours on Jaguar (#1 supercomputer on the Top 500) under DoE INCITE program for 2010 and a further 20M in 2011.


Finally, I was appointed to a National Academy panel: A National Strategy for Climate Modeling, in October 2010.

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

Publications:
Progress Report Title: Investigating Tropical Cyclogenesis on an Aquaplanet

Principal Investigator: Andrew Ballinger (Princeton Graduate Student)

CICS/GFDL Collaborator: Isaac Held (Princeton/GFDL)

Other Participating Researchers: Ming Zhao, Gabriel Vecchi, Steve Garner (GFDL)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis and Earth System Model Applications

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

Objectives: To understand the large-scale controls on tropical cyclogenesis using high-resolution climate model simulations on an aquaplanet

Methods and Results/Accomplishments:
GFDL's High Resolution Atmospheric Model (HIRAM) version 2.1 (on a C180 grid) has been shown to simulate hurricane statistics consistent with observations (Zhao et al., 2009, 2010). For the current investigation the model has been run in an aquaplanet configuration, with a fixed sea surface temperature distribution characteristic of boreal summer solstice. A global snapshot of the zonal wind field (e.g. Figure 1) shows realistic typical synoptic features, along with several apparent tropical cyclones that have developed to the north of the ITCZ.

Figure 1: A snapshot taken from the HIRAM2.1 (C180) aquaplanet simulation, showing the 850-mb zonal wind. Light (dark) shading indicates westerly/eastward (easterly/westward) flow.
Analyses were conducted on 6 model years (72 summer months) to obtain a variety of cyclone statistics, focusing on the spatial and temporal variability of cyclogenesis. The model generates about 250 tropical cyclones (near surface winds > 17 m/s) per year, with approximately 60-65% reaching hurricane strength (winds > 33 m/s). By employing a storm compositing technique, we have attempted to characterize the large-scale environment coincident with genesis. Of particular interest are the analyses of composited timeslices (days and hours) leading up to a genesis event. Through this approach we hope to systematically identify some of the core ingredients or pathways leading to tropical cyclogenesis.

Over recent years the “marsupial paradigm” of tropical cyclogenesis (Dunkerton et al., 2009) has been proposed as a pathway to genesis. In this framework a tropical disturbance is able to grow within the quiescent “cat’s-eye” region of a tropical easterly wave critical layer. This particular region of the parent wave moves with the mean flow, continually being moistened through convection while remaining relatively protected from the intrusion of dry air and vertical shear. Hence, it is suggested these regions (“pouches”) provide a favorable location wherein an initial vortical structure can strengthen into a self-maintaining entity.

Indeed, from preliminary results it seems that the marsupial pouch theory could well describe one of the (major) genesis pathways apparent in our aquaplanet simulations. These results are promising, but it is clear that much more work is needed to develop a testable model for genesis in these simulations.

References:


The Progress Report Title is "Understanding Aerosol-Induced Regional Circulation and Hydroclimate Changes with Climate Model Simulations and Observations.

The Principal Investigator is Massimo A. Bollasina (Princeton Postdoctoral Research Associate).

The CICS/GFDL Collaborators are Yi Ming (GFDL), V. Ramaswamy (GFDL).

Task II is Cooperative Research Projects and Education.

NOAA Sponsor is Brian Gross (GFDL).

The Theme is Earth System Modeling and Analysis.

The NOAA Goals include the Climate Goal: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond.

Objectives: To improve the understanding of the mechanisms and key physical processes (and their representation in models) underpinning aerosols-driven changes in regional hydroclimate and atmospheric circulation over South Asia.

Methods and Results/Accomplishments:

In the Aerosol footprint on the long-term precipitation change over South Asia, we used a series of perturbation experiments with the GFDL CM3 coupled model, which realistically simulates the observed historical trend when driven by all known climate forcings, to investigate the South Asian monsoon response to natural and anthropogenic factors, with particular focus on aerosols and greenhouse gases. We find that the observed precipitation decrease is very likely of anthropogenic origin, and can be attributed almost entirely to aerosols. The drying is a robust outcome of a slowdown of the tropical meridional overturning circulation, which is fundamentally driven by the need to counteract the aerosol-induced energy imbalance between the northern and southern hemispheres. In contrast, greenhouse gases give rise primarily to a weakening of the equatorial zonal overturning circulation. These results provide compelling evidence of the prominent role of aerosols in shaping regional climate change over South Asia.

In the Precipitation Bias over the western Indian Ocean in an atmospheric GCM (AGCM): role of the meridional SST gradient, most of current AGCMs show a remarkable positive precipitation bias over the western south-equatorial Indian Ocean (IO) which develops in spring and reduces during the monsoon season. A comprehensive characterization of this anomaly and associated atmospheric circulation by means of the GFDL AM3 model shows that the precipitation bias is related to anomalous near-surface meridional convergence over the western IO (and associated anomalous lower-tropospheric secondary circulation). The convergence is suggested to be in large part modulated by the local meridional sea surface temperature (SST) gradient. The enhanced equatorial precipitation is responsible for an anomalous Hadley-type meridional circulation which greatly affects the simulated monsoon evolution over India. Experiments with the GFDL spectral dry dynamical core model show that an anomalous heat source over the western IO (mimicking the AM3 precipitation anomaly) induces a poleward anomalous convergence and associated large-scale subsidence over northwestern India, with eastward Rossby wave propagation. Sensitivity experiments with AM3 are...
also run to test the impact of the strength of a prescribed meridional SST gradient over the western IO. As expected, the pattern of the vertical circulation (e.g., shallow versus deep convection) is very sensitive to the magnitude of the gradient (Fig. 2), with important feedbacks on clouds, diabatic heating, and radiation. An important implication follows: regional (e.g., aerosols) or global (e.g., greenhouse gases) forcing may alter the SST meridional gradient in the IO, with the potential of significantly affecting the spatial and temporal evolution of the South Asian monsoon.

Publications:


Figure 1: Schematic of the large-scale circulation changes caused by greenhouse gases and aerosols. The changes in the circulation in the all-forcing ensemble (ALL_F) result from the overall warming (which is predominant in the longitudinal direction along the equator) and aerosol forcing (which overwhelms the warming in the latitudinal direction). The climatological circulation is also provided for reference. Warming by greenhouse gases (WMGGO3) induces a strong anomalous zonal circulation (red) between the eastern Indian (subsiding branch) and the western Pacific (rising branch), in addition to a modest weakening of the equatorial zonal circulation (black). Aerosols (AERO) are responsible for a meridional circulation over the Indian subcontinent with rising branch over the western Indian Ocean and subsidence over the western Pacific and Southeast Asia (purple), which opposes the local Hadley circulation. Besides, the aerosol-induced cooling excites a strong anomalous zonal circulation (red), with enhanced rising motion in the eastern Indian Ocean and subsidence to the east, and strengthens the equatorial zonal circulation (black).
Figure 2: Effect of a reduced meridional SST gradient over the western IO. The upper panel shows the difference in precipitation (shades) and 925-hPa circulation (streamlines) between AM3 and observations (CMAP and ERA40, respectively) for perpetual May ensemble simulations forced by an idealized (but realistic) May SST distribution. The middle panel shows the simulated changes in precipitation and 925-hPa circulation when reducing the meridional SST gradient by 20% over the south Equatorial IO in the idealized perpetual ensemble runs. The bottom panel shows the change in the vertical divergent circulation over the western IO.
Progress Report Title: Cross-shelf Exchange Processes in the Bering Sea: Downscaling Climate Models and Ecosystems Implications

Principle Investigator: Enrique Curchitser (Associate Research Professor, Rutgers)

CICS/GFDL Collaborator: Charles Stock (Research Oceanographer, GFDL)

Other Participating Researchers: Gaelle Hervieux (Postdoctoral Researcher, Rutgers)

Task III: Individual Projects

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis and Earth System Model Applications

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

Objective: To identify the mechanisms responsible for exchanges of physical and biological properties between the Bering Sea shelf and surrounding waters, quantify their importance, and assess their response to climate variability and change using a high-resolution (3-10 km) regional ocean model designed for shelf ecosystems coupled with a region-specific ecosystem model.

Methods and Results/Accomplishments:
We have completed 40 years of CORE-forced hindcast simulations and a 50 year projection using boundary conditions from GFDL CM2.1IPCC-AR4 A2 scenario (one-way nesting). Both the model hindcast and projection include biological dynamics from an ecosystem model designed for the North Pacific, providing powerful combination of high-resolution physical simulations and region-specific biology.

Tracer experiments (Fig. 1A,B) with these simulations suggests that the flow of water through Unimak pass, a narrow strait in the Aleutian Island chain that is poorly resolved by most climate models, is an essential transport pathway for physical and biological properties onto much of the highly-productive southeastern Bering Sea Shelf. Motivated by this somewhat surprising result, we have decided to focus our study on nitrogen transport onto and within the Bering Sea Shelf. We have tracked total nitrogen fluxes for a control volume covering the entire shelf (Fig. 1C) and for 8 control volumes within the shelf (inshore/offshore for 4 along-shore stretches). General software for tracking these fluxes was developed as part of this project. Initial results show considerable variations in nitrogen fluxes on inter-annual to decadal time-scales which are presently being investigated (Fig. 1C). We are diagnosing these patterns and working with collaborators from the Lamont-Doherty Earth Observatory (Ray Sambrotto, Didier Burdloff) to put them in an observational context. The timeline for a submitted paper based on this work is 3-5 months.
Figure 1: Distribution of tracers released along the Bering Sea shelf-break (A) and in Unimak pass (B). Warm colors indicate high concentrations of tracer. The shelf tracer is mainly advected north along the shelf break until bifurcating along the Russian coast. The tracer is largely absent from the Bering shelf near Alaska, which is dominate by the flow through Unimak pass. Panel C shows the nitrogen exchanges for a control volume covering the entire shelf for 35 year hindcast simulation. Substantial fluctuations at 3-5 year time-scales are apparent and are under investigation.
Progress Report Title: The Effect of Surface Gravity Waves on Short Term Tropical Cyclone Forecasts

Principal Investigator: Yalin Fan (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: S. J. Lin (GFDL)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: Improve global model forecasts on tropical cyclones

Methods and Results/Accomplishments:

During this year of my appointment, I’ve coupled the NOAA operational wave model, Wavewatch III, to the GFDL prototype Global Cloud-Resolving Model (HiRAM), which includes the atmospheric model (AM2), ice model, and land model (LM3), and implemented the coupled system within the GFDL FMS framework. The coupled system runs successfully at both low and high resolution. A ten-year climate run at C180 resolution is done with the coupled system and demonstrated that the new system is very stable. Initial tests of the coupled system in the GFDL high resolution (C360) global forecast system has begun. During this year of my appointment, I’ve coupled the NOAA operational wave model, Wavewatch III, to the GFDL prototype Global Cloud-Resolving Model (HiRAM), which includes the atmospheric model (AM2), ice model, and land model (LM3), and implemented the coupled system within the GFDL FMS framework. The coupled system runs successfully at both low and high resolution. A ten-year climate run at C180 resolution is done with the coupled system and demonstrated that the new system is very stable. Initial tests of the coupled system in the GFDL high resolution (C360) global forecast system has begun. The retrospective run for the entire 2008 hurricane season has shown encouraging results in both track and intensity prediction with the coupled system.

Publications:

Fan, Yalin, S.J. Lin, Wave Coupling impact on tropical cyclone simulations in global models. AMS annual meeting, Jan 25, 2011, Seattle, WA.
**Progress Report Title:** Implementing a Fully Coupled Land Ice Model in GOLD

**Principal Investigator:** Daniel Goldberg (Princeton Postdoctoral Research Associate)

**CICS/GFDL Collaborator:** Olga Sergienko (Princeton), Chris Little (GFDL), Robert Hallberg (GFDL), Anand Gnanadesikan (Johns Hopkins)

**Other Participating Researchers:** Nathan Urban (Princeton), Michael Oppenheimer (Princeton)

**Task II:** Cooperative Research Projects and Education

**NOAA Sponsor:** Brian Gross (GFDL)

**Theme:** Earth System Modeling and Analysis

**NOAA Goals:**

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

**Objectives:** My goal is to understand the short, medium and long term behavior of the Antarctic Ice Sheet and how its evolution relates to other components of the climate, i.e. the ocean.

**Methods and Results/Accomplishments:**

With my collaborators I have investigated the interaction between fast-flowing ice streams and ice shelves and oceans at high latitudes, in both simplified and more complex settings. Chris Little has used a simplified model that I provided him to analyze the behavior of a marine ice sheet exposed to ocean melting in an idealized setting, and we recently submitted a paper on the study. Meanwhile, I have used Chris's ocean cavity model in conjunction with a more sophisticated ice flow model that I created in order to examine the coupled system in a more realistic setting. The study has gone on for a while because it is new ground and there are a lot of uncertainties about how to proceed, but we are fairly close to writing up our findings.

Additionally, I investigated the feasibility of inversions of satellite-derived data for basal properties of ice sheets using a hybrid model which is more comprehensive than flow models used to do similar inversions. (I submitted a paper on this same hybrid model last year, which has since been published.) I have submitted a paper on this study.

**Publications:**

Goldberg, D N. A variationally derived, depth integrated approximation to a higher order glaciological flow model. J. Glaciology, Vol. 57, No. 201, 2011

Goldberg, D N. and O. V. Sergienko. Data assimilation using a hybrid flow model. The Cryosphere, in press.

C M Little, D N Goldberg, A Gnanadesikan, M Oppenheimer, On the coupled response to basal melting. Submitted to J Glaciology.
Progress Report Title: Regional-Global Two-Way Nesting in the High-Resolution Atmosphere Model (HiRAM)

Principal Investigator: Lucas Harris (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Shian-Jiann Lin (GFDL), Morris Bender (GFDL), Isaac Held (GFDL)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Weather & Water Goal: Serve Society’s Needs for Weather and Water Information

Objectives: Develop a two-way nested-grid version of the GFDL HiRAM atmospheric model, primarily for hurricane forecasting but also useful for regional climate simulation and long-range pollutant transport.

Methods and Results/Accomplishments:
A prototype two-way nested model with a fixed nested grid has been developed and is currently being tested in hydrostatic, dry simulations of lengths ranging from days to years. The nesting currently produces acceptably little noise at the boundary of the nested grid, does not degrade the large-scale flow, and is able to conserve dry air mass by simply not performing two-way updating of the mass field to the coarse grid. A manuscript describing the nesting methodology is planned based off of this prototype.

Additional work has involved assisting development of a nested-grid model with a deformed (or stretched) grid, as well as work with the modeling services group in developing frameworks for grid nesting useful in other GFDL models, and in developing conservative remapping for use in the model coupler.
Progress Report Title  Terrestrial Carbon-Nutrient Interactions in the Earth System

Principal Investigator:  Lars O. Hedin (Princeton Professor)

CICS/GFDL Collaborator:  Nina Wurzburger (Princeton), Stefan Gerber (Princeton), Ray Dybzinski (Princeton)

Task III: Individual Projects

NOAA Sponsor:  Brian Gross (GFDL)

Other Participating Researchers:  Elena Shevliakova (Princeton), Sonja G. Keel (Princeton), Stephen W. Pacala (Princeton)

Theme:  Earth System Modeling and Analysis

NOAA Goals:
Ecosystem Goal:  Protect, Restore, and Manage the Use of Coastal and Ocean Resources through Ecosystem Approach to Management (10%)
Climate Goal:  Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond (90%)

Objectives:  The potential for anthropogenic carbon (C) sequestration on land critically depends on nutrient availability. Using empirical and theoretical approaches we explore interactions between carbon and nutrient cycling at ecosystem to global scales.

Methods and Results/Accomplishments:
Nina Wurzburger studies factors that constrain nitrogen (N)-fixation, the major natural source of external N in many land ecosystems (Galloway et al. 2004). Along a steep gradient of soil phosphorus in Panamanian tropical forests asymbiotic fixation was limited by molybdenum in phosphorus-rich soils, but co-limited by both molybdenum and phosphorus in phosphorus-poor soils. Her findings indicate that asymbiotic nitrogen fixation is constrained by the relative availability and dynamical interaction of phosphorus and molybdenum.

Stefan Gerber has developed a global N model integrated in Princeton-GFDL’s LM3V. He performed and analyzed model simulations of the terrestrial C and N cycles, covering the past 200 years. The simulations reveal critical influences of the land’s N dynamics on the uptake of anthropogenic C: fossil fuel sequestration in terrestrial systems is hampered by about 50 PgC between 1800 and 2000. The simulations also revealed that land-use on the one hand and CO₂ fertilization and N deposition on the other hand interact in a manner that is strongly non-additive and currently produce a loss of 0.3 to 0.4 PgC per year.

Competition for nutrients between individual plants is poorly understood and contemporary land models thus lack mechanistic detail for such processes. Ray Dybzinski has developed a forest ecosystem model to advance the understanding of interactions between individual trees. In the model trees are allowed to compete for light and nitrogen across a gradient of soil nitrogen to their community-level consequences. The model predicts the most competitive (i.e., the evolutionarily stable strategy [ESS]) allocations to foliage, wood, and fine roots for canopy and understory stages of trees growing in old-growth forests. Data from 152 stands support the model’s surprising prediction that the dominant structural trade-off is between fine roots and wood, not foliage, suggesting the “root-shoot” trade-off is more precisely a “root-stem” trade-off for long-lived trees (Dybzinski et al. 2011). Assuming other resources are abundant, the model predicts that forests are limited by both nitrogen and light.
References:

Publications:
**Progress Report Title:** Influence of Small Scale Processes in the Ocean on the Large-Scale Circulation

**Principal Investigator:** Mehmet Ilicak (Princeton Postdoctoral Research Associate)

**CICS/GFDL Collaborator:** Sonya Legg (Princeton), Robert Hallberg (GFDL), Alistair Adcroft (Princeton)

**Task II:** Cooperative Research Projects and Education

**NOAA Sponsor:** Brian Gross (GFDL)

**Theme:** Earth System Modeling and Analysis

**NOAA Goals:**

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

**Objectives:** The affect of small scale processes have been investigated to improve the GFDL global ocean model.

**Methods and Results/Accomplishments:**

A high resolution idealized model is set up to investigate the mixing over topography such as canyons and ridges. A new parameterization is proposed to reproduce the small scale mixing due to ridges and canyons. A coarse resolution idealized model is employed to investigate the performance of new parameterization. The results indicate that the new parameterization can be used to increase the local shear and mixing. In addition to this, we try to diagnose the numerical mixing in z- and terrain following coordinates. Our aim is to understand and reduce the numerical mixing in GFDL MOM model.

**Publications:**


Progress Report Title: Analyzing Links Between Changing Biogeochemistry and Ecosystem Shifts Using an End-To-End Ecosystem Model

Principal Investigator: Kelly Kearney (Princeton Graduate Student)

CICS/GFDL Collaborator: Charlie Stock (GFDL), Jorge Sarmiento (Princeton)

Task III: Individual Projects

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Ecosystem Goal: Protect, Restore, and Manage the Use of Coastal and Ocean Resources through Ecosystem Approach to Management (50%)
Climate Goal: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond (50%)

Objectives: Investigate decadal variability throughout a pelagic food web using an end-to-end food web model

Methods and Results/Accomplishments:
Over the past year, I have been working primarily on building a fully coupled end-to-end ecosystem model for the Eastern Subarctic Gyre region of the North Pacific. This is a continuation of the work that I have done over previous years under this same project. The most important adjustments I have made to the model in the last year are: 1) I added simple iron dynamics to the NEMURO-based processes controlling primary production. With this addition, I am able to replicate observed levels of production as well as surface nutrient concentrations compared to measurements at Ocean Station Papa. 2) I incorporated a more robust functional response for zooplankton feeding. The functional response I am using now is based on Kerim Aydin’s version of the foraging arena functional response. It provides the same functionality as the formula used in the Ecopath with Ecosim software package, but in a formulation that allows more easily customized ingestion curves. In this form, I am able to match the zooplankton functional responses in my fully coupled model to those used in NEMURO, allowing better modeling of zooplankton and phytoplankton seasonal blooms. 3) I created an ensemble approach to parameterizing the model, allowing me to incorporate the high level of uncertainty that is associated with upper trophic level parameters.

As a result of these modifications, the model now runs stably over decadal timescales. I am in the process of writing up a paper that fully describes and validates this model framework.
**Progress Report Title:** Dynamics of the Poleward Shift of the Mid-latitude Jet Stream

**Principal Investigator:** Joseph Kidston (Princeton Postdoctoral Research Associate)

**CICS/GFDL Collaborator:** G. K. Vallis (Princeton University/GFDL)

**Task II:** Cooperative Research Projects and Education

**NOAA Sponsor:** Brian Gross GFDL

**Theme:** Earth System Modeling and Analysis

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

**Objectives:** Understand the dynamics of the poleward shift of the mid-latitude jet stream

**Methods and Results/Accomplishments:**
Idealized modeling of eddy-driven jets. A stirred barotropic model has been used to understand the relationship between the speed and latitude of the eddy-driven jet. In this highly idealised model, when the damping on the zonal-mean zonal wind is reduced, the eddy-driven jet moves poleward, despite the fact that the stirring remains statistically constant. Diagnosis of the dynamics of this shift suggests that either shear instability, or an inverse energy cascade, are important in causing this shift. Further analysis will determine the applicability of these dynamics to more realistic flows.

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

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

**CICS/GFDL Collaborator:** Robert Hallberg (GFDL), Steve Griffies (GFDL), Alistair Adcroft (CICS), Mehmet Ilicak (CICS), Maxim Nikurashin (CICS), He Wang (CICS)

**Other Participating Researchers:** Maarten Buijsman (Princeton), Jody Klymak (UVic), Rob Pinkel (SIO), Jennifer MacKinnon (SIO), Mathew Alford (UW), Mike Gregg (UW), Steve Jayne (WHOI), Lou St Laurent (WHOI), Kurt Polzin (WHOI), Eric Chassignet (FSU), Brian Arbic (UMich), Harper Simmons (UAlaska).

**Task II:** Cooperative Research Projects and Education

**NOAA Sponsor:** Brian Gross (GFDL)

**Theme:** Earth System Modeling and Analysis

**NOAA Goals:**
**Climate Goal:** 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 respect to tidal mixing, a fruitful collaboration with Jody Klymak at the University of Victoria led to three publications in 2010 (Klymak and Legg, 2010; Klymak et al, 2010a; Klymak et al 2010b). These articles, which follow on from a publication in JPO in 20098 (Legg and Klymak, 2008) examine the tidal mixing at tall steep ridges, such as the Hawaiian ridge, and develop a parameterization for use in ocean general circulation models. Maxim Nikurashin, who has been working as a postdoc under my supervision for the past 2 years, has been examining the complementary problem of mixing generated by tides at smaller amplitude rough topography. A paper in press (Nikurashin and Legg, 2011) describes the nonlinear wave-wave interactions which transfer energy to internal waves on small length-scale where wave breaking ultimately occurs. An exciting feature of this study is the identification of a dependence of tidal mixing on latitude, since wave-wave interactions are enhanced at a critical latitude. A further topic of study is the ultimate fate of large length-scale internal waves, and I am currently writing a manuscript describing the breaking of waves by reflection from topography, and the dependence of the resultant dissipation on topographic slope and height. All of these studies form part of the subject area of the recently funded Internal Wave Driven Mixing Climate Process Team, headed by Jennifer MacKinnon, and involving researchers from different US institutions, including GFDL. A first workshop for this team was held at GFDL in October 2010.

With regard to overflows, I have been working with Mehmet Ilicak, a postdoctoral researcher who has been at GFDL since August 2009. He has carried out a study of the role of corrugated topography in enhancing mixing in overflows, with a publication in press in Ocean Modeling (Ilicak, Legg, Adcroft and Hallberg). Now he is continuing with a study of eddy formation processes in overflows. AOS student He Wang is working under my supervision to investigate the behavior of overflows in the climate models, and in particular their variability and role in the climate system, work which will be presented for his general exam in a few weeks. I have been continuing to investigate the
sensitivity of overflows to recently developed parameterizations using idealized configurations of the GOLD model.

Publications:


Progress Report Title: Top-down Controls on Marine Microbial Diversity and its Effects on Primary Productivity in the Oceans

Principal Investigator: Simon A. Levin (Professor, Princeton University)

CICS/GFDL Collaborator: Jorge L. Sarmiento (Princeton), Charles Stock (GFDL), and John Dunne (GFDL)

Other Participating Researchers: Juan Bonachela (EEB, Princeton University) and Michael Raghib (Los Alamos National Laboratory)

Task III: Individual Projects

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals: Ecosystem Goal: Protect, Restore, and Manage the Use of Coastal and Ocean Resources through Ecosystem Approach to Management

Objectives: Improve the predictive skills of the Earth System Models by i) converging to a flexible and justified trait-based representation of the phytoplankton community, and ii) investigating how the top-down control exerted by viruses contribute to generate and maintain diversity in different regimes of nutrient availability. Both goals are closely related (see below).

Methods and Results/Accomplishments:

We have tackled the first goal by developing an individual-based model that describes the uptake of nutrient by phytoplankton cells as a dynamic, flexible process where the organism decides its own strategy of allocation of resources attending to the external conditions and its own nutrient state. By means of a simple regulatory process to control the (dynamic) number of uptake sites, the cell acclimates to the different conditions by changing its effective maximum uptake rate (Vmax) and half-saturation constant (Ks) –also called uptake parameters–, and its specific affinity (aff), a measure of the efficiency of the individual in taking up nutrient. This model is essential to discern what the key traits that characterize the community are, and how they are altered under changes in external nutrient concentration.

Models like ours, where the uptake parameters are dynamic, are difficult to find in the current literature. One possible candidate against which carry out the benchmark of the theoretical performance of our model is the “modified Geider model” (GM). The GM is the result of adapting the Geider model [1], which has a dynamic Vmax, to cover even cases when diffusion limits the uptake [2]. We can compare the performance of our model with the GM, if we parametrize our model to show the same uptake rate, V, when plotted against the external nutrient concentration, [Next] (see Fig.1). This “generalized” GM shares the qualitative behavior of Vmax and Ks (with a much smaller rate of change, see inset, Fig.1). However, it fails in describing the enhanced affinity shown by phytoplankton organisms in low nutrient concentration regimes. This mechanism alone is enough to generate a saturating uptake curve even when the model is simplified (considering instantaneous incorporation of the incoming, diffusion nutrient ions), in which case V depends linearly on [Next] (see curves labeled “Simple” in Figs.1 and 2). Therefore, our model predicts i) enhanced Vmax and aff under nutrient-depleted conditions, ii) a time lag between environmental changes and the individual response, and iii) different strategies that depend on the nutritional history of the organism, all features previously reported in experimental works [3-5]. We have developed, thus, a simple
but mechanistically well based and supported model, with which we can reach a deep understanding of the phytoplankton nutrient uptake process, how the saturating curve emerges from it, and identify the key traits that describe it [6].

The model is also general enough to be adapted to different nutrients and situations. It is an essential part in the understanding of the relation between the existence of a pool of viruses and community diversity (see “Future Plans” report).

References:


**Progress Report Title:** Dynamical Mechanisms for the Late Winter Teleconnection between ENSO and NAO

**Principal Investigator:** Ying Li (Princeton Graduate Student)

**CICS/GFDL Collaborator:** Gabriel Lau (GFDL)

**Task II:** Cooperative Research Projects and Education

**NOAA Sponsor:** Brian Gross (GFDL)

**Theme:** Earth System Modeling and Analysis

**NOAA Goals:**

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

**Objectives:** To identified possible pathways in both the troposphere and stratosphere for the late winter teleconnection between ENSO and NAO using observations and simulations

**Methods and Results/Accomplishments:**

We showed that the teleconnection between ENSO and NAO is strongest in late winter, and have identified possible pathways in both the troposphere and stratosphere for this teleconnection. By analyzing a 2000-yr long control simulation of the GFDL CM2.1 coupled model and comparing it with observations. We showed that the tropospheric teleconnection between ENSO and NAO is mediated via transient eddy forcing over the North America-North Atlantic sector. For this study, we also designed and analyzed numerical experiments with atmospheric GCM integrations to achieve better understanding of the atmospheric response to SST forcing in the tropical Pacific.

We further examined the behavior of the synoptic eddies during persistent events. We found that the downstream development of the wave packet extends farther eastward into the Atlantic storm track region in the course of these persistent episodes. These persistent anomalous episodes are characterized by a strong Pacific subtropical jet stream and equatorward-shifted Pacific storm tracks, which are the signatures of El Niño. We also conducted a case study of the winter season of 2009/2010, which featured a moderate El Niño and a persistent negative NAO and was also affected by a series of significant winter storms across the United States.

In addition to studying possible pathways in the troposphere for the teleconnection between ENSO and NAO, I have also studied the role of stratospheric processes in that relationship, using outputs from the new GFDL climate model CM3, which has a better vertical resolution in the upper atmosphere than the CM2.1 model.

**Publications:**


Li, Y. and N.-C. Lau.: Contributions of downstream eddy development to the teleconnection between ENSO and atmospheric circulation over the North Atlantic. *J. Climate*, to be submitted.
**Progress Report Title:** Improving Simulations of Black Carbon and Secondary Organic Aerosols (SOA) in GFDL AM3

**Principal Investigator:** Junfeng Liu (Princeton Associate Research Scholar)

**CICS/GFDL Collaborator:** Larry Horowitz (GFDL), Hiram Levy II (GFDL), Songmiao Fan (GFDL)

**Other Participating Researchers:** AnnMaria Carlton (Rutgers)

**Task II:** Cooperative Research Projects and Education

**NOAA Sponsor:** Brian Gross (GFDL)

**Theme:** Earth System Modeling and Analysis

**NOAA Goals:**

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

**Objectives:** Improving the simulation of black carbon and organic carbon simulation in GFDL coupled chemistry-climate model AM3

**Methods and Results/Accomplishments:**

Methods: 1) Using sensitivity tests to identify the most important processes of black carbon simulation over the Arctic region. 2) Using parameterized and detailed cloud chemistry schemes to quantify the global in-cloud production of secondary organic aerosols.

Results/Accomplishments: 1) Successfully improved the magnitude and seasonal cycle of black carbon simulation over the Arctic region. 2) Quantified the global in-cloud production of secondary organic aerosols (SOA) and found that in-cloud production of SOA by detailed cloud chemistry is a factor of 2 lower than that using parameterized scheme.

**Publications:**


**Progress Report Title:** Diagnostics Comparing Sea Surface Temperature Feedbacks from Operational Hurricane Forecasts to Observations

**Principal Investigator:** Ian D. Lloyd (Princeton Graduate Student)

**CICS/GFDL Collaborator:** Gabriel A. Vecchi (GFDL), Timothy Marchok (GFDL)

**Task II:** Cooperative Research Projects and Education

**NOAA Sponsor:** Brian Gross (GFDL)

**Theme:** Earth System Modeling and Analysis

**NOAA Goals:**  
*Climate Goal:* Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond (75%)  
*Weather & Water Goal:* Serve Society’s Needs for Weather and Water Information (25%)

**Objectives:** Assess the ability of the GFDL Hurricane Forecast model to simulate the hurricane-induced SST cooling response as a function of intensity, by making comparisons with observations and a simple conceptual model of hurricane intensity.

**Methods and Results/Accomplishments:**
This research examines the ability of recent versions of the Geophysical Fluid Dynamics Laboratory Operational Hurricane Forecast Model (GHM) to reproduce the observed relationship between hurricane intensity and hurricane-induced Sea Surface Temperature (SST) cooling. The analysis was performed by taking a lagrangian composite of all hurricanes in the North Atlantic from 1998-2009 in observations and 2005-2009 for the GHM. A marked improvement in the intensity-SST relationship for the GHM compared to observations was found between the years 2005 and 2006-2009 due to the introduction of warm-core eddies, a representation of the loop current, and changes to the drag coefficient parameterization for bulk turbulent flux computation. A Conceptual Hurricane Intensity Model illustrates the essential steady-state characteristics of the intensity-SST relationship and is explained by two coupled equations for the atmosphere and ocean. The conceptual model qualitatively matches observations and the 2006-2009 period in the GHM, and is used to show that the inclusion of oceanic feedback is crucial to explaining the observed SST-intensity pattern. The diagnostics proposed by the conceptual model offer an independent set of metrics for comparing operational hurricane forecast models to observations.

**References:**


**Publications:**
Progress Report Title: Impact of the Atlantic Meridional Overturning Circulation Variability on Arctic Climate

Principal Investigator: Salil Mahajan (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Rong Zhang (GFDL), Thomas Delworth (GFDL)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Goal: 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:
Satellite observations show a long-term decline of sea-ice cover over the Arctic from 1979 to present. However, centennial records of sea-ice thickness and extent do not exhibit a statistically significant long-term trend and are dominated by multidecadal/decadal oscillations over the Arctic marginal seas, suggesting that trends in shorter records may not be indicative of long-term tendencies. Whether the recent rapid warming of the Arctic climate is caused by enhanced anthropogenic greenhouse gas emissions directly or is amplified by oceanic low frequency variability, is still a matter of debate. The Atlantic Meridional Overturning Circulation (AMOC) is often thought to be a major source of decadal/multidecadal variability in the climate system and is believed to contribute to the Atlantic multidecadal oscillation (AMO). The AMO has been linked to global and regional climate variability, and a recent analysis of observed centennial records (1910-2008) suggests a significant correlation between the AMO and Arctic SAT on decadal timescales [Chylek et al. 2009].

We study the simulated impact of the Atlantic Meridional Overturning Circulation (AMOC) on the low frequency variability of the Arctic climate with a 1000 year-long segment of a control simulation of GFDL CM2.1. The simulated Arctic-averaged climate variability broadly compares well with detrended observed centennial data. Simulated Arctic sea-ice extent and Arctic Surface Air Temperature (SAT) are found to be significantly anti-correlated on decadal timescales ($r = -0.74$), similar to observations. The AMO which is mainly induced by AMOC variations in the control simulation, is found to be significantly anti-correlated with the Arctic sea-ice extent anomaly ($r = -0.52$) and significantly correlated with the area-averaged Arctic SAT anomaly ($r = 0.55$) on decadal timescales. A positive AMO phase is associated with a poleward retreat of the Arctic sea-ice and an increase of the Arctic SAT in the control simulation, with the strongest linkages in the Labrador, Greenland, Barents and Bering seas in the winter season. This simulated spatial distribution of the reduction of Arctic sea-ice associated with the positive AMO phase is similar to the spatial pattern of the recent declining trend in the observed sea-ice extent (Figure 1), suggesting the possibility of a role of the AMOC in the Arctic climate in addition to anthropogenic greenhouse gas induced warming. A declining AMOC in the next few years, as predicted from a statistical model of its fingerprints [Mahajan et al. 2011], could potentially reduce the rate of decline of the Arctic sea-ice by counter-acting the effects of the anthropogenic greenhouse gas induced global warming in the Labrador and Nordic Seas.
References:

Publications:

Figure 1: (a) Regression of annual mean (top), winter (middle) and summer (bottom) seasonal average Arctic sea-ice concentration (CN) on standardized AMO index. (b) Linear trend (percentage per decade) of observed Arctic sea-ice concentration from 1979-2008.
Progress Report Title: Developing Methods for Fast Spin-up of Ocean Biogeochemical Models

Principal Investigator: Joseph Majkut (Princeton Graduate Student)

CICS/GFDL Collaborator: Steve Griffies (GFDL), John Dunne (GFDL), Jorge Sarmiento (Princeton)

Task III: Individual Projects

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: Developing methods for fast spin-up of ocean biogeochemical models

Methods and Results/Accomplishments:
The methods we have been considering for the fast spin-up of ocean biogeochemical models rely on the transport matrix method, which represents the steady transport of passive tracers in an ocean model in matrix form. This allows long simulations of ocean biogeochemistry to be carried out as a series of matrix-vector products. The code to extract the tendency terms from the current generation of ocean circulation models has been written and subsequently corrected. At this stage, I am testing the transport matrix extraction code with idealized domains from the MOM4.1 documentation. More work remains to be done, namely finishing testing and applying the method to ocean domains.

Along with the testing of the tracer tendency extraction modules, I have been investigating different mixing parameterizations within the ocean model. By examining the impact of different deep mixing mechanisms, I hope to come up with an interesting experiment that would utilize the matrix method to examine the effect of different mixing mechanisms on the ocean circulation and distributions of tracers such as carbon-14.
**Progress Report Title:** Sensitivity of Isoprene Emission Changes to Future Climate and Air Quality

**Principal Investigator:** Jingqiu Mao (Princeton Postdoctoral Research Associate)

**CICS/GFDL Collaborator:** Larry Horowitz (GFDL), Arlene Fiore (GFDL)

**Task II:** Cooperative Research Projects and Education

**NOAA Sponsor:** Brian Gross (GFDL)

**Theme:** Earth System Modeling and Analysis

**NOAA Goals:**

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

**Objectives:** To understand the sensitivity of isoprene emission changes to future ozone, secondary organic aerosols and oxidation capacity. Also we will study the role of human activities in these tests.

**Methods and Results/Accomplishments:**

Methods: We are using GFDL AM3/CM3 model with future emission scenarios to study the sensitivity of isoprene emission changes to future climate and air quality.

Accomplishments: I have implemented a new isoprene oxidation mechanism into AM3 model.

**References:**


**Publications:**

**Progress Report Title:** Seasonal Variability in Forest Leaf Area and its Consequences for Terrestrial Carbon Budgets and Ecosystem Structure

**Principal Investigator:** David Medvigy (Princeton Assistant Professor)

**CICS/GFDL Collaborator:** Su-Jong Jeong (Princeton), Elena Shevliakova (Princeton), Sergey Malyshev (Princeton), Ron Stouffer (GFDL)

**Task III:** Individual Projects

**NOAA Sponsor:** Brian Gross (GFDL)

**Theme:** Earth System Modeling and Analysis

**NOAA Goals:**

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

**Objectives:** Identify and quantify the physical and biological drivers of phenological variability in deciduous forests. Understand implications of phenological variability for terrestrial carbon budgets and ecosystem structure.

**Methods and Results/Accomplishments:**

Phenology is the study of the seasonal variations of terrestrial ecosystems. Springtime leaf budburst is a phenological process that is particularly sensitive to climate variations (Menzel 1999; Sparks et al. 2005; Schwartz et al. 2006; Richardson et al. 2006). These variations have consequences for both terrestrial ecosystems and land-atmosphere interactions (Myneni et al. 1997; Baldocci et al. 2005; Piao et al. 2007; Bonan 2008; Jeong et al. 2009; Richardson et al. 2010).

In the first 5 months of this project, we used budburst data from a mixed deciduous forest in central Massachusetts (42.5°N, 72.2°W), where ground-based observations of budburst have been recorded for 33 species since 1990 (O’Keefe 2000), to evaluate 3 hypotheses: (1) budburst only depends on springtime temperatures (Foley et al. 1996; Levis et al. 2004); (2) budburst depends on springtime and wintertime temperatures (Krinner et al. 2005; Sato et al. 2007); (3) budburst depends on springtime temperature, wintertime temperature, and species. These hypotheses have different levels of complexity, and depend on different numbers of free parameters. Hypotheses were evaluated using reversible jump Markov chain Monte Carlo (RJMCMC) (Green 1995; Al-Awadhi et al. 2004). This method is designed to maximize goodness-of-fit between model and data while also penalizing more complicated models. Like a traditional Markov chain Monte Carlo, RJMCMC yields a posterior probability density function (PDF) for each model parameter. However, RJMCMC is also designed to generate a posterior PDF on scientific hypotheses, allowing us to quantify our confidence in different models. This is the first application of RJMCMC to terrestrial biosphere modeling.

Our results indicate that our hypothesis (2) was most strongly supported by the observations (posterior probability of 88%). In other words, both wintertime and springtime temperatures are important, but species-dependence is not. To illustrate this, Fig. 1 shows the observed budburst dates for the 2 predominant species at the site: red maple (black circles) and red oak (black triangles). In most years, their respective budburst dates are only separated by a few days. These observations are compared to the expected values (red “X”s) and 95% credible intervals (error bars) derived from the RJMCMC under hypothesis (2). It is satisfying to see that 93% of the observations fell within the credible intervals of the simulation.
FIGURE 1: Observed budburst dates for red maple and red oak, and simulated budburst dates (species-independent) from the RJMCMC. Error bars represent the 95% credible intervals.

References:


Publications:

Jeong S-J, Medvigy D, Shevliakova E, Malyshev S, Stouffer R. Variability in budburst date at a mixed deciduous forest. To be submitted to Ecology, spring/summer 2011.
Progress Report Title: Self-aggregation in a Cloud Resolving Model

Principal Investigator: Caroline Muller (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Isaac Held (GFDL)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: Several studies using high-resolution cloud resolving models point out the tendency of atmospheric convection to self-aggregate. The large changes in the means climate state and radiative fluxes accompanying self-aggregation raise questions as to what simulations at lower resolutions with parameterized convection, in similar homogeneous geometries, should be expected to produce to be considered successful in mimicking a cloud-resolving model. The goal of my research is to investigate the sensitivity of self-aggregation to various parameters in a high resolution model.

Methods and Results/Accomplishments:
A high resolution model is used to investigate the onset of self-aggregation for a large range of domain sizes and resolutions. With random initial conditions, self-aggregation only occurs on very large domains with fairly coarse resolution. Interestingly, it does not seem to occur at very fine resolutions. We are currently investigating the possibility of hysteresis, in other words does self aggregation occur at very fine resolution when the model is initiated in a self-aggregated state.

References:
Progress Report Title:  GFDL Data Portal IPCC AR5 Infrastructure

Principal Investigator:  Serguei Nikonov (Princeton Professional Technical Specialist)

CICS/GFDL Collaborator:  V.Balaji (Princeton), Aparna Radhakrishnan (GFDL/HPTi), Kyle Olivo (GFDL/HPTi).

Task II:  Cooperative Research Projects and Education

NOAA Sponsor:  Brian Gross (GFDL)

Theme:  Earth System Modeling and Analysis

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

Objectives: Design and development GFDL Data Portal publishing system for IPCC AR5 GFDL model simulations

Methods and Results/Accomplishments:
Accomplished and tested in collaboration with K.Olivo fremetar (FRE metadata rewriter) – the FRE-Curator subsystem for metadata preparation of IPCC AR5 data. The program is the final part of GFDL Data Portal publisher. It prepares data fully complied with PCMDI metadata requirements with minimal computational expenses (achieving up to 100 times greater efficiency then officially IPCC distributed CMOR package). Mechanism of metadata equipping implemented in fremetar is fast and flexible – all needed metadata is loaded from curator DB where it is populated to from FRE experiment XML. Metadata process, XML→DB→data, carried out by FReatorMapper and fremetar is fully automatic and error pro of. It is also quite flexible for usage for other project needed to publish in metadata standardized manner.

For decreasing errors in IPCC AR5 data to minima new standard for Quality Assurance control were establish in GFDL – all files should be reviewed by responsible field scientists using dedicated tool of Data Portal publisher embedded in curator web interface. This web application designed and developed with A. Radhakrishnan allows users to trace any of CMIP5 files (expected ~2000000) using group functions for their reviewing, annotation, checking with saving result in curator DB. Checked files are published automatically on Data Portal.

References: http://www.nomads.gfdl.noaa.gov; http://cobweb:8080/extmdbCW

Publications:
Progress Report Title: Deep Stratification, Overturning Circulation, and Mixing in the Ocean

Principal Investigator: Maxim Nikurashin (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Sonya Legg (CICS/GFDL) and Geoffrey Vallis (CICS/GFDL)

Other Participating Researchers: Raffaele Ferrari (MIT)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: Study generation and dissipation of internal waves at rough topography, associated abyssal mixing in the ocean, and its impact on the large-scale stratification, overturning circulation, and climate.

Methods and Results/Accomplishments:
We produce a global estimate of the energy conversion rate from geostrophic flows into internal waves by applying a linear theory of lee wave generation to topographic characteristics and bottom stratification estimated from observations, and bottom geostrophic flows obtained from a global ocean model. We show that generation of topographic internal waves is a significant energy sink for the geostrophic flows as well as an important energy source for abyssal mixing in the ocean.

We study radiation and dissipation of internal waves generated by tidal flows using high-resolution numerical simulation explicitly resolving internal wave generation and breaking. We find that the tidal energy is transferred from the large-scale internal tides to small dissipation scales through a mechanism of resonant wave-wave interactions.

We developed, and tested with an ocean general circulation model, a novel theory for the deep stratification and overturning circulation of the ocean. The theory and simulations show that, in the limit of weak mixing typical for the present mid-depth ocean, the deep stratification throughout the ocean is set by wind and eddies in the circumpolar channel and the rate of the overturning circulation is set by mixing acting across the deep stratification in the ocean basins away from the channel.

Publications:
Nikurashin, M. and R. Ferrari, 2011: Global energy conversion rate from geostrophic flows into internal waves in the deep ocean, Geophysical Research Letters, in press.
Progress Report Title: Offsetting and Complimentary Characteristics of Sulfate and Soot Direct Radiative Forcings

Principal Investigator: Ilissa Ocko (Princeton Graduate Student)

CICS/GFDL Collaborator: V. Ramaswamy (GFDL)

Other Participating Researchers: Paul Ginoux and Larry Horowitz (GFDL)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

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

Objectives: To study the radiative forcing of aerosols in the context of a successful climate model

Methods and Results/Accomplishments:
This study investigates the competing and complementary features of the anthropogenic sulfate and soot direct radiative forcings in the context of the GFDL global climate model CM2.1, which has yielded a reasonable representation of aerosol concentrations and the evolution of the 20th century global-mean surface temperature. Considering the preindustrial to present-day simulated concentrations, we focus on the factors governing the offset posed by the sulfate and soot aerosols on the global-mean and spatial aerosol radiative forcings at the top-of-atmosphere (TOA) and surface.

The simulated sulfate and black carbon all-sky top-of-atmosphere global-mean direct radiative forcings offset one another (+0.87 W/m² black carbon; -0.96 W/m² sulfate), and this offset (-0.09 W/m²) is consistent with the -0.06 W/m² offset reported in the IPCC AR4. The surface forcings, on the other hand, are additive, and the combined soot and sulfate effect yields a value of -2.12 W/m², which has strong potential implications for the hydrological cycle. The quantitative roles of the main physical factors that determine the offsetting effects at the TOA are examined; specifically cloud coverage, surface albedo and relative humidity. Cloud distributions and high relative humidity effects are critical in arriving at the top-of-atmosphere offset.

Accomplishments include presenting this work at the Annual AMS Conference in Seattle, WA, where I won the Outstanding Student Poster Presentation Award. I am currently working on a paper to be submitted to JGR in the near-future.
Progress Report Title: 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)

Task III: Individual Projects

NOAA Sponsor: John Calder (OAR-Arctic Research Office)

Theme: Earth System Modeling and Analysis

NOAA’s Goals:
Climate Goal: 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 mechanism for the formation of ice bands is proposed as a coupled response of ice edge and lee waves to wind under the hydrostatic approximation. A high-resolution ice-ocean coupled model is used in an x-z domain with grid sizes (x,z)= (250 m,1 m). Under an along-ice-edge wind, such that the Ekman transport is away from the ice edge, the nearly discontinuous surface stress between the ice-covered and open seas generates lee waves. A thin layer of high-potential vorticity fluid under the ice is produced by the Ekman forcing, enabling the ice edge to rapidly slip over less stratified water. This is favorable for supercritical conditions when lee waves are generated. Ice bands are formed by the corresponding convergences and divergences. The flow becomes subcritical farther behind the ice-edge but secondary lee waves and ice bands form because of the secondary stress discontinuity behind the lead ice band. An analytical solution is derived to show that ice bands have longer widths than the lee-wavelengths because the ice-ocean stress creates the smoothing effect. Vertical motions associated with the lee waves have speed of the order of 10 m/day, extend to the bottom (300 m), and contribute to deep vertical mixing and the subsequent melting of the ice. These small-scale features are not modeled well with horizontal grids coarser than approximately 2.5 km.

Publications:
**Progress Report Title:** Sensitivity of the Remote Response of ENSO to SST Extra-tropical Anomalies

**Principal Investigator:** Isidoro Orlanski (Princeton Senior Research Scholar)

**CICS/GFDL Collaborator:** Peter Phillips (GFDL)

**Other Participating Researchers:** Silvina Solman (CIMA-UBA, University of Buenos Aires)

**Task II:** Cooperative Research Projects and Education

**NOAA Sponsor:** Brian Gross (GFDL)

**Theme:** Earth System Modeling and Analysis

**NOAA Goals:**

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

**Objectives:** To understand the atmosphere-ocean extra-tropical remote response of tropical forcing

**Methods and Results/Accomplishments:**

The authors hypothesize a simple feedback mechanism between external Rossby waves and diabatic heating from convection. This mechanism could explain the large amplitude that external Rossby waves attain as they propagate to mid- and high latitudes. A series of experiments has been carried out with a core dynamic global spectral model. These simulations with the idealized atmospheric GCM and a simple parameterization of thermal forcing proportional to the low-level wave meridional velocity suggest that external Rossby waves can be enhanced by convection, which they themselves induce. It is shown that in the tropospheric upper levels the amplitude of the external waves can be twice as large with feedback as for a control simulation that does not allow feedback.

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 (SEP). A spectral analysis performed to the bandpass-filtered time series of daily precipitation anomalies for the La Plata Basin (LPB) and the South Atlantic convergence zone (SACZ) regions revealed several statistically relevant peaks corresponding to periods of roughly 23 days and 14–16 days—with the lower (higher) frequency peaks more prevalent for the SACZ (LPB). The large-scale circulation patterns preconditioning precipitation variability over both regions were explored by means of a regression analysis performed on the daily 500-hPa geopotential anomaly field provided by the NCEP–NCAR reanalysis dataset. 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 associated with positive rainfall anomalies over the LPB (SACZ) and, emanating from that high (low), an external Rossby wave propagating northeastward toward the South American continent. The synoptic-scale activity, quantified in terms of a frontal activity index, showed a strong influence on precipitation over the LPB and to a lesser extent over the SACZ. Moreover, the frontal activity is actually modulated by the anomalous high circulation over the SEP region. The behavior of this anomalous circulation may be supported by a positive feedback mechanism that can enhance the response of the high anomaly itself, which in turns reinforces the Rossby wave train propagating toward the South American continent.
Publications:


Progress Report Title: Mechanisms of Jet Interaction and Climate Variability

Principal Investigator: Amanda O'Rourke (Princeton Graduate Student)

CICS/GFDL Collaborator: Geoff Vallis (Princeton-CICS)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: The objective of this project is to understand how the interactions of the subtropical and eddy driven jets pertain to midlatitude climate variability.

Methods and Results/Accomplishments:

The atmosphere supports two dynamically distinct mechanisms for the maintenance of zonal mean zonal winds, one related to conservation of angular momentum in the poleward branch of the Hadley circulation and the other related to the meridional convergence of eddy momentum flux from baroclinic turbulence. These mechanisms lead respectively to a baroclinic jet at the edge of the Hadley cell and a more barotropic, midlatitude eddy-driven jet in the region of the storm tracks. We have investigated the interaction of these two jets using two idealized models, namely a quasigeostrophic barotropic model on the torus and a 1.5 layer shallow water model on the sphere. Both models simulate baroclinic instability within the storm tracks with meridionally localized stirring. Additionally, both models generate an analogue of the subtropical jet in the absence of stirring using relaxation of either the vorticity or thickness fields to a zonally symmetric prescribed mean state.

A particular focus of the work thus far has been to develop an understanding of the characteristics of jet separation. We find that the interaction of the jet forcing mechanisms typically leads to jet merger even when the centers of forcing are well-separated. This tendency can be attributed to eddy propagation characteristics and the location of critical lines within the flow, both of which are strongly tied to the structure of the zonal mean zonal wind.
Progress Report Title: Water Mass Formation Processes and their Evolution under Warming Scenarios in Coupled Climate Models

Principal Investigator: Jaime Palter (Princeton Postdoctoral Teaching Fellow)

CICS/GFDL Collaborator: Anand Gnanadesikan (GFDL), Stephen Griffies (GFDL)

Other Participating Researchers: Irina Marinov (University of Pennsylvania), Eric Galbraith (McGill University)

Task III: Individual Projects

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: To assess the processes responsible for the formation of mode, intermediate, and deep waters in GFDL’s coupled climate models and compare these processes to those inferred from the observational record. To evaluate how projected warming will alter these processes. To enhance our understanding of expected changes in the ocean carbon sink due to the evolution of water mass formation processes.

Methods and Results/Accomplishments:

The formation of mode waters provides a pathway for heat, carbon and other tracers to efficiently invade a massive volume of the ocean. Thus, understanding the processes that govern water mass formation is a critical component of understanding climate variability and change. Over the past year, we have made progress in designing and implementing the diagnostic tools that will be used to understand the interaction between water mass formation and the ocean’s uptake of tracers with collaborators at NOAA’s Geophysical Fluid Dynamics Laboratory. These model diagnostics aim at elucidating the physical processes responsible for water mass formation [Griffies, unpublished notes]. In the water mass formation framework, first proposed by Walin [1982] and generalized in subsequent papers [eg. Iudicone et al., 2008a; 2008b], the addition of fluid to a density layer via water mass formation can be related to its export from the formation region, if the effects of interior mixing processes are known. Moreover, the precursor waters that are transformed into dense water can be identified and their properties and variability cataloged. A limitation of many previous studies that used this technique was the inability to quantify how mixed layer and interior mixing processes influence water mass formation [eg. Brambilla et al., 2008; Speer and Tziperman, 1992], despite the first order role of these processes [Brandt et al., 2007; Iudicone et al., 2008a]. Our ongoing work with collaborators at GFDL should eliminate this limitation by calculating the mass budget for density layers at every time step during model integration [Griffies, unpublished notes]. Still a work in progress, this model capability will allow us to describe the time-dependent transformation of precursor water masses into mode, deep and bottom waters, the mechanisms by which they are transformed, and their effect on the ocean interior.

Nonlinearities in the equation of state can lead to water mass transformation in the ocean interior through a set of processes most often neglected in water mass formation studies. The potential of these processes to produce dense water at similar rates to air-sea forcing in the North Atlantic was recently demonstrated by Klocker and McDougall [2010]. We have also found that there is a strong potential for these processes to vary over time, as they are largely determined by along-isopycnal gradients in
temperature and salinity, which are introduced at the ocean’s surface by the temporally-varying air-sea forcing. As with water mass formation at the ocean’s surface, these processes can also allow heat and other tracers to invade the deep ocean (Figure 1). During the reporting period, we have evaluated the size of the heat flux to the deep ocean due nonlinear processes in GFDL’s MOM4p1 [Griffies et al., 2005] forced by CORE-reanalysis [Large and Yeager, 2009] (Figure 1). We have also started investigating the temporal variability of the water mass transformation and heat flux due to nonlinear processes in a GFDL’s coupled model used in the IPCC Assessment Report 4 (CM2p1 model forced by historical CO$_2$ and aerosols). Our analysis seeks to quantify the degree to which these water mass transformations provide a conduit of heat to the deep ocean that is capable of producing anomalies in deep ocean temperatures.

In addition to these diagnostics of the physics of water mass formation, we have also started designing related diagnostics to calculate tracer budgets for water masses. These tools will help answer how the transformation of surface and thermocline waters to mode, deep and bottom waters shapes the interior distribution of carbon [Palter et al., Relating the temporal variability of ocean’s interior carbon distribution to the formation of water masses. In preparation.]. For example, North Atlantic Deep Water is exposed to the atmosphere on time scales too short to equilibrate all of its gas constituents, and the water mass is subducted with a CO$_2$ disequilibrium [Toggweiler et al., 2003]. Thus, the solubility carbon pump, which is driven by the sinking and subduction of cold CO$_2$-rich waters into the ocean interior, is not operating at full efficiency. The degree of CO$_2$ disequilibrium in the exported water mass hinges on both the disequilibrium in the precursor waters and the rate at which they are transformed to deep water. Our new diagnostic tools will allow for the detailed assessment of the carbon concentration in the precursor water masses, the processes by which these water masses are transformed and the influence of these processes on the carbon disequilibrium in the resultant deep water, and how all of these factors are altered under various climate regimes.

Figure 1: Vertical heat flux to the ocean interior due to cabbeling and thermobaracity (water mass transformation processes resulting from the non-linear equation of state). a) the vertical heat flux across 2000 m (W m$^{-2}$). b) the global average vertical heat flux (W m$^{-2}$) as a function of depth.

References:


Publications:

Palter, J. B., J. Sarmiento, A. Gnanadesikan, J. Simeon, and R. Slater (2010), Fueling export production: nutrient return pathways from the deep ocean and their dependence on the Meridional Overturning Circulation, Biogeosciences, 7(11), 3549-3568.
Progress Report Title: Improving the Representation of Well Mixed Greenhouse Gases in the GFDL Radiation Code

Principal Investigator: David Paynter (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator V. Ramaswamy (GFDL)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: To improve the GFDL GCM radiation code using state of the art radiative transfer calculations. To produce an empirical continuum model for the radiative transfer community.

Methods and Results/Accomplishments:
Our recent work has involved continuing to use line by line radiation codes updated with the latest spectral line and continuum data to improve the accuracy of the approximations utilized in GCM radiation codes. This year we have finished our continuum model called the BPS continuum and have written a FORTRAN code which makes it accessible to the radiative transfer community. This represents the first attempt to quantify the continuum over both longwave and shortwave spectral regions using experimental data. This allows for reasonable estimates of uncertainty in radiative transfer associated with the continuum. Using the code in a radiation model demonstrates that while the continuum is fairly well constrained in the longwave, the uncertainty in the continuum still has a direct effect upon CO2 forcing, that may not be well accounted for in radiation codes. The continuum is contributing extra absorption in the shortwave not presently accounted for in any radiation codes.

The work has been written up into 2 papers. The first one which is presently under external review introduces the BPS continuum. The second is presently under internal review and investigates the impact of new continuum on radiative transfer calculations in wide range of atmospheric conditions. We are currently in the process of updating the GFDL radiation code in the longwave and shortwave to operationally include the new BPS continuum formulation.

We have also further investigated the impact of other issues with gaseous radiative transfer in the GFDL radiation code. We have shown that the accuracy of overlap in radiative transfer calculations can be improved by narrowing the bands of each absorber.

Publications:
An assessment of recent water vapor continuum measurements upon longwave and shortwave radiative transfer, D.J. Paynter, V.Ramaswamy, 2011, submitted to JGR.
Using ERA-40 data to improve our understanding of the water vapor continuum, D.J. Paynter, V.Ramaswamy, 2011, under internal GFDL review.
Progress Report Title: Decoupling the Nitrogen Cycling in an Ocean Biogeochemical Model

Principal Investigator: John Paul Reid (Princeton Graduate Student)

Other Participating Researchers: Anand Gnanadesikan (GFDL)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: To understand and model the interactions of oceanic nutrient cycling

Methods and Results/Accomplishments:

The ocean nitrogen cycle plays a significant role in the availability of nutrients and the biological uptake of carbon. The ocean biogeochemical model BLING has been shown to successfully reproduce many characteristics of the large-scale nutrient and chlorophyll fields (Galbraith et al. 2009). By modifying this model to include a separate nitrogen cycle, the role of processes unique to the nitrogen cycle in varying ocean regimes can be examined.

Processes of nitrogen fixation and denitrification are critical to this cycle but are poorly constrained. Nitrogen fixation is crucial for maintaining biological productivity in the oceans, because it replaces the biologically available nitrogen that is lost through denitrification (Deutsch et al. 2007). The maintenance of the traditional Redfield ratio may be related to a coupling between these two processes (Capone and Knapp 2007). The current study allows an examination of any coupling between these processes.

Because nitrogen fixation usually is accompanied by a higher demand for iron, it is reasonable to examine a connection between fixation and iron limitation. In regions where iron is limiting, nitrogen fixation may be unable to supply new fixed nitrogen, leading to consequences for the regional ecosystem. Similarly, nitrogen-fixing blooms may lead to iron limitation, disrupting the long-term regional ecosystem. Therefore, an understanding of the interactions of nitrogen fixation with iron cycling is imperative.

The next step of this research is the application of this model to a GCM under conditions of forced upwelling in various regions. Artificial upwelling has been proposed as a method of carbon sequestration through nitrogen-fixating phytoplankton blooms in traditionally nitrate-depleted regions (Karl and Letelier 2008). Given the vast scales and uncertain consequences of this geoengineering undertaking, a comprehensive study of the effectiveness and resulting outcomes of such a project is necessary.

References:


Progress Report Title: Development of an Ice-Sheet Model

Principal Investigator: Olga Sergienko (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Robert Hallberg (GFDL)

Other Participating Researchers: Daniel Goldberg (Princeton)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: Development of a large scale ice-sheet model and coupling to GFDL climate system model. Understanding of physical processes governing ice-sheet behavior and its role in climate system

Methods and Results/Accomplishments:
To better understand ice-sheet behavior and interaction of ice sheets with other components of the climate system we develop an ice-sheet model capable of capturing major known processes governing behavior of ice sheets. The model is capable of running in a stand-alone configuration, and produces present day configuration of Antarctic Ice Sheet reasonably well. Figure 1 show the modeled surface elevation, ice speed (log10 scale) and surface temperature.

Numerous physical parameters that important for adequate simulation of ice sheets cannot be directly observed. It is common to get estimates for such parameters using inverse techniques. Estimates of inverted parameters are sensitive not only to observations used in inversions but also to inverse methods. Development of a robust inverse model is another research activity. In collaboration with Daniel Goldberg a new inverse model was developed. This model accounts for physical aspects traditionally neglected in existing inverse models (Goldberg and Sergienko, 2011).

Interaction of ice shelves with ocean is important (if not crucial for their stability) process. However, it remains poorly understood. Several research activities are underway to improve understanding of various aspects of ice-shelf/ocean interaction. In collaboration with Robert Hallberg and Daniel Goldberg a two-way coupling of an ice-stream-shelf model with the GOLD ocean model has been developing. Such coupling is necessary two addresses a number of scientific questions how ice shelves and surrounding ocean affect each other.

To address another aspect of such interaction – mechanical effects of ocean waves on ice-shelf stress regime, a new theoretical treatment has been developed (Sergienko, 2010). Such a treatment allows to assess ice-shelf flexural stresses induced by ocean waves. Application of this treatment to recently disintegrated Wilkins Ice Shelf demonstrate that ocean swell generated by storms might have produced stresses large enough to trigger its disintegration (Sergienko, 2011).
Figure 1. Present day Antarctic fields: (a) ice thickness (m); (b) surface speed (m yr$^{-1}$, log10 scale); (c) surface temperature ($^\circ$C)

**Publications:**


**Progress Report Title:** Quantifying the Role of Bacterial Extracellular Enzymes in Marine Remineralization Processes for Oxygen Minimum Zone Regions

**Principal Investigator:** K. Allison Smith (Princeton Postdoctoral Research Associate)

**CICS/GFDL Collaborator:** Jorge Sarmiento (AOS, Princeton), Charles Stock and John Dunne (GFDL)

**Other Participating Researchers:** Laura Hmelo (University of Washington), Mike Stukel (University of Maryland), Moira Decima (Scripps Institute of Oceanography)

**Task III:** Individual Projects

**NOAA Sponsor:** Brian Gross (GFDL)

**Theme:** Earth System Modeling and Analysis

**NOAA Goals:**
**Ecosystem Goal:** Protect, Restore, and Manage the Use of Coastal and Ocean Resources through Ecosystem Approach to Management

**Objectives:** In order to assess the nonlinear effects of remineralization, I am developing a model to look at production and activity of bacterial extracellular enzymes in the context of marine ecosystems. I am also reviewing the portrayal of detritus in ecosystem models in a collaboration with Mike Stukel, Laura Hmelo, and Moira Decima, that will be integrated as part of a larger review on the identity and fates of detritus in marine ecosystems.

**Methods and Results/Accomplishments:**

*Enzyme model:* I have created the first version of the model which is 0D in spatial dimensions and designed for a depth below the euphotic zone. Parameters include six state variables: dissolved organic matter, particulate organic matter, free-living bacteria, particle-attached bacteria, extracellular enzyme, and hydrolysate. The model is forced with particulate organic carbon and temperature as input variables. Some important dynamics incorporated in the model stem from recent experimental discoveries: extracellular enzymes lifetimes are temperature dependent ranging from 24 to 100 hours or more; extracellular enzymes diffuse from particulates to the surrounding seawater where they are active. These components, in particular, may have important impacts on the timing and rates of remineralization. I am using data from the Bermuda Atlantic Time-Series Study to explore the dynamics of model. I have downloaded relevant bottle data including bacteria counts, chlorophyll a concentrations, dissolved organic carbon concentrations, oxygen concentrations, particulate organic carbon concentrations, and temperature. I am starting with one year, 2005, but plan to expand the analysis over a longer time span. I plan present results from the enzyme model at the Advances in Marine Ecosystem Modelling Research Conference at the Plymouth Marine Laboratory in June 2011.

*Detritus review:* Fasham et al. (1990) was a seminal paper in the development of ecosystem models that describes a model that has served as the basis for most ecosystem models created between 1990 and the present. I used the ISI Web of Knowledge database to find the journal articles that cite Fasham et al. 1990 and found 564 articles published prior to December 31, 2010. On a spreadsheet, I am documenting the total number of state variables, the detritus state variables, detritus sources, detritus sinks, model dimensions, and location for each model described. Some of the models were used for multiple studies and I am currently tracking the different applications of each model and the location the model was applied.

**References:**
**Progress Report Title:** Arctic (Extreme) Weather and Climate Variability In The GFDL High-Resolution Global Climate Simulations

**Principal Investigator:** Thomas Spengler (Princeton Postdoctoral Research Associate)

**CICS/GFDL Collaborator:** Isaac Held (GFDL), Stephen Garner (GFDL), Sam Potter (Princeton), Andrew Ballinger (Princeton)

**Task II:** Cooperative Research Projects and Education

**NOAA Sponsor:** Brian Gross (GFDL)

**Theme:** Earth System Modeling and Analysis

**NOAA Goals:**

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

**Objectives:** Diagnose and validate the high-resolution climate simulations of the GFDL cubed sphere simulations with reanalysis data (i.e. ERAInterim) and identify differences between models runs for current and a warm future climate, and continue research on fundamental atmospheric dynamics in both dry and moist atmospheres.

**Methods and Results/Accomplishments:**

High latitude extreme weather events such as or Polar Lows (e.g. Renfrew 2003) are of climatic (e.g. ocean mixed layer see Pickart et al., 2003) as well as socio-economic importance. The statistics of their occurrence in space and time are investigated utilizing the University of Melbourne Cyclone Tracking Software (Murray and Simmons, 1991). First we compare the GFDL high-resolution cubed sphere global climate model (C180) output (see Fig. 1) with the recently established ERAInterim reanalysis dataset from the European Centre for Medium Range Weather Forecast (ECMWF). There has also been an increasing focus on changes in polar low frequencies in a future climate. Diverse studies indicate that polar low genesis regions shift northward in tandem with the retreating sea ice edge (e.g., Bracegirdle and Gray, 2008; Kolstad and Bracegirdle, 2008; Zahn and von Storch, 2010). GFDL C180 data for current and future climates will be compared to address this potential shift in polar low occurrence and further diagnosis will be used to indicate dynamical reasons for these changes.

Furthermore the causality often assigned to potential vorticity attribution has been investigated (Spengler and Egger 2011). The process of hydrostatic and geostrophic adjustment is addressed with a numerical model. It is argued that the common perception in synoptic meteorology, that potential vorticity acts at a distance, thereby initiating a far field flow, is mid-leading. A more physical interpretation of the lateral and vertical boundary conditions necessary for inversion of potential vorticity is also discussed. In addition the reflection of Rossby waves propagating through a meridionally varying basic state zonal flow profile is investigated (Potter et al. 2011). The main focus is on the breakdown of the WKB solution utilizing a numerical model indicating that despite the nominal breakdown of the WKB solution it still yields reasonable results in regimes without total reflection. A new approximation of the reflection coefficient is proposed, within the realm of the WKB framework. The new approximation compares well with the full solution of barotropic reflection for a large swath of the parameter space.

Moreover, the non-linearity of mountain torques, in particular the breakdown of linearity for flow over and around large-scale topography is investigated. The characteristics of mountain torques are investigated utilizing the dynamical core of the GFDL global spectral model. The model is run in an idealized setup, i.e. Held-Suarez, with idealized mountains of different shape and height. A range of experiments with mountains of different heights is performed and will be analyzed.
References:


Publications:


Figure 1: Cyclone density for polar low season (October-April) for GFDL C180 atmospheric control run with perpetual mean annual cycle in boundary forcing (e.g. sea ice, sea surface temperature)
Progress Report Title: Variability of Nordic Seas Overflows

Principal Investigator: He Wang (Princeton Graduate Student)

CICS/GFDL Collaborator: Sonya Legg (Princeton), Robert Hallberg (GFDL), Tom Delworth (GFDL)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: Understand the decadal variability of the Nordic Seas overflows, their forcing mechanisms and their influence on the Atlantic Meridional Overturning Circulation and climate

Methods and Results/Accomplishments:
The Nordic Seas overflows, which contribute to about 2/3 of the deep western boundary current, are flows carrying dense water mainly through the Denmark Strait and Faroe Bank Channel. My research is mainly focused on using the GFDL climate model CM2G to study the decadal variability of the Nordic Seas overflows. Spectrum analysis shows that the Denmark Strait overflow, which flows in the same direction as its upper level transport, has a feature of decadal oscillation at the time scale of around 10 years, while the Faroe Bank Channel overflow does not. This time scale however, shows in the upper level transport (Atlantic Inflow) at Faroe Bank Channel, which is in the opposite direction. Also, the flow through Denmark Strait is anti-correlated with this Atlantic Inflow.

The simple hydraulic control model for overflows was proposed by Whitehead et al. (1974). In this model, the transport of an overflow is determined by the upstream depth of the critical density layer as well as the stratification, with the former being a stronger factor. The hydraulic control predicted overflows in CM2G are correlated with the actual overflows, but there is no periodicity in the variation of upstream layer depth. However, the change of upstream layer depth is possibly linked to the strength of Atlantic Inflow over Faroe Bank Channel, which has a 10-year oscillation. The second mechanism influencing the overflow is the wind stress curl (Biastoch et al. 2003). A positive wind stress curl will enhance the transport through DS and reduce that through FBC. Regression analysis of sea level pressure on the overflow transport supports this point of view. It is proposed the North Atlantic Oscillation being an influential factor of the overflow, in that a positive NAO coincides with a stronger DS overflow and weaker FBC overflow. However, this relationship is not observed in CM2G.

References:
Progress Report Title: Data Comparison for Phytoplankton Community Composition Input to Topaz

Principal Investigator: Bess B. Ward (Princeton Professor of Geosciences)

CICS/GFDL Collaborator: John Dunne (GFDL)

Other Participating Researchers: Amal Jayakumar (Senior Research Scientist, Department of Geosciences, Princeton University), Diana Chien (Undergraduate Student, Department of Ecology and Evolutionary Biology, Princeton University)

Task III: Individual Projects

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Ecosystem Goal: Protect, Restore, and Manage the Use of Coastal and Ocean Resources through Ecosystem Approach to Management (60%)
Climate Goal: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond (40%)

Objectives: Continue and expand our comparison of model and experimental data from a simulated phytoplankton bloom. Expand our analysis of phytoplankton community composition from archived surface ocean samples, using the phytoarray.

Methods and Results/Accomplishments:
In this last year the project continued under a no cost extension, wrapping up previously begun analyses. Our goal was to produce microarray data on the diversity, community composition and relative abundance of different phytoplankton types in order to compare the community composition with predictions from Topaz. All of the samples (approximately 32 samples from the simulated upwelling experiment described in previous progress reports and ~30 samples from the North Atlantic) have been processed and the microarray data are currently being analyzed.
Progress Report Title: Interactions of the Deep Western Boundary Current (DWBC) with Topography and the North Atlantic Current (NAC)

Principal Investigator: Yu Zhang (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Geoffrey Vallis (Princeton), Robert Hallberg (GFDL)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: Understand the influence of topography and NAC on the path and variability of DWBC

Methods and Results/Accomplishments:

The primary focus of my research from November, 2010 through February, 2011 is to set up an idealized, high-resolution, regional model to investigate interactions between NAC and DWBC in the presence of steep topography and rugged western coast as in North Atlantic basin. We attempted to prescribe NAC and DWBC as inflows into the domain through the northern and the southern boundary while maintain the mass balance by opening the domain in the south and east. However, the work progress was hindered by difficulties in applying proper open boundaries with sponge layers next to them. Finally we decided to study the problem using a different idealized model. This model is closed in all boundaries, but a differential buoyancy forcing is applied at the surface, inducing convection in high latitudes and formation of the DWBC. At the first stage, only a coarse resolution model is set up to understand the basic picture of the meridional overturning circulation and its relation to the forcing agents. At later stages, effects of topography will be incorporated in high-resolution models.

Publications:


Progress Reports:

Data Assimilation
Progress Report Title: Global Carbon Data Management and Synthesis Project

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

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

Task III: Individual Projects

NOAA Sponsor: Joel Levy (Ocean Climate Observation Program)

Theme: Data Assimilation

NOAA Goals:

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

Objectives: The goal of the Global Carbon Data Management and Synthesis Project is to understand the ocean carbon cycle and how it is changing. We use high-quality ocean carbon observations to produce products that are useful to other scientists and the public. We use these data to investigate the rate of change in oceanic carbon uptake and storage.

Methods and Results/Accomplishments:

Scientific interpretation of the CARINA (described in previous reports) data with U.S. colleagues has begun. Key and Lin are working with J.R. Toggweiler (GFDL) and J.L. Sarmiento (Princeton U.) to investigate the influence of river input on the carbon chemistry of the surface ocean. In the first study a new ocean tracer, Alk*, is introduced to examine alkalinity variations at the ocean’s surface. Its purpose is to reveal anomalies that are not due to evaporation and precipitation. Positive values of Alk* are found around the ocean’s margins and are due to inputs of river water. The most negative values are found in the Red Sea, the Arabian Sea, and in the subtropical gyre of the North Atlantic. The deficit in the subtropical Atlantic appears to be a byproduct of the salinification associated with the Atlantic’s meridional overturning circulation, which raises the CO3= concentration in Atlantic surface waters. A manuscript (Key, et al., 2011) is in review. In a companion manuscript, we use a box model to investigate the impact of rivers and the hydrologic cycle on the carbon chemistry of the Atlantic Ocean (Toggweiler et al., 2011). We demonstrate how weathering, the organic input from the terrestrial biosphere, and a net export of fresh water give rise to three loops of the carbon cycle that combine to make the Atlantic a net exporter of CO2 via gas exchange. The export of freshwater also makes the surface waters of the Atlantic relatively alkaline and helps explain why organisms in the Atlantic produce more CaCO3 than organisms elsewhere. If these results withstand scrutiny, we will have explained the seemingly anomalous surface Atlantic Ocean estimates of anthropogenic CO2 produced by GLODAP (Sabine et al. 2004, Key et al. 2004). During March and April, 2010, J. Bullister (NOAA/PMEL) and R. Key served as co-chief scientists for CLIVAR cruise A13.5 aboard the NOAA vessel Ron Brown. A13.5 essentially followed the prime meridian from 54S to 5N and included 129 hydrographic/CTD stations. This line had not been occupied since 1983. Even with the shipboard preliminary data it was immediately obvious that the old DIC measurements had significant measurement bias (estimated at 10-20 μmol/kg), demonstrating once again how critical it is to continue data synthesis activities (i.e. this estimated bias is about the same size as the expected increase in surface ocean DIC over the time interval separating the cruises). R. Key is working with graduate student Y. Plancherel and Princeton researcher K. Rodgers to produce a global estimate of the integrated decadal DIC inventory change based on GLODAP and CLIVAR era data. The method we are using is not restricted to lines that have exact repeats. Developmental tests imply that the
inventory change estimate will have an error not significantly larger than the original GLODAP estimates (~15%). Errors in the distribution of the change may be larger.

References:


Publications:


76


Progress Reports:

Earth System Model Applications
Progress Report Title: Detection and Attribution of Shifts in the Carbon System

Principal Investigator: Claudie Beaulieu (Princeton Postdoctoral Research Fellow)

CICS/GFDL Collaborator: Jorge L. Sarmiento (Princeton University)

Other Participating Researchers: David Medvigy (Princeton University), Rong Zhang (GFDL), Georgyi Stenchikov (GFDL), Ni Golaz (Princeton University), Sara Mikaloff-Fletcher (National Institute of Water and Atmospheric research, New Zealand), Jie Chen (University of Missouri-Kansas City)

Task III: Individual Projects

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

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

Objectives: To investigate an abrupt shift in the mean land carbon sink that seemed to occur in 1988/1989

Methods and Results/Accomplishments:

In the past year, my research focused on the analysis of temporal variations of the net land uptake estimated as the balance between the growth rate of atmospheric CO₂, the fossil fuel emissions and the ocean uptake from a suite of ocean models. We developed a general change point detection technique able to discriminate between abrupt and gradual changes in time series. This technique was applied to detect past abrupt shifts in the net land uptake and confirmed the analysis of Sarmiento et al. (2010), in which a shift in the mean land uptake was detected. We showed that this shift seems to come from the atmospheric growth rate. Similar results were obtained with the atmospheric growth rate from several observing stations including Mauna Loa and South Pole. We also found unlikely the hypothesis that this shift was driven by the El Niño Southern Oscillation (ENSO) and/or by volcanic eruptions. We also verified if this shift could be associated to shifts in global temperatures, in the Atlantic Multidecadal Oscillation (AMO) or in the Atlantic meridional overturning circulation (AMOC) and did not find similar shifts in the observations used. We also analyzed global land fluxes from the GFDL-LM3V land model with land use, land use and current climate, land use and current CO₂ and land use and current climate and CO₂. The shift we detect in our land uptake estimate does not seem to occur in the land model.

In order to refine this analysis at the monthly time scale, we extended the change point technique to take into account the autocorrelation. Since climate time series are known to exhibit autocorrelation, it corresponds to a model misspecification if not taken into account and can lead to the detection of nonexistent shifts. Thus, we extended the change point technique allowing discriminating between several models and also taking into account the autocorrelation in the models.

The magnitude of the shift detected in the net land uptake relative to the variability of the noise is very small (smaller than one standard deviation) and therefore, the confidence level is small. We performed a simulation study in order to investigate the number of years after which an abrupt shift is detectable. This depends on the magnitude of the shift relative to the standard deviation in the time series of observations. We showed that if not detected after ten years, the probabilities of detecting the shift will not increase with more observations, but the confidence level will keep increasing with more observations. In the land uptake case, the magnitude relative to the standard deviation is smaller than one, which is very small. Thus the confidence level on the shift detected might increase with more observations.
Publications:


**Progress Report Title:** Predictability of Tropical Cyclone Inter-annual Variability with 25-km GFDL High-Resolution Atmospheric Model (HiRAM)

**Principal Investigator:** Jan-Huey Chen (Princeton Postdoctoral Research Associate)

**CICS/GFDL Collaborator:** Shian-Jiann Lin (GFDL)

**Task II:** Cooperative Research Projects and Education

**NOAA Sponsor:** Brian Gross (GFDL)

**Theme:** Earth System Model Applications

**NOAA Goals:**

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

**Objectives:** Predictability of tropical cyclone inter-annual variability is studied by using a newly developed global high-resolution model which is currently being used for both weather and climate-change predictions at GFDL. An unprecedented prediction skill of the year to year Atlantic hurricane counts during the past decade has been shown.

**Methods and Results/Accomplishments:**

Seasonal prediction of tropical cyclones (TCs) is an important research topic due to its enormous social and economical impacts. In this study, a newly developed global model, the Geophysical Fluid Dynamics Laboratory (GFDL) High-Resolution Atmospheric Model (HiRAM) which is designed for both weather and climate-change predictions, is used to predict the TC activity in the North Atlantic and the western North Pacific basins at 25-km resolution. Assuming the persistence of the SST anomaly during the forecast period, the inter-annual variability of seasonal hurricane counts in the North Atlantic basin is highly predictable for the past decade. A remarkable correlation of 0.96 between the observed and model predicted hurricane counts is achieved, while the root mean square error of the predicted hurricane number is less than 1 per year after correcting the model’s negative bias. The model performance in the western North Pacific is also skillful. The correlation is 0.77 between the model prediction and the observation of tropical storm counts. The predictive skill of the model in the tropics is further supported by the successful prediction of a Madden-Julian Oscillation event initialized 7-day in advance of its onset.
Figure: July to October (A) hurricane and (C) tropical storm counts for each year during the period of 2000-2010 in the North Atlantic basin. (B) As in (A), but for typhoons in the western North Pacific basin. (D) As in (B), but for tropical storms. IBTrACS observations are shown by black line and circles. Four-ensemble members are shown by magenta open circles, while the ensemble mean is denoted by magenta line and closed circles. The red line and circles represent the bias removed ensemble mean.

Publications:
Progress Report Title: Seasonal Phase-locking of the Year-to-Year Variation of SST in the Atlantic Hurricane Main Developing Region and its Climate Change Response

Principal Investigator: Takeshi Doi (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Gabriel A. Vecchi (GFDL)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

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

Objectives: To understand the mechanism of the seasonal phase-locking of the year-to-year variation of tropical Atlantic SST and improve the simulation and prediction skill of the GFDL climate models.

Methods and Results/Accomplishments:
The year-to-year variation of sea surface temperature (SST) in the northern tropical Atlantic is strongly phase-locked to the season; it develops from early winter, reaches the peak in spring, and decays suddenly in summer. To reasonably simulate this seasonal phase-locking is critical for accurate prediction of the Atlantic hurricane activity and rainfall in northeastern Brazil and Sahel. In the fully coupled ocean-atmosphere model GFDL-CM2.1 (Climate Model version 2.1 developed at the Geophysical Fluid Dynamics Laboratory), the decay of the interannual SST anomaly in the northern tropical Atlantic is slow and weak compared to that in observations (Fig.1). This bias is due to the unrealistic air-sea coupled positive feedback linked with the subsurface doming of thermocline in the northeastern tropical Atlantic: the Guinea Dome. Anomalously large meridional swing of the ITCZ associated with the warm SST anomaly in the northern tropical Atlantic leads to the Ekman downwelling anomaly in the Guinea Dome region. This suppresses the decay of the warm SST anomaly through entrainment. Therefore, realistic simulation of the meridional ITCZ swing and ocean dynamics in the subsurface Guinea Dome may be critical for improvement of the bias in the seasonal phase-locking of the year-to-year SST variation in the northern tropical Atlantic.

Using outputs from the pre-industrial control run of Climate Model version 2.1 developed at the Geophysical Fluid Dynamics Laboratory (GFDL-CM2.1) and its double carbon dioxide (CO₂) increase experiment, the idealized climate change response of the year-to-year variation of SST in the Atlantic hurricane main developing region is investigated. We found that the year-to-year SST variation is 25% stronger in the double CO₂ increase experiment than that in the control run and the maximum peak of the interannual SST anomaly delays about 1 month from May in the control run to June in the double CO₂ experiment (Fig.2). This finding is quite interesting and unique because most of previous works have discussed the annual mean state in a warmer climate.
Fig. 1: (a) Monthly standard deviation of the year-to-year variation of SST averaged in the main developing region for the Atlantic hurricane (MDR: 80°-20°W, 10°-25°N) from ERSSTv3 (bar) and GFDL-CM2.1 (red dot line) (°C). (b) Horizontal map of the standard deviation of the interannual SST anomaly averaged in the hurricane season; August-November (°C) from the observational data of ERSSTv3. Contour interval is 0.1°C. MDR is shown by solid line box. The Guinea Dome region (40°-20°W, 10°-15°N) is shown by dash line box. (c) Same as (b), but from GFDL-CM2.1. (d) Difference of (c) minus (a). Contour interval is 0.1°C. (e) Same as (a), but for the Guinea Dome region.

Fig. 2: (a) Monthly standard deviation of the year-to-year variation of northern tropical Atlantic SST averaged in Main Developing Region for Atlantic hurricane (MDR: 80°-20°W, 10°-25°N) from ERSSTv3 (bar), the control run of GFDL-CM2.1 (black line), and its double CO2 increase experiment (red line) (°C). (b) Monthly standard deviation of the year-to-year variation of northern tropical Atlantic SST in June from the control run of GFDL-CM2.1 (°C). Contour interval is 0.1°C. Black box shows MDR. (c) Same as (b), but from the double CO2 increase experiment of CM2.1. (d) (e) minus (b). Contour interval is 0.1.
Publications:


Tozuka, T., T. Doi, T. Miyasaka, N. Keenlyside, and T. Yamagata, 2010: How to simulate the zonal SST gradient in the equatorial Atlantic realistically in a coupled GCM, JGR, revised.


Progress Report Title: Warmer Wetter Climate, More Soluble Pollutants

Principal Investigator: Yuanyuan Fang (Princeton Graduate Student)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

CICS/GFDL Collaborator: Arlene Fiore (GFDL), Larry Horowitz (GFDL), Anand Gnanadesikan (GFDL), Hiram Levy (GFDL), Isaac Held (GFDL), Gabriel Vecchi (GFDL)

Other Participating Researchers: Gang Chen (Cornell)

Theme: Earth System Model Applications

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

Objectives: Examine the impacts of changing transport and precipitation on air pollution in a future climate

Methods and Results/Accomplishments:

Air quality is strongly influenced by meteorological conditions and thus is sensitive to climate change [e.g., Denman et al., 2007]. Understanding the impact of climate change on air quality is essential for managing future air quality and evaluating the societal consequences of climate change. Climate change could alter air quality via affecting atmospheric circulations, altering natural pollutant precursor emissions that depend strongly on meteorology (lightning NOx, biogenic emissions), and influencing the rates of chemical reactions [e.g., Jacob and Winner]. Estimating the climate change impact on air quality requires a good understanding of each of these processes.

In order to isolate the responses of air pollutant transport and wet removal to a warming climate, we examine a simple carbon monoxide (CO)–like tracer (COt) and its soluble version (SAT), both with the 2001 CO emissions, in simulations with the GFDL chemistry-climate model (AM3) [Donner et al., 2010] for present (1981-2000) and future (2081-2100) climates.

We found that in 2081-2100, projected reductions in lower tropospheric ventilation and wet deposition contribute to exacerbating surface air pollution as evidenced by higher surface COt and SAT concentrations. While precipitation is an important factor controlling soluble pollutant wet removal, we found that the total global precipitation change alone is not a sufficient indicator of the soluble pollutant response to climate change. Over certain latitudinal bands, however, the annual wet deposition change can be explained mainly by the simulated changes in large-scale (LS) precipitation. In regions such as North America, differences in the seasonality of LS precipitation and tracer burdens contribute to an apparent mismatch of changes in annual wet deposition versus annual precipitation. We then developed a diagnosed precipitation impact (DPI) index to directly infer soluble pollutant wet deposition responses from changes in precipitation as simulated by a climate model. Specifically, we expressed DPI as the global mean of present-day pollutant burden weighted LS precipitation change divided by the global mean of present-day pollutant weighted LS precipitation. This index captures the sign and magnitude (within a factor of 2) of the relative annual and July mean changes in the global wet deposition of the soluble pollutant tracer. If our findings that LS precipitation dominates wet deposition and that horizontal transport patterns change little in a future climate are broadly applicable, the DPI could be applied to LS precipitation fields in other climate models to obtain estimates of the distributions of soluble pollutants under future scenarios.
Our findings support the need for tighter emission regulations, for both soluble and insoluble pollutants, to obtain a desired level of air quality as climate warms.

References:


Jacob, D. J., and D. A. Winner (2009), Effect of climate change on air quality, Atmospheric Environment, 43, 13.

Publications:
Progress Report Title: Background Ozone Variability and Trends over the Western United States

Principal Investigator: Meiyun Lin (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Arlene Fiore (GFDL)

Other Participating Researchers: Larry Horowitz (GFDL), Bruce Wyman (GFDL), John Wilson (GFDL), Vaishali Naik (GFDL)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

NOAA Goals:
Climate Goal: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond (50%)
Weather & Water Goal: Serve Society’s Needs for Weather and Water Information (50%)

Objectives: Advance knowledge on background ozone sources, variability and trends over the western United States and implications for air quality attainment; ultimately seeking to determine how these will respond to a warming climate

Methods and Results/Accomplishments:
We employ the GFDL AM3 global chemistry-climate model at two horizontal resolutions (50 and 200 km), in conjunction with a suite of observations, ranging from ground-based networks to ozonesondes, aircraft and satellite-based platforms, to advance our understanding of key mesoscale to synoptic scale processes controlling background ozone sources and variability over the western US. In particular, we have explored the impacts of Asian anthropogenic emissions and stratospheric intrusions on the day-to-day variability of lower tropospheric ozone over the west US during the 2010 NOAA supported CalNex campaign. Our results suggest that both Asian emissions and stratospheric intrusions exert a greater influence on the local high-ozone episodes and its exceedance of air quality standard than previously reported in the literature. Comparing the typical AM3 simulation (~200 km horizontal resolution) with the higher resolution (~50 km) indicates important mesoscale to sub-synoptic scale processes governing tropopause folding and subsequent descent of injected stratospheric ozone from the upper to the lower troposphere. These results highlight the three-dimensional nature of background ozone distributions, and will serve as a foundation for our next study. That study will examine long-term trends and the response of background ozone over the western United States to a warming climate and changing precursor emissions. We delivered a well-received talk at the 2010 American Geophysical Union Fall Meeting. Two papers are in preparation to summarize the key findings from the current project.
Progress Report Title: Modeling the Effects of Rising Sea Surface Temperatures on Global Coral Reefs

Principal Investigator: Cheryl Logan (AOS Postdoctoral Researcher)

CICS/GFDL Collaborator: John Dunne (GFDL)

Other Participating Researchers: Simon Donner (University of British Columbia), Mark Eakin (NOAA/Coral Reef Watch)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

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

Objectives: To predict global coral bleaching rates for the next IPCC Assessment (AR5) using the GFDL Earth System Model (ESM). To incorporate physiologically realistic coral adaptive ability into this model.

Methods and Results/Accomplishments:

Background: Climate warming threatens to increase the frequency of mass coral bleaching events. Previous estimates suggest that corals will experience biannual bleaching by mid-century unless they can adapt or acclimatize at a rate of ~0.2–1.0°C per decade (Donner et al. 2005). I sought to explicitly model corals’ potential adaptive ability by incorporating thermal history into a simple bleaching predictive model. The model I have been working on is based on the following observations from the literature: 1. Corals living in more variable thermal environments may have higher resistance to bleaching (e.g. McClanahan et al. 2007). 2. More generally, background thermal history may influence bleaching susceptibility (e.g. McClanahan et al. 2007). 3. Some corals may be able to transiently increase thermal tolerance following a bleaching event via symbiont reshuffling (e.g. LaJeunesse et al. 2009).

Methods/Results: I used Landsat derived UNEP-WCMC 2010 warm water coral reef locations to identify ESM grid cells where reefs exist (Fig. 1). I then compared 3 different methods for incorporating corals’ potential adaptive ability into a global predictive bleaching model through 2100. I used SSTs from the GFDL ESM2M using the NOAA-based Coral Reef Watch “standard” coral bleaching threshold. This threshold accumulates Degree Heating Months (DHMs) at 1°C above a maximum monthly mean annual temperature (MMM) climatology between 1981-2000 (Donner et al. 2005) (Fig. 2 in red). DHM>1 predicts a bleaching event; DHM>2 predict a severe bleaching event.

Method #1: Thermal tolerance increases in more variable environments. Corals accumulate DHMs >2 standard deviations (2σ) above the MMM climatology (Donner 2009; Teneva et al. in review) (Fig. 2A in black).

Method #2. Thermal tolerance varies with thermal history over time. Corals “adapt” to their thermal history over the previous 100 yrs via a rolling climatology that moves forward in time using the standard threshold (Teneva et al. in review) (Fig. 2A in green).

Method #3. Thermal tolerance increases after bleaching. Corals transiently increase thermal tolerance following a bleaching event by accumulating DHMs > 2°C above the MMM climatology (instead of >
1°C) followed by a linear decay rate to the standard threshold over 1, 2 or 10 years (e.g. symbiont reshuffling towards a dominant thermally resistant clade) (Fig. 2B in dotted lines).

Given the assumptions in this simple model, I found that a variability-based threshold does not change the total fraction of reefs bleaching over time compared to the standard threshold. However, regional hotspots differ in the Indo-Pacific and identification of these hotspots will be critical for management. If corals can adapt or acclimatize to their thermal history over the previous 100 years, severe bleaching could be prevented in over half of global reefs by 2100. Finally, a transient increase in thermal tolerance after a bleaching event only moderately delays severe bleaching events.

References:


Fig.1

Figure 1. Global warm water coral reefs locations from the Millennium Landsat Project (UNEP-WCMC 2010) gridded at the scale of the Earth System Model.
Figure 2. Global bleaching predictions using the GFDL Earth System Model (AR5 IPCC RCP 8.5 scenario) with 3 bleaching models that incorporate corals’ potential adaptability. A) A 1°C standard threshold (red) and a variability based 2σ threshold (black) above the MMM climatology between 1981-2000. A 1°C threshold above a rolling MMM climatology for the previous 100 years (green). B) A threshold that increases by 1°C after a bleaching event and decays back to the pre-bleaching threshold over 1, 2 or 10 years.

Figure 3. On regional basis, the 1°C and the 2σ threshold reveal slightly different bleaching hotspots towards the end of the century, but hotspots both lie in the Indo-Pacific. A) Frequency of severe bleaching events between 2066-2085 by region using a 1°C threshold and B) using the variability based 2σ threshold above the MMM climatology.
Progress Report Title: Global Land-Atmosphere Coupling Experiment: Soil Moisture Contributions to Subseasonal Forecast Skill

Principal Investigator: Sergey Malyshev (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: C. T. Gordon (GFDL), E.F. Wood (Princeton)

Other Participating Researchers: R. D. Koster (GMAO, NASA/Goddard Space Flight Center), S. P. P. Mahanama (GMAO, NASA/Goddard Space Flight Center), T. J. Yamada (GMAO, NASA/Goddard Space Flight Center), Gianpaolo Balsamo (ECMWF), A. A. Berg (Dept. of Geography, University of Guelph, Guelph, Canada), M. Boisserie (FSU/Center for Ocean-Atmospheric Prediction Studies, Tallahassee, FL), P. A. Dirmeyer (Center for Ocean-Land-Atmosphere Studies, Calverton, MD), F. J. Doblas-Reyes (ICREA Research Professor at the Institut Català de Ciències del Clima, Barcelona, Spain), G. Drewitt (Dept. of Geography, University of Guelph, Guelph, Canada), Z. Guo (Center for Ocean-Land-Atmosphere Studies, Calverton, MD), J.-H. Jeong (Dept. of Earth Sciences, Univ. Gothenburg, Gothenburg, Sweden), W.-S. Lee (CCCMA, Environment Canada, Victoria, Canada), Z. Li (GMAO, NASA/Goddard Space Flight Center), L. Luo (Dept. of Geography, Michigan State Univ., East Lansing, MI), W. J. Merryfield (Princeton University), S. I. Seneviratne (Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland), T. Stanelle (Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland), B. J. J. M. van den Hurk (KNMI, De Bilt, The Netherlands), and F. Vitart (ECMWF, Reading, United Kingdom)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

NOAA Goals: Weather & Water Goal: Serve Society’s Needs for Weather and Water Information

Objectives: To understand influence of accurate soil moisture initialization on the seasonal forecast skills in multi-model ensemble

Methods and Results/Accomplishments:

Numerical weather forecasts rely on atmospheric initialization, essential for forecast skill at leads of up to about ten days. Forecasts at longer leads, however, must take advantage of slower variables of the climate system. While sea surface temperature (SST) is typically the most important, among the slow variables, the timescales of soil moisture memory are also long, 1 or 2 months (Vinnikov and Yeserkepova 1991; Entin et al. 2000). For the prediction of summer midlatitude precipitation over continents at subseasonal and longer leads, soil moisture initialization may be important.

GLACE-2 is an international model intercomparison experiment that provides a multi-model, comprehensive view of the impact of land state initialization — in particular soil moisture initialization — on forecast skill. GLACE-2 aims to learn, probably for the first time ever, the quantitative benefits that can stem from the incorporation of realistic land surface state initialization into their forecast algorithms. The list of project's participants currently includes CCCma (Canada), NASA/GSFC (USA), COLA (USA), Princeton University (USA), IACS (Switzerland), KNMI (Netherlands), ECMWF (UK), GFDL (USA), University of Gothenburg (Sweden), CCSR/NIES/FRCGC (Japan), FSU/COAPS (USA).

The impact of soil moisture on near-surface air temperature is straightforward: higher soil moisture can induce higher evaporation and thus greater evaporative cooling of the surface and the overlying air. The impact of soil moisture on precipitation is more complex. If higher soil moisture induces higher
evaporation, the correspondingly lower sensible heat flux can lead to shallower boundary layers and thus an easier build-up of the conditions that trigger convective rainfall. However, under certain conditions, higher evaporation rates may have the opposite effect – they may act to inhibit precipitation (Findell and Eltahir, 2003; Cook et al., 2006).

Figure 1 shows the contribution of land initialization to the consensus forecast skill compared to the observed anomalies. The salient result from this figure is that on the global scale, precipitation forecast skill is close to zero everywhere, and air temperature skill is limited to North America, eastern Australia, and parts of Europe. Note that Figure 1 shows a measure of consensus behavior of an ensemble of models. The skill levels of participating models vary greatly, and models that appear to do well for one field at one location may do poorly for another field or another location.

The investigation of potential predictability — that is, the upper limit of skill that can be achieved given the nature of the processes and the current structure of the models — revealed that for precipitation it is not great, even for small lead times. The consensus potential predictability for temperature is much larger. Even so, hope for skillful consensus air temperature forecasts are highly limited in many parts of the world (e.g., Asia and Europe after Day 30).

This skill is limited to areas for which the underlying observational precipitation network provides adequate coverage and thus trustworthy initialization. There is a strong impact of both underlying model predictability and gauge density on the ability to extract true skill from the experiments. As expected, skill appears only where the background predictability is sufficiently large. For the most part, skill also appears only for higher values of gauge density – the study suggests that a density of about 10 gauges per 2x2.5 degree cell is needed to produce the larger values of skill in the forecasts. The results for the 30-day lead (Days 31-45) in particular show a clear impact of gauge density on skill, though a similar impact is also seen for the 15-day lead results.

One benefit of the GLACE-2 experiment is the identification of areas for which enhanced soil moisture measurement may prove especially fruitful, according to the consensus of model behavior. Perhaps the most important role of the experiment, however, is to provide an objective means by which any forecasting group can evaluate, for its own model in isolation, the practical benefit of realistic land initialization. Because the GLACE-2 forecasts are compared to actual observations, the consensus skill levels presented here should be interpreted as “lower bounds” for what could be achieved using better modeling systems and more complete measurement networks.
Figure 1. Consensus precipitation and air temperature forecast skill as a function of lead, considering all 15-day forecast periods during JJA. Dots are shown where the plotted results are statistically different from zero at the 98% confidence level; white areas lack available validation data.

References:

Publications:
**Progress Report Title:** Assessing the Decadal Variability and Predictability of Climate in the GFDL Coupled Models

**Principal Investigator:** Rym Msadek (Princeton Postdoctoral Research Associate)

**CICS/GFDL Collaborator:** Tom Delworth (GFDL), Tony Rosati (GFDL), Keith Dixon (GFDL)

**Task II:** Cooperative Research Projects and Education

**NOAA Sponsor:** Brian Gross (GFDL)

**Theme:** Earth System Model Applications

**NOAA Goals:**

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

**Objectives:** The objective of my work is to identify and better understand the potential predictability of climate on decadal time scales and to determine the oceanic processes that provide some predictability skills.

**Methods and Results/Accomplishments:**

The decadal predictability of climate has been investigated in the GFDL CM2.1 coupled model using the perfect model approach, which gives the upper limit of the potential predictability. The Atlantic Meridional Overturning Circulation (AMOC) is thought to be one driver of the decadal variability and it is thus a good candidate to be potentially predictable. Thus I first focused on the potential predictability of the AMOC and I showed that the AMOC and its fingerprints are potentially predictable on decadal time scales. Beyond the AMOC, I investigated the regions and the oceanic variables of highest potential predictability. It was found that the extratropics were more predictable than the tropics and that sea surface salinity and vertically integrated quantities like ocean heat content and freshwater content were more predictable than sea surface temperature, which is damped by atmospheric heat fluxes. Little predictability was found over land.

Assessing the potential predictability of climate relies on the understanding of the processes governing decadal variability. I have analyzed the AMOC decadal variability in different GFDL coupled models that differ by the atmospheric and oceanic resolution and by the parameterization of non resolved processes. Preliminary results suggest that decadal prediction skills will critically depend on model formulation. In collaboration with observational oceanographers at PMEL (Dongxiao Zhang and Mike McPhaden) and University of Miami (Bill Johns) I have compared the AMOC variability in the CM2.1 GFDL coupled model with the available observations. Like in observations, the North Brazil Current was identified to be a potential fingerprint of the AMOC. Using control simulations of the GFDL and NCAR coupled models, I have compared the AMOC seasonal cycle and the relationship between the AMOC and the Atlantic meridional heat transport with the RAPID-array data. The discrepancies with observations highlight the origin of some model biases, which should help improve them in the future.

**Publications:**


**Progress Report Title:** Offsetting and Complimentary Characteristics of Sulfate and Soot Direct Radiative Forcings

**Principal Investigator:** Ilissa Ocko (Princeton Graduate Student)

**CICS/GFDL Collaborator:** V. Ramaswamy (GFDL)

**Other Participating Researchers:** Paul Ginoux and Larry Horowitz (GFDL)

**Task II:** Cooperative Research Projects and Education

**NOAA Sponsor:** Brian Gross (GFDL)

**Theme:** Earth System Model Applications

**NOAA Goals:**

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

**Objectives:** To study the radiative forcing of aerosols in the context of a successful climate model

**Methods and Results/Accomplishments:**

This study investigates the competing and complementary features of the anthropogenic sulfate and soot direct radiative forcings in the context of the GFDL global climate model CM2.1, which has yielded a reasonable representation of aerosol concentrations and the evolution of the 20th century global-mean surface temperature. Considering the preindustrial to present-day simulated concentrations, we focus on the factors governing the offset posed by the sulfate and soot aerosols on the global-mean and spatial aerosol radiative forcings at the top-of-atmosphere (TOA) and surface.

The simulated sulfate and black carbon all-sky top-of-atmosphere global-mean direct radiative forcings offset one another (+0.87 W/m² black carbon; -0.96 W/m² sulfate), and this offset (-0.09 W/m²) is consistent with the -0.06 W/m² offset reported in the IPCC AR4. The surface forcings, on the other hand, are additive, and the combined soot and sulfate effect yields a value of -2.12 W/m², which has strong potential implications for the hydrological cycle. The quantitative roles of the main physical factors that determine the offsetting effects at the TOA are examined; specifically cloud coverage, surface albedo and relative humidity. Cloud distributions and high relative humidity effects are critical in arriving at the top-of-atmosphere offset.

Accomplishments include presenting this work at the Annual AMS Conference in Seattle, WA, where I won the Outstanding Student Poster Presentation Award. I am currently working on a paper to be submitted to JGR in the near-future.
Progress Report Title: Superrotation and Tropical Variability in Dry Atmospheres

Principal Investigator: Samuel F. Potter (Princeton Graduate Student)

CICS/GFDL Collaborator: Geoff Vallis (Princeton)

Other Participating Researchers: Thomas Spengler (Postdoctoral Research Associate, Princeton)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

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

Objectives: To improve the theory of the general circulation of the atmosphere, in an attempt to understand why and how the Earth's climate has changed and will change

Methods and Results/Accomplishments:
I have been studying the general circulation of the atmosphere using highly idealized models. In one line of my research I have been studying how an Earth-like dynamical core can transition to superrotation, wherein the winds at the equator move faster than the planet beneath them. Superrotation is interesting in that it is a signature of strong tropical variability, a poorly understood phenomenon. I have learned that GFDL's dry atmospheric dynamical core with zonally symmetric forcing only strongly superrotates only at high Rossby number, a parameter regime found on planetary atmospheres (Venus, Titan) but not on Earth (Mitchell and Vallis 2010). This seems to signify that moisture processes are a key component to recreating the potentially strong tropical variability of future hot climates (Caballero and Huber 2010).

In my other line of research I have been studying the applicability of the WKB approximation to wave propagation in highly idealized models of the atmosphere. The WKB approximation has proved useful for understanding the propagation of Rossby waves and teleconnection patterns (Hoskins and Karoly 1981). I have found that the WKB approximation does fail in surprising ways, but that it does hold up very well in applications to Earth-like atmospheric winds. In addition I have derived analytic forms for the reflection coefficient for idealized wind profiles. This work is currently being put into a manuscript for submission to a refereed journal in the upcoming months.

References:
Caballero and Huber, 2010: Spontaneous transition to superrotation in warm climates simulated by CAM3. GRL, 37.
Progress Report Title: El Nino, Radiation & Precipitation: Global and Regional Analysis

Principal Investigator: Claire Radley (Princeton Graduate Student)

CICS/GFDL Collaborator: Leo Donner (GFDL)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

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

Objectives: Compare the GFDL atmospheric models to observations during El Nino events over the 1981-2000 time period

Methods and Results/Accomplishments:
The model globally averaged top of atmosphere longwave and shortwave fluxes have smaller variability than what we see from satellite observations. This is true for both of GFDL’s atmospheric models – AM2 and AM3. When we look at the regional patterns however, we see that both AM2 and AM3 have larger variability than observations, and the small global variability is due to cancellation between various regions.

The convective parametrization in AM3 is significantly different to that in AM2 and through comparisons with satellites we see that it does a better job of capturing both the middle and high clouds. The high clouds do however appear to have too much ice water content in AM3. The low clouds in AM3 seem to be overly sensitive to perturbations in sea surface temperature, and it appears that this is due to a larger erosion coefficient.
**Progress Report Title:** Estimate of Anthropogenic Carbon Inventory Changes between the WOCE and CLIVAR Decades

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

**CICS/GFDL Collaborator:** Robert Key (Princeton)

**Other Participating Researchers:** Yves Plancherel (Princeton), Andrew Jacobson (University of Colorado)

**Task III:** Individual Projects

**NOAA Sponsor:** Joel Levy (Ocean Climate Observation Program)

**Theme:** Earth System Model Applications

**NOAA Goals:**

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

**Objectives:** How did the ocean interior inventory of anthropogenic carbon change between the WOCE (1990s) and CLIVAR (2000s) decades? In answering this question, it will be critical to develop new methods that can identify changes in ocean carbon with uncertainty of order 15% of expected uptake with this corresponding to the target precision for Repeat Hydrography specified in the LSCOP report of Bender et al. (2002). There are two principal challenges to achieving this objective. The first is to develop satisfactory empirical methods for estimating changes along Repeat Hydrography lines. Methods for identifying such changes have been developed over the last two decades, beginning with the multiple linear regression (MLR) method of Wallace (1995) and with a more sophisticated extended MLR (eMLR) method developed by Friis et al. (2005). The second challenge involves the extrapolation of estimates of the increase in anthropogenic carbon from repeat sections to get basin-scale inventories. To date, it has commonly been assumed that a coordinated WOCE-to-CLIVAR estimate of global changes in ocean carbon would proceed in two stages, with this second challenge being addressed only after changes in anthropogenic carbon have been evaluated section-by-section over the global ocean.

**Methods and Results/Accomplishments:**

Work in this direction is currently underway in collaboration with Yves Plancherel, a PhD student at Princeton, and Robert Key at Princeton. This work has as its goal to develop a method that simultaneously accomplishes both of the objectives listed above. In its first stage, this is being pursued with hindcast simulations of ocean carbon uptake using GFDL’s MOM4-TOPAZ model. This observing system simulation experiment (OSSE) has as its goal the development of a framework that can subsequently be applied to the WOCE and CLIVAR measurements to arrive at a global ocean carbon inventory changes between the WOCE and CLIVAR decades.

Preliminary efforts with the OSSE have focused on the North Atlantic. Here the ocean model has been sampled precisely at the WOCE and CLIVAR station locations for its monthly mean tracer fields in July 1995 and July 2005, and the eMLR calculation has been applied independently on depth levels in the model. We refer to this approach as horizontal eMLR, or HeMLR. Once calculated for each depth level, the resulting estimates of decadal changes in anthropogenic carbon at each depth have been vertically to arrive at inventories for each station location, and then extrapolated from the station locations to the basin scale. Through a comparison with the explicitly resolved anthropogenic carbon tracer in the model, this preliminary effort reveals an estimate that is within the 15% uncertainty threshold specified by the LSCOP report.
References:

Publications:
**Progress Report Title:** Seasonality in CO₂ Fluxes with Earth System Model

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

**CICS/GFDL Collaborator:** John Dunne (GFDL)

**Other Participating Researchers:** Anand Gnanadesikan (Johns Hopkins), Y. Plancherel (Princeton), K. Lindsay (NCAR), S. Peacock (NCAR), M. Jochum (NCAR)

**Task III:** Individual Projects

**NOAA Sponsor:** Joel Levy (Ocean Climate Observation Program)

**Theme:** Earth System Model Applications

**NOAA Goals:**

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

**Objectives:** One of the important issues being addressed through the ongoing IPCC AR5 effort is to understand how the ocean carbon cycle may respond under future climate change. This was addressed in the model intercomparison study of Friedlingstein et al. (2006). There the amplitude of climate feedbacks was addressed quantitatively for a suite of concentration scenarios with coupled climate/carbon models. Although the study of Friedlingstein et al. (2006) pointed to the potential importance of ocean feedbacks, it was largely descriptive, and did not explore the implications of future carbon cycle changes on monitoring and detection studies.

**Methods and Results/Accomplishments:**

We are currently evaluating a set of six state-of-the-art coupled climate models from a variety of modeling centers in North America, Europe, and Japan to evaluate both the mechanisms driving future changes to the ocean carbon cycle and the implications to the future extension of the current observing system. Each of the models has been initialized with a pre-anthropogenic climate state in 1860, and then run through a scenario with increasing atmospheric CO₂ concentrations through the year 2100. Our analysis has begun with a consideration of climatologies (monthly mean structure of an average seasonal cycle) over the years 1990-1999 and 2090-2099.

The main result to date is that there are dramatic increases in the seasonal cycle of air-sea CO₂ fluxes over the extratropics of both hemispheres, with these changes being especially pronounced in mode water formation regions. The increase in the seasonal cycle of pCO₂ between the pre-industrial state and the climate state in 2090-2099 is approximately a factor of two, and this occurs despite only modest changes in the amplitude of seasonal variations in both DIC and SST. The changes are consistent across the models, with a trend towards increased uptake over the extratropics in winter, but only modest or even slightly negative increases occurring over summer. Our analysis indicates that the underlying mechanism is the nonlinear effect of changes in DIC concentrations on the solubility of CO₂ in the ocean. In other words, increased annual mean DIC concentrations in the surface ocean, in the absence of changes in the amplitude of the seasonal cycle of DIC concentrations, can be expected to drive changes in the amplitude of pCO₂ in the surface ocean.

**References:**

Publications:

**Progress Report Title:** Projecting the Response of an Endangered Marine Vertebrate to Climate Change: The Eastern Pacific Leatherback Turtle Population Model

**Principal Investigator:** Vincent Saba (Princeton Associate Research Scholar)

**CICS/GFDL Collaborator:** Charles Stock (GFDL)

**Other Participating Researchers:** James Spotila and Maria Santidrián-Tomillo (Drexel University)

**Task II:** Cooperative Research Projects and Education

**NOAA Sponsor:** Brian Gross (GFDL)

**Theme:** Earth System Model Applications

**NOAA Goals:**
- **Ecosystem Goal:** Protect, Restore, and Manage the Use of Coastal and Ocean Resources through Ecosystem Approach to Management (25%)
- **Climate Goal:** Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond (75%)

**Objectives:** The main objective of this research is to reconcile the impacts of climate change in the terrestrial (nesting beach) versus the oceanic habitats of endangered eastern Pacific leatherback turtles (*Dermochelys coriacea*).

**Methods and Results/Accomplishments:**

The impacts of anthropogenic induced climate change on ecosystems and biodiversity is one of the key topics for the upcoming fifth assessment report from the Intergovernmental Panel on Climate Change (IPCC). Sea turtles are excellent candidates for this assessment because their response to climate change can be driven by both terrestrial and oceanic dynamics. The nesting population of eastern Pacific leatherbacks at Playa Grande, Costa Rica has been extensively studied in terms of its sensitivity to present-day climate variability in the ocean and beach. Therefore, these turtles are an ideal species for a climate change impacts study. Fisheries and historic egg poaching have rendered this population critically endangered yet even if these threats are reduced or eliminated; the population still faces the challenge of recovery in a rapidly changing climate.

We used IPCC-class climate models from the CMIP3 database to force a nesting population model based on empirical climate sensitivity data. We designed a population model that estimates nesting recruitment and remigration as a function of mature female foraging success determined by El Niño Southern Oscillation (ENSO) variability (Saba et al. 2007) and nest success/hatchling sex ratios determined by air temperature and precipitation (Santidrián-Tomillo et al., in review; Sieg et al., in review). In the eastern equatorial Pacific, the projected relationship between sea surface temperature and net primary productivity from 2000-2100 was established using GFDL’s ESM 2.1. Monthly precipitation/air temperature data and sea surface temperature data were extracted from 14 IPCC climate models from 1975-2100 such that the period from 2000-2100 represented the projected CO2 trends under the IPCC A2 scenario. All modeled data was bias-corrected based on empirical data from 1975-1999. We assumed no significant effect of sea level rise on the nesting beach, eliminated fisheries mortality, and only considered models that resolved the empirical relationship between ENSO, precipitation, and air temperature. This resulted in the use of 7 models. Considering the mean projection from these 7 climate models, the nesting population remains stable until the decade beginning in 2030 when the population begins to decline (Figure 1). By the year 2100, the nesting population is reduced by 75%. Although the
beach is projected to become warmer and dryer, the primary driver of the decline was increasing air temperature (Figure 1) that reduced hatching success and emergence rate. Hatchling sex ratios became increasingly female-biased due to the warmer, dryer conditions but never reached 100% female over a decadal time period. Changes in ENSO variability from 1975 to 2100 had a minimal effect on the population trend when compared to the effect of beach conditions (Figure 1). Therefore, decreased neonate recruitment was due to warmer, dryer conditions in Costa Rica and thus caused the nesting population to decline by 2100. This suggests that sea turtle populations in a changing climate may be more sensitive to nesting beach conditions than to oceanic conditions. Finally, we projected the population trend assuming that a climate-controlled hatchery program begins in 2001 and thus maintaining present-day hatching success/emergence rates and sex ratios. These projections resulted in no decline and stabilized the population (Figure 1). If a significant warming and drying over multiple decades becomes evident at eastern Pacific leatherback nesting beaches, climate controlled hatchery programs may be able to offset the negative impacts of rapid climate change.

References:

Publications:
Figure 1. Projected response of the leatherback nesting population at Playa Grande, Costa Rica under various climate scenarios. Projections are a 10-year moving average using seven CMIP3 models.
**Progress Report Title:** Combining Atmospheric Observations, Land and Ocean Models to Understand the Global Carbon Cycle

**Principal Investigator:** Jorge L. Sarmiento (Princeton Professor of Geosciences)

**Other Participating Researchers:** Ni Golaz (Princeton) and Keith Rodgers (Princeton)

**Task III:** Individual Projects

**NOAA Sponsor:** James Butler (ESRL)

**Theme:** Earth System Model Applications

**NOAA Goals:**

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

**Objectives:** The goal of this project was to study the adaptation and acclimation within ecosystems, which may affect the future of carbon sources and sinks in response to climate change by accounting correctly for the varied spatiotemporal scales of carbon processes in the Dynamic Vegetation Model LM3V, jointly developed at GFDL and Princeton University (Shevliakova et al. 2009). To increase the efficiency of the parameter optimization process, we continued our effort to develop an automated system to fit parameters in this land model to forest inventory (FIA) data using formal, quantitative methods. The improved fit of the optimized model to data provides better estimates of terrestrial carbon stocks and fluxes, including a more credible estimate of the land sink. The capacity to simultaneously fit many model parameters opens the door to future work of developing a more biodiversity-rich vegetation model in order to quantify the impact of biodiversity on feedbacks between the terrestrial biosphere and the Earth's climate system. Other work is underway to study the Nonlinear Rectification with the terrestrial carbon cycle and variability on daily to interannual timescales

**Methods and Results/Accomplishments:**

During our earlier studies, we developed a semi-automated system to perform sensitivity analysis within GFDL's FMS system, which is independent of the model code itself and therefore can be used for different models and different versions. As a continuation of the above work and as a participant in the NACP site synthesis project, we further developed a system to process all the input data from 54 NACP sites which have different observation periods, different time frequencies, different variable names etc. to be LM3V ready, so LM3V can directly read-in each location and be run at all the sites simultaneously. The development of this system paves the way for the optimization efforts using the FIA data.

Working closely with Jeremy Lichstein, we configured the LM3V model to mirror as closely as possible the conditions on the selected FIA plots and the model was forced by the historical weather-reanalysis product (Sheffield 2006) extracted for each site. Landuse disturbance were excluded from the model, because large disturbances are unlikely to have occurred on FIA plots during the time that their stand age accrued. We implemented four regional simulations (in the eastern U.S.) for comparison with FIA data on above ground biomass (AGB), growth, and mortality rate. The optimization converged after six Gauss-Newton iterations, requiring a total of 48 model runs for each of the 20 optimization grid-cells. The regional LM3V runs with optimized parameter values yielded geographic temperature and precipitation sensitivities that were similar to those observed in FIA data. Optimization reduced the mean squared error (MSE) for both AGB and growth by roughly a factor of two compared to the baseline run. However, the model appeared too sensitive to soil water-holding capacity (SWC).

The main outcome of these studies is that they have provided a unique knowledge base for future carbon data assimilation projects and built a framework for combining a multitude of constraints for the
dynamic land model with observed data sets. The long-term goal is to improve global ecosystem models using a variety of data sources. Expanding the work to include other regions, PFTs, and data sources (such as eddy flux data) will require additional efforts but the methodology is in place. Another goal for future work is to replace the current constant mortality rate in LM3V with a wind, ice, and drought-dependent mortality parameterization. This automated optimization system can hopefully help us to achieve the goal of improving the models, and allow us to improve our understandings of the processes governing the exchanges of the CO2 between land and atmosphere.

To better understand the dynamical controls on exchange of carbon between the atmosphere and the terrestrial biosphere, we tested the hypothesis that the nonlinearities in the terrestrial response are sufficiently large that the “mean state” framework, where the mean state for the physical state variables for the atmosphere and the state of terrestrial ecosystems are characterized by a stationary time-mean state, no longer applies. Perturbations from the physical state (for example ENSO or NAO, Rodgers et al. 2004) drive perturbations from the mean state in terrestrial carbon fluxes. Two model runs were performed over a period corresponding to 1977-1996, with the only difference lying in the atmospheric forcing fields used for the terrestrial ecosystem model. The control run used the full 3-hour forcing fields (Sheffield et al. 2006) over the 20-year period. For the second run, the forcing fields were filtered/smoothed to create a seasonally varying climatology that preserves the diurnal cycle but neither the synoptic storm timescales of variability (1-8 days), nor the timescales of interannual variability (year-to-year). The preliminary sensitivity study shows that growing conditions are favorable in the absence of droughts or extreme events and the land retains less carbon in the presence of the full real-world variations. However, it is not clear from this sensitivity study alone the extent to which this is due to nonlinearities that manifest themselves on the timescale of synoptic scale storms (1-8 days) or on interannual timescales. Our next goal is to provide a quantitative estimate of the relative contributions from synoptic storms which will hopefully be achieved through the use of a “weather generator” (Ivanov et al., 2007) to simulate a climate that includes storminess but doesn’t exhibit interannual variability.

References:


Papers in preparation:


**Progress Report Title:** Improving Understanding of the Terrestrial Carbon Cycle Dynamics

**Principal Investigator:** Elena Shevliakova (Princeton Associate Research Scholar)

**CICS/GFDL Collaborator:** Sergey Malyshev, Steve Pacala, Sonja Keel, Lars Hedin and Brian Magi (Princeton), Ron Stouffer, Lori T. Sentman, and John P. Dunne (GFDL)

**Other Participating Researchers:** P.C.D. Milly (USGS)

**Task II:** Cooperative Research Projects and Education

**NOAA Sponsor:** Brian Gross (GFDL)

**Theme:** Earth System Model Applications

**NOAA Goals:**

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

**Objectives:** Development and application of Earth System models to improve understanding of terrestrial biogeochemical cycling and its role in climate

**Methods and Results/Accomplishments:**

As a part the Fifth Intergovernmental Panel on Climate Change (IPCC) Assessment Report (AR5), the NOAA GFDL has conducted a suite of new climate simulations. Four GFDL models have a new land component, LM3, which includes vegetation dynamics and carbon cycling modules originally developed for the LM3V model (Shevliakova et. al. 2010) and the new hydrology and soil physics modules (Milly et al., in prep). The manuscript describing the new physical climate model CM3 is accepted for publication (Donner et al., 2011.) Evaluation of the AR5 Earth System Model (ESM2G and ESM2M) simulations was my research focus in 2010 (Dunne et al., in prep). Our ESMs are among few models in AR5 capable to simulate both vegetation dynamics and the full set of land-use scenarios including wood harvesting. The new simulations demonstrate significant role of terrestrial biosphere and land-use processes in the climate system (Shevliakova et al. in prep)

In addition, I have collaborated with other scientists on the following projects and contributed to joint projects: development and evaluation of the coupled carbon–nitrogen land model LM3-N (Gerber et al, 2010, Gerber et al. in prep); “optimal” timing for initialization of land-use scenarios in the GFDL ESMs (Sentman et al, in review); analysis of future land-use scenarios for ESMs (Hurtt et al, submitted); development of the new seasonal fire model (Magi et al, in prep.); improvements of the LM3 land model using the US Forest service inventory data (Lichtein, et al. in prep); and the organization of the First Meeting of Integrated Network for Terrestrial Ecosystem Research on Feedbacks to the Atmosphere and Climate (INTERFACE).

In the fall of 2010, I developed and co-taught EEB course 533A (Earth System Modeling). In this course 10 Princeton University graduate students gained hands-on experience with the NOAA/GFDL models and learned how to conduct simulations with the GFDL land model LM3. In addition, 5-7 EEB postdocs regularly attended the lectures and participated in the class discussions. During the summer of 2010 I have prepared and submitted three proposals to different US funding agencies. One of the proposals (to NSF-USDA-DOE) was recommended for funding (Total $900,000K over 3 years, PI Pacala) “Understanding Coupling between Biogeochemical Cycling and Climate Change in Northern Ecosystems: Historical Analysis and future projections with the GFDL Earth System Model.”
Publications:


Progress Report Title: Regional Climate Studies Using the Weather Research and Forecasting Model

Principal Investigator: James A. Smith (Princeton Professor, Civil and Environmental Engineering)

CICS/GFDL Collaborator: Leo Donner (GFDL), Tim Marchok (GFDL), Gabe Vecch (GFDL), Tom Knutson (GFDL), Ming Zhao (GFDL) and Paul Ginoux (GFDL)

Other Participating Researchers: June Yeung, Yan Zhang, Dan Wright, Ning Lin, Gabriele Villarini, Mary Lynn Baeck (Princeton)

Task III: Individual Projects

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

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

Objectives: The objectives of this project are: 1) to characterize the regional precipitation and flood climatologies of the US through combined modeling and observational studies and 2) to assess the error structure of regional climate model simulations using the Weather Research and Forecasting (WRF) model. Analyses focus on urban impacts on precipitation, landfalling tropical cyclones, orographic precipitation mechanisms, and heavy rainfall from mesoscale convective systems.

Methods and Results/Accomplishments:
Analyses of long-term trends in heavy rainfall and flooding have been examined for the US (Smith et al. 2010 and 2011b, Villarini and Smith 2010, Villarini et al. 2011b, 2011f) and Europe (Villarini et al. 2011a, 2011e, 2011g). Analyses in the US center on long stream gaging records from the US Geological Survey. Analyses of non-stationarities in flood peaks suggest that "change points", i.e. abrupt changes in flood frequency, are common, but that slowly varying trends are not. Change points can be attributed in many cases to river regulation or major changes in land use (urbanization and changing agricultural practices). Key elements of heavy rainfall and flood hydroclimatology studies are: i) "mixtures" of flood peak distributions (with a focus on landfalling tropical cyclones for the eastern US), ii) upper tail properties of flood peaks, iii) scaling properties of flood peaks, iv) spatial heterogeneities of flood peak distributions and v) temporal non-stationarities of annual flood peaks.

Analyses have also been completed concerning counts of tropical cyclones in the Atlantic basin (Villarini et al. 2010, Villarini et al. 2011c, 2011d). We analyze and model time series of annual counts of tropical cyclones in the North Atlantic basin using a Poisson regression model (Villarini et al. 2010) with tropical Atlantic Sea Surface Temperature (SST), tropical SST, the North Atlantic Oscillation (NAO), and the Southern Oscillation Index (SOI) as covariates. We develop a parsimonious family of models using as covariates Atlantic and tropical SSTs. The impact of increased greenhouse gases on the frequency of tropical storms in the North Atlantic basin is examined using the statistical model with climate model fields as covariates. We show in Villarini et al. [2010b] how the disagreement among climate modeling studies can be largely explained by the large scale sea surface temperature (SST) patterns from the different climate models used as well as by the different control and perturbation periods used in the various studies. Our results do not support the notion of large changes in tropical storm activity in the North Atlantic basin over the 21st century (Villarini et al. 2011c). We also examine
the role of "shorties", i.e. tropical cyclones lasting less than 48 hours, for apparent trends in tropical cyclone frequency (Villarini et al 2011d). Results suggest that the trends in shorties are consistent with changing sampling properties of tropical cyclones, as opposed to climate trends.

Simulations of heavy rainfall from Hurricane Isabel (2003) using WRF have been used to examine distribution of heavy rainfall from landfalling tropical cyclones (Lin et al., 2010a). The analyses focus on storm evolution following landfall and center on simulations using the Weather Research and Forecasting (WRF) model. Hurricane track and intensity during and after landfall are well predicted in the WRF model, although storm motion of the simulated storms is slower than the observed storm after landfall. Initial conditions have significant effects on the storm development and thus on the associated hazards. Broad features of the rainfall distribution associated with storm track and orographic amplification in the central Appalachians are well represented in the model simulations. GFDL-initialized simulations produce the best simulations of rainfall in this case, compared with the Hydro-NEXRAD rainfall fields derived from the regional WSR-88D network. The radial distribution in rainfall relative to the center of the circulation is not, however, well represented in model simulations. The model simulation captures the azimuthal distribution relatively well. In Lin et al. [2010b] we apply a model-based risk assessment methodology to investigate hurricane storm surge climatology for New York City (NYC). We couple a statistical/deterministic hurricane model with the hydrodynamic model SLOSH (Sea, Lake, and Overland Surges from Hurricanes) to generate a large number of synthetic surge events. Empirical and numerical modeling analyses of heavy rainfall and flooding from landfalling tropical cyclones have been expanded in the previous year, focusing on major flood events during 2004 (Villarini et al. 2011h). These analyses build on the Lagrangian approaches adopted in Lin et al. [2011a]).

Urbanization and heavy rainfall were examined for the New York - New Jersey metropolitan region using WRF simulations for 5 warm seasons and rainfall fields from the Hydro-NEXRAD system (Yeung et al. 2011). Regional climate model simulations are characterized by an overall wet bias in the rainfall fields, with the largest bias in the high-elevation regions of the model domain. Model simulations do not capture spatial gradients in radar rainfall fields around the New York metropolitan region or and land-water boundaries to the east. We show that model simulations do capture broad features of the interannual, seasonal and diurnal variation of rainfall. The model climatology of convective available potential energy (CAPE) is used to interpret the regional distribution of warm season rainfall and the seasonal and diurnal variability of rainfall. We use hydrologic and meteorological observations from July 2007 to illustrate the interactions of land surface processes and regional rainfall. Urban rainfall in Numerical modeling studies of heavy rainfall in the Beijing metropolitan region (Zhang et al. 2011) highlight the role of urban canopy effects in altering the regional climatology of heavy rainfall. We have initiated climatological analyses of urban modification of rainfall in Baltimore (Smith et al. 2011c) and Atlanta (Wright et al. 2011).

The climatology of catastrophic rainfall in the central Appalachian region has been examined through empirical and numerical modeling studies (Smith et al. 2011a). The central Appalachian region has experienced some of the largest rainfall accumulations in the world at time intervals less than 6 hours, including the 18 July 1942 Smethport, Pennsylvania storm which produced 780 mm in less than 5 hours. Catastrophic flooding along the western margin of the central Appalachians is dominated by four storms that occurred on 18-19 July (1889, 1942, 1977 and 1996), which were associated with strong warm season extratropical systems and were characterized by rapidly moving storm elements in complex terrain. The tight concentration of catastrophic flooding along the western margin of the central Appalachians around 18-19 July is linked to the climatology of extratropical cyclones and reflected in the seasonal climatology of cloud-to-ground lightning. Along the eastern margin and interior of the central Appalachians, catastrophic flooding is linked to four “terrain-locked” orographic convective systems that occurred 17-18 June 1949, 18-19 August 1969, 27 June 1995 and 11 August 2003. Model simulations of the “Hack and Goodlett” storm (June 1949) and “Rapidan Storm” (June 1995) capture broad features of the heavy rainfall distribution for the events, but not the extreme rainfall rates associated with terrain-locked convection. Analyses suggest that the frequency of catastrophic flooding varies substantially over the central Appalachian region and that small-scale variation may be linked to the role of complex terrain
in altering thunderstorm dynamics. Simulations of the July 1942 (using North American reanalysis fields) and June 1949 storms provide new insights to storms responsible for extreme flooding and debris flow events in the eastern US.

**Publications:**


Progress Report Title: Understanding Climate Sensitivity in the Presence of Uncertainty and Natural Variability

Principal Investigator: Geoffrey Vallis (Princeton Professor)

CICS/GFDL Collaborator: Isaac Held, Mike Winton, Steve Griffies (GFDL)

Other Participating Researchers: K. Shafer Smith (NYU)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

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

Objectives: The PI has been engaged in a variety of topics in climate dynamics and atmospheric and oceanic dynamics. Here we describe one research topic that is central to our efforts to understand anthropogenic global warming. Our goal is to understand the impact of uncertainty and natural variability on estimates of transient climate sensitivity (TCS) of the globally averaged surface temperature, including both uncertainty in past forcing and internal variability in the climate record. We provide a range of probabilistic estimates of the TCS that combine these two sources of uncertainty for various underlying assumptions about the nature of the uncertainty. We also provide estimates of how quickly the uncertainty in the TCS may be expected to diminish in the future as additional observations become available.

Methods and Results/Accomplishments:
We make these estimates using a nonlinear Kalman filter coupled to a stochastic, global energy balance model, using the filter and observations to constrain the model parameters. We verify that model and filter are able to emulate the evolution of a comprehensive, state-of-the-art atmosphere-ocean general circulation model and to accurately predict the TCS of the model, and then apply the methodology to observed temperature and forcing records of the 20th century.

For uncertainty assumptions best supported by global surface temperature data up to the present time, we find a most-likely present-day estimate of the transient climate sensitivity to be 1.6 K with 90% confidence the response will fall between 1.3-2.6 K, and we estimate that this interval may be 45% smaller by the year 2030. We calculate that emissions levels equivalent to forcing of less than 475 ppmv carbon dioxide concentration are needed to ensure that the transient temperature response will not exceed 2 K with 95% confidence. This is an assessment for the short-to-medium term and not a recommendation for long-term stabilization forcing; the equilibrium temperature response to this level of CO2 may be much greater. The flat temperature trend of the last decade has a detectable but small influence on TCS. We describe how the results vary if different uncertainty assumptions are made, and we show they are robust to variations in the initial prior probability assumptions.

Publications:


Progress Report Title: Improved Hurricane Risk Assessment with Links to Earth System Models

Principal Investigator: Erik Vanmarcke (Professor of Civil and Environmental Engineering, Princeton)

CICS/GFDL Collaborator: Tim Marchok (GFDL)

Other Participating Researchers: Ning Lin (Princeton), Siu-Chung Yau (Princeton)

Task III: Individual Projects

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

NOAA Goals:
Climate Goal: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond (50%)
Weather & Water Goal: Serve Society’s Needs for Weather and Water Information (50%)

Objectives: This project aims to improve existing hurricane risk assessment methodology by constructing a stochastic framework within which the main components of hurricane damage and loss prediction are consistently modeled, their sensitivity to various climate change scenarios made more readily quantifiable and their contribution to the overall uncertainty in near-future loss predictions made more evident.

Methods and Results/Accomplishments:
The model comprises (1) a hurricane event module, which predicts hurricane landfall probability; (2) a hazard environment module, which describes a multiplicity of hazards associated with landfalling hurricanes (e.g., Lin et al, 2010b); and (3) a structural vulnerability module, which estimates the hurricane damage, initially only due to wind, to residential neighborhoods (Lin, Vanmarcke and Yau, 2010c, d, e).

In the first module, the hurricane landfall probability is modeled in function of the characteristics of tropical-cyclone genesis, storm track, and intensity at landfall, based on Poisson random measure theory. We identified a methodology to estimate the Poisson parameters from a large number of synthetic hurricane tracks, in order to overcome the difficulty of data scarcity as well as account for future climate change effects. We worked with Professor Kerry Emanuel of MIT to analyze and apply his synthetic tracks (Emanuel et al., 2006 and 2008) to estimate the statistical parameters in our model. (Ning Lin is presently a NOAA-sponsored postdoctoral scholar working (for a period of 2 years) with Kerry Emanuel in the Department of Earth and Planetary Sciences at MIT.)

We also worked closely with GFDL (through Timothy Marchok) and Professor James Smith of CEE (Princeton) to develop the second module. We investigated the multiple hazards (wind, rainfall, storm surge) associated with landfalling hurricanes, through simulations of historical hurricanes by using the Weather Research and Forecasting (WRF) model coupled to GFDL's hurricane initialization scheme. The effectiveness of current modeling technology to predict hurricane hazards is examined in Lin et al. (2008 & 2009a). We applied Prof. Emanuel’s synthetic tracks to storm surge simulation (Fig. 1), with the aim of developing methodology to estimate the probability distribution of surge heights in data-scare regions such as New York City (see Lin, Emanuel, Smith and Vanmarcke, 2010a). The simulation results from the WRF/GFDL model were used to validate simplified strategies to make it possible to greatly increase the number of simulation runs.

The estimation of hurricane event probability and hurricane wind fields is applied to predict hurricane wind-related damage risk in the third module. We model the over-threshold wind speed at a coastal location of interest with a generalized (heavy-upper-tail) Pareto distribution. A consequence of the Poisson-based modeling of hurricane events is that the unconditional distribution of the wind speed
becomes a generalized extreme value (GEV) distribution (Coles, 2001). We performed statistical testing and estimation of these distributions, making use of Prof. Emanuel’s synthetic tracks and wind field model (Emanuel et al., 2006). The probability distribution of wind speeds is then combined with our advanced structural vulnerability model (Lin et al., 2008 and 2009b) to predict aggregate annual damage and economic losses to coastal residential neighborhoods. The uniqueness of this vulnerability model lies in its detailed presentation of the interaction between wind pressure and windborne debris effects, which is a major mechanism leading to structural failures during hurricanes (Fig. 2). This vulnerability model is also used to evaluate wind loads and structural performance at each time step of a wind-speed series, thus accounting for, in addition to the common peak-wind-speed parameter, the effects of the duration and the changing directions of strong winds during a hurricane’s passage (Fig. 3) (Yau and Vanmarcke, 2010c; and Lin and Vanmarcke, 2010d; Lin et al, 2010e; Vanmarcke and Lin, 2011; Yau, 2011).

Figure 1. Storm surge risk analysis: (a) Ten most intense synthetic storms among a large number of simulations (Emanuel et. al., 2006) that make landfall in New Jersey area; (b) Storm tide (m), predicted by ADCIRC, at the Battery, New York, due to the most intense synthetic storm in the data set.

Figure 2. Structural vulnerability curves without (a) and with (b) debris effects for a study area of 358 residential houses in Sarasota County, Florida.
Figure 3. Time histories of damage ratio without (a) and with (b) debris effects for the study area during (WRF/GFDL) model simulated Hurricane Charley (2004) landfall.

References:

Publications:
Vanmarcke, E. and Lin, N. (2011), “Quantitative Risk analysis of Damage to Structures During Windstorms: Random Field and System Reliability Aspects”, Keynote Lecture at the International Conference on Vulnerability and Risk Assessment and Management (ICVRAM-ISUMA), Hyattsville, Maryland, April 2011; Proceedings to be Published by the American Society of Civil Engineers.
Progress Report Title: High Resolution Climate Model Simulations over the South Pacific

Principal Investigator: Kevin Walsh (Visiting Scientist, University of Melbourne)

CICS/GFDL Collaborator: Tom Knutson (GFDL)

Other Participating Researchers: Steve Garner (GFDL), Chris Kerr (GFDL)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

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

Objectives: The GFDL regional climate model ZETAC was implemented over a tropical domain in the South Pacific, to provide climate change simulations in this region of unprecedented horizontal resolution.

Methods and Results/Accomplishments:

Following the methodology of Knutson et al. (2008), the ZETAC model was nested within NCEP reanalyses and its simulation of present-day tropical climate evaluated. The model has a good simulation of observed climatological January-March rainfall. It also has some ability to simulate the observed interannual variability of rainfall in this region, which is dominated by extremes of ENSO. The model is also able to generate tropical cyclones, although in the test configuration adopted for the initial set of climate simulations, too many tropical cyclones are generated. The model has also been nested within model output of the CSIRO CCAM model (McGregor and Dix 2008) and good results have also been obtained for simulation of current rainfall climatology. Analysis of other variables from this model run is ongoing. Simulations of future climate are now under way.

References:


Progress Reports:

Education/Outreach
Progress Report Title: Cooperative Institute for Climate Science Professional Development
Summer Institute in Weather and Climate July 19-23, 2010

Principal Investigator: Steven Carson (Princeton Township Middle School Chemistry Teacher)

Other Participating Researchers: Anne Catena, Program in Teacher Preparation (Princeton)

Task I: Administration & Outreach

NOAA Sponsor: Brian Gross (GFDL)

Education/Outreach

NOAA Goals:
Climate Goal: 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 complexity of understanding and predicting climate and environmental consequences, we designed and delivered professional development for New Jersey teachers to improve their students’ understanding of earth system modeling. This work is a collaboration of Princeton University science and education professors as well as local educators: Dr. Steven Carson, formerly of the Geophysical Fluids Dynamics Laboratory and currently a middle school science teacher in Princeton Township, New Jersey; and Dr. Anne Catena, Program in Teacher Preparation at Princeton University.

Methods and Results/Accomplishments:
Teachers explored the fundamentals of weather and Earth’s climate as a system and the interaction of land, ocean and atmosphere. Models were introduced to help the participants better understand weather conditions as well as weather predicting. Teachers specifically responded to the value of modeling for their own classroom instruction: “The overall highlights were a great understanding of models to demonstrate the teaching of weather.” Inquiry-based investigations included air pressure, temperature, seasons, the greenhouse effect, humidity, clouds, wind, the Coriolis effect, storms, and colors in the sky. Teachers responded positively to learning through inquiry; “I will do more inquiry-based experiments and less lecturing. I know my students will be more engaged.” Discussions on climate change including consideration of the public communication of research to improved understanding. Teachers’ comments include “I had the opportunity to ask questions which clarified subject matter knowledge and cleared up misconceptions I had.”

The class was taught by Dr. Steven Carson, former scientist at the Geophysical Fluid Dynamics Laboratory and currently a middle school teacher in Princeton Township, NJ. The instructional team also included Travis Merritt, a middle school teacher in Lawrence, NJ. Ten teachers in grades 2-8 participated in the seminar representing seven different school districts. Teacher serving underrepresented students in urban district comprised 40% of the districts.
Teacher feedback:

"The overall highlights were a great understanding of models to demonstrate the teaching of weather."

"I will do more inquiry-based experiments and less lecturing. I know my students will be more engaged."

"I had the opportunity to ask questions which clarified subject matter knowledge and cleared up misconceptions I had."
Progress Report Title: Coral Workshop

Principal Investigator: John Dunne (Research Oceanographer, GFDL)

CICS/GFDL Collaborator: Cheryl Logan (Princeton), Andrew Wittenberg (GFDL), Charles Stock (GFDL), Ryan Rykaczewski (GFDL), Allison Smith (Princeton), John Krasting (GFDL), Jasmin John (GFDL), Vince Saba (GFDL)

Other Participating Researchers: Simon Donner (University of British Columbia), Mark Eakin (NOAA Coral Reef Watch), Gang Liu (NOAA Coral Reef Watch)

Task I: Administration & Outreach

NOAA Sponsor: Brian Gross (GFDL)

Education/Outreach

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

Objectives: The goal of this coral project is to develop a globally-robust means of characterizing coral bleaching and to apply the GFDL earth system models to project coral vulnerability to climate change and ocean acidification.

Methods and Results/Accomplishments:
Through CICS, the NOAA Coral Reef Conservation Program sponsored a “Coral Vulnerability Workshop” from August 30-September 1, 2010 at Princeton University. The primary focus of the workshop was to provide the cross-disciplinary background necessary to approach this topic and introduce our AOS postdoc, Cheryl Logan, to the various experts at GFDL and Princeton available to provide guidance as she spearheads this project. Approximately 10-15 various members of GFDL and AOS were in attendance at the workshop. Presentations included: 1) Background on GFDL's IPCC class models and their application, 2) Background on state of the art coral bleaching predictions, 3) Physiological mechanisms of coral bleaching, and 4) Observational and representational challenges. The workshop culminated in a Synthesis session in which the core members of the team (Dunne, Logan, Eakin, and Donner) devised a work plan and timeline for developing a new coral bleaching model.
Shadow Award Progress Reports:

Earth System Modeling and Analysis
Progress Report Title: Improving Climate Predictions by Reducing Uncertainties about CO₂ Fertilization in the Terrestrial Biosphere

Principal Investigator: Lars O. Hedin (Princeton Professor)

CICS/GFDL Collaborator: Sonja G. Keel (Princeton), Stefan Gerber (Princeton), Elena Shevliakova (Princeton), Stephen W. Pacala (Princeton), Ronald J. Stouffer (GFDL), John P. Dunne (GFDL)

Other Participating Researchers: S. Joseph Wright (Smithsonian Tropical Research Institute)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Ecosystem Goal: Protect, Restore, and Manage the Use of Coastal and Ocean Resources through Ecosystem Approach to Management (10%)
Climate Goal: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond (90%)

Objectives: Forest trees represent the largest biomass carbon (C) pool on land. Whether they will grow faster and store more C in response to the continued rise in atmospheric CO₂ is unclear.

Methods and Results/Accomplishments:
Using the Princeton-GFDL global land model LM3V-N we explore how land-use history, atmospheric nitrogen (N) deposition, and climatic conditions interact to generate growth responses of trees observed in free-air CO₂ enrichment (FACE) experiments. In line with experimental evidence (McCarthy et al. 2010), we found a sustained increase in net primary production (NPP) at the Duke-FACE site. Model results also broadly agreed with observations from the Swiss Forest site, where no response was detected, likely due to nutrient limitation (Körner et al. 2005). At the Oak Ridge National Laboratory (ORNL) FACE site, the stimulation of NPP in the model was weaker compared to experimental data and was very sensitive to land use history (Norby et al. 2010). We could show that former agricultural use had a pronounced and long-lasting effect on N availability in the soil, which in turn affected the response to elevated CO₂ (Keel et al.). These results demonstrate that inclusion of feedbacks between the C and the N cycle and interactions with land use can account for potential biogeochemical constraints on C uptake in terrestrial ecosystems. We suggest that these interactions are critical for capturing spatial and temporal variations in the response of terrestrial ecosystems to rising CO₂.

References:

Publications:
**Progress Report Title:** Ensemble Hydrologic Forecasts over the Southeast in Support of the NIDIS Pilot

**Principal Investigator:** Eric F. Wood (Princeton Professor)

**Other Participating Researchers:** Kingtse C. Mo (Climate Prediction Center/NCEP/NWS/NOAA)  
Michael Ek (EMC/NWS/NOAA)

**Theme:** Earth System Modeling and Analysis

**NOAA Goals:**

**Climate Goal:** Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond (66%)  
**Weather & Water Goal:** Serve Society’s Needs for Weather and Water Information (33%)

**Objectives:** The goal of this proposal is to use the Climate Forecast System Reanalysis and Reforecast System (CFSRR) to provide hydrologic predictions of drought indices with a focus on the selected basins over the Southeast. The project will apply the PI’s hydrological seasonal forecasts system, initially using CSFv1 until CFSv2 is available, to develop and test a drought early warning system and hydrological forecast application for the SE RFC.

**Methods and Results/Accomplishments:**

The framework used is the hydrologic prediction system developed by the Princeton Group. It starts from all members of the CFS seasonal forecasts of monthly mean precipitation (P) and Tmax and Tmin. The first step is to correct biases of the model and to downscale from the global model coarse grid to the hydrologic fine grid, which is done in a Bayesian probabilistic framework based on CFS reforecast data. Then, the corrected P, Tmax and Tmin are used to drive a land-surface VIC model to produce soil moisture and runoff forecasts.

The SPI can be derived directly from the bias corrected and downscaled P forecasts. The soil moisture (SM) anomaly percentiles and SRI can be derived from the hydrologic forecasts from the VIC model outputs.

The system can be applied to any river basin over the United States. For this project, we will apply to the Southeast. The key beneficiary is the Southeast River Forecast Center. Tests and applications developed can be used for other basins and will be beneficial to water resources managers.

The project has successfully analyzed CFS hindcasts to develop seasonal forecasts over the SE NIDIS testbed with particular focus on forecast points selected by the SE RFC. The project has transferred the hydrologic forecast system from the Princeton University to CPC. The system is running at CPC. CPC has compared the bias correcting and downscaling technique with three other approaches to assess skill in forecasting SPI.

**Publications and Presentations:**


Kingtse Mo: Objective Drought Monitoring and Prediction: Recent activities at CPC: CTB seminar 14 April 2010.

Shadow Award Progress Reports:

Earth System Model Applications
Progress Report Title: Development of an Experimental National Hydrologic Prediction System

Principal Investigator: Eric F. Wood (Princeton Professor)

Other Participating Researchers: Dennis Lettenmaier (University of Washington); Pedro Restrepo (OH/OHD), John Schaake (OH/OHD)

Theme: Earth System Modeling Applications

NOAA Goals:
Climate Goal: Understand Climate Variability and Change to Enhance Society’s Ability to Plan and Respond (40%)
Weather & Water Goal: Serve Society’s Needs for Weather and Water Information (60%)

Objectives: The project will integrate the hydrologic forecast methods and products developed under previous CPO/CPPA research into an experimental national hydrologic prediction system through the following tasks: integrate existing UW and Princeton hydrologic forecast and drought recovery systems to produce seamless national hydrologic nowcasts and forecasts at a common spatial resolution; expand the unified system to include multiple land schemes; implement improved methods of parameter transfer from catchment-scale model implementation to the gridded national system; develop an ensemble seasonal reservoir storage capability for large reservoirs; implement methods for hydrologic forecast error estimation and forecast verification; develop methods of assimilating streamflow observations to overcome uncertainties in the first month(s) of seasonal hydrological forecasts; develop GFS-based near-term hydrologic forecast capability to improve month-1 outlooks and provide a seamless hydrologic forecast suite bridging weather and climate time scales.

Methods and Results/Accomplishments:
A unification of the systems has been accomplished with multiple hydrological seasonal forecasts being provided across the US based on the two NCEP methods: the ‘official’ CPC forecast based departures from climate normal and NCEP/EMC CFS dynamical seasonal forecasts. As NCEP upgrades CFS to CFSv2, we are analyzing the CFS re-forecast data set (CFSRR) to calibrate the new seasonal forecasts. A multi-model drought nowcast system has been implemented that will allow the project to develop improved error estimates of the seasonal forecasts.
<table>
<thead>
<tr>
<th>CI Name</th>
<th>PI Name / Author Names</th>
<th>Publication Date</th>
<th>Publication Title</th>
<th>Published In (Journal Name, volume and page number)</th>
<th>Type of Publication</th>
<th>Citation No. (Digital Object Identifier)</th>
<th>Research Support Award No.</th>
<th>CI Lead Author</th>
<th>NOAA Lead Author</th>
<th>Other Lead Author</th>
<th>Peer Reviewed</th>
<th>Non-Peer Reviewed</th>
</tr>
</thead>
<tbody>
<tr>
<td>CICS-P</td>
<td>Kidston, J., Vallis, G. K., Deon, S. M. and Renwick, J. A.</td>
<td>&quot;In Press&quot;</td>
<td>Can the increase in the eddy length scale under global warming cause the poleward shift of the jet streams?</td>
<td>Journal of Climate</td>
<td>Journal Article</td>
<td>doi:10.1175/JCLI-D-10-04831.1</td>
<td>MAB004A320752</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CICS-P</td>
<td>Xie, P. and Vallis, G. K.</td>
<td>“In Press”</td>
<td>The passive and active nature of ocean heat uptake in heat in idealized climate change experiments</td>
<td>Climate Dynamics</td>
<td>Journal Article</td>
<td>10.1007/s00382-011-1064-8</td>
<td>NA08OAR4320752</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>JI Lead Author</td>
<td>NOAA Lead Author</td>
<td>Other Lead Author</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>------------------</td>
<td>---------------</td>
<td>------------------</td>
<td>-------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>FY09</td>
<td>FY10</td>
<td>FY11</td>
<td>FY09</td>
<td>FY10</td>
<td>FY11</td>
<td>FY09</td>
<td>FY10</td>
<td>FY11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peer-reviewed</td>
<td>14</td>
<td>31</td>
<td>30</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>6</td>
<td>21</td>
<td>29</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non Peer-reviewed</td>
<td>14</td>
<td>13</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>7</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chapters in books</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ph.D. Thesis</td>
<td>2</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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 Administrative Assistant**
Joanne Curcio
Administrative Assistant, CICS
Phone: 609-258-6047
Fax: 609-258-2850
jcurcio@princeton.edu
Task I: Administrative Activities and Outreach Supported Personnel

<table>
<thead>
<tr>
<th>Name</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carson, Steven</td>
<td>QUEST Lead Teacher</td>
</tr>
<tr>
<td>Curcio, Joanne</td>
<td>Administrative Assistant</td>
</tr>
<tr>
<td>Doolittle, Ken</td>
<td>QUEST Novice Teacher</td>
</tr>
<tr>
<td>Merritt, Travis</td>
<td>QUEST Lead Teacher</td>
</tr>
<tr>
<td>Sarmiento, Jorge</td>
<td>CICS Director</td>
</tr>
</tbody>
</table>

Departures - Task II and Task III
Dilip Ganguly - May 2010: Scientist at the Pacific Northwest National Laboratory
Stefan Gerber - November 2010: Assistant Professor at the University of Florida
Joseph Kidston - July 2010: Lecturer (Assistant Professor) at the University of New South Wales
Salil Mahajan - August 2010: Scientist at Oak Ridge National Laboratory
Jaime Palter - December 2010: Assistant Professor at McGill University

Ph.D. Defenses
Student: Yuanyuan Fang
Advisor: Larry Horowitz - September 2010
Dissertation: The impacts of emissions, meteorology and climate change on pollution transport
Current Affiliation: Princeton University Woodrow Wilson School
Postdoctoral Research Associate

Student: Sui Chung Yau
Advisor: Eric Vanmarcke - January 2011
Dissertation: Wind Hazard Risk Assessment and Management for Structures
Current Affiliation: Returned to China

Student: Yan Zhang
Advisor: James Smith - August 2010
Dissertation: Heavy Rainfall in the Urban Environment
Current Affiliation: Princeton University Civil and Environmental Engineering
Postdoctoral Research Associate
**Task II: Cooperative Research Projects and Education Supported Personnel**

<table>
<thead>
<tr>
<th>Name</th>
<th>Rank</th>
<th>Host</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adcroft, Alistair</td>
<td>Research Oceanographer</td>
<td>GFDL Director</td>
</tr>
<tr>
<td>Balaji, V.</td>
<td>Sr. Professional Technical Specialist</td>
<td>GFDL Director</td>
</tr>
<tr>
<td>Bollasina, Massimo</td>
<td>Postdoctoral Research Associate</td>
<td>Ming</td>
</tr>
<tr>
<td>Ballinger, Andrew</td>
<td>Graduate Student</td>
<td>Held</td>
</tr>
<tr>
<td>Chen, Jan-Huey</td>
<td>Postdoctoral Research Associate</td>
<td>SJ Lin</td>
</tr>
<tr>
<td>Doi, Takeshi</td>
<td>Postdoctoral Research Associate</td>
<td>Vecchi</td>
</tr>
<tr>
<td>Fan, Yalin</td>
<td>Associate Research Scholar</td>
<td>Lin</td>
</tr>
<tr>
<td>Fang, Yuanyuan</td>
<td>Graduate Student</td>
<td>Horowitz/Levy</td>
</tr>
<tr>
<td>Goldberg, Daniel</td>
<td>Postdoctoral Research Associate</td>
<td>Sergienko</td>
</tr>
<tr>
<td>Harris, Lucas</td>
<td>Postdoctoral Research Associate</td>
<td>Lin</td>
</tr>
<tr>
<td>Ilicak, Mehmet</td>
<td>Postdoctoral Research Associate</td>
<td>Hallberg</td>
</tr>
<tr>
<td>Kidston, Joe</td>
<td>Postdoctoral Research Associate</td>
<td>Vallis</td>
</tr>
<tr>
<td>Legg, Sonya</td>
<td>Research Oceanographer</td>
<td>GFDL Director</td>
</tr>
<tr>
<td>Li, Ying</td>
<td>Graduate Student</td>
<td>Lau</td>
</tr>
<tr>
<td>Lin, Meiyun</td>
<td>Postdoctoral Research Associate</td>
<td>Fiore</td>
</tr>
<tr>
<td>Liu, Junfeng</td>
<td>Associate Research Scholar</td>
<td>Horowitz</td>
</tr>
<tr>
<td>Lloyd, Ian</td>
<td>Graduate Student</td>
<td>Lau/Vecchi</td>
</tr>
<tr>
<td>Logan, Cheryl</td>
<td>Postdoctoral Research Associate</td>
<td>Dunne</td>
</tr>
<tr>
<td>Mahajan, Salil</td>
<td>Postdoctoral Research Associate</td>
<td>Zhang</td>
</tr>
<tr>
<td>Malyshev, Sergey</td>
<td>Associate Research Scholar</td>
<td>Pacala</td>
</tr>
<tr>
<td>Mao, Jingqiu</td>
<td>Postdoctoral Research Associate</td>
<td>Horowitz</td>
</tr>
<tr>
<td>Muller, Caroline</td>
<td>Postdoctoral Research Associate</td>
<td>Held</td>
</tr>
<tr>
<td>Ms'adek, Rym</td>
<td>Postdoctoral Research Associate</td>
<td>Delworth</td>
</tr>
<tr>
<td>Nikonov, Sergey</td>
<td>Professional Technical Specialist</td>
<td>Balaji</td>
</tr>
<tr>
<td>Nikurashin, Maxim</td>
<td>Associate Research Scholar</td>
<td>Legg</td>
</tr>
<tr>
<td>Ocko, Ilissa</td>
<td>Graduate Student</td>
<td>Ramaswamy</td>
</tr>
<tr>
<td>Orlanski, Isidoro</td>
<td>Sr. Research Meteorologist</td>
<td>GFDL Director</td>
</tr>
<tr>
<td>O'Rourke, Amanda</td>
<td>Graduate Student</td>
<td>Vallis</td>
</tr>
<tr>
<td>Paynter, David</td>
<td>Postdoctoral Research Associate</td>
<td>Ramaswamy</td>
</tr>
<tr>
<td>Potter, Sam</td>
<td>Graduate Student</td>
<td>Vallis</td>
</tr>
<tr>
<td>Radley, Claire</td>
<td>Graduate Student</td>
<td>Donner</td>
</tr>
<tr>
<td>Reid, John Paul</td>
<td>Graduate Student</td>
<td>Gnanadesikan</td>
</tr>
<tr>
<td>Saba, Vince</td>
<td>Postdoctoral Research Associate</td>
<td>Stock</td>
</tr>
<tr>
<td>Sergienko, Olga</td>
<td>Associate Research Scholar</td>
<td>Hallberg</td>
</tr>
<tr>
<td>Shevliakova, Elena</td>
<td>Associate Research Scholar</td>
<td>Pacala</td>
</tr>
<tr>
<td>Spengler, Thomas</td>
<td>Postdoctoral Research Associate</td>
<td>Held</td>
</tr>
<tr>
<td>Vallis, Geoffrey</td>
<td>Sr. Research Geoscientist</td>
<td>GFDL Director</td>
</tr>
<tr>
<td>Walsh, Kevin</td>
<td>Visiting Scientist</td>
<td>Knutson</td>
</tr>
</tbody>
</table>
**Task II: Cooperative Research Projects and Education Supported Personnel Continued**

<table>
<thead>
<tr>
<th>Name</th>
<th>Position</th>
<th>Advisor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wang, He</td>
<td>Graduate Student</td>
<td>Legg</td>
</tr>
<tr>
<td>Zhang, Sophie</td>
<td>Postdoctoral Research Associate</td>
<td>Vallis</td>
</tr>
</tbody>
</table>
### Task III: Individual Research Projects Supported Personnel

<table>
<thead>
<tr>
<th>Name</th>
<th>Rank</th>
<th>Advisor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beaulieu, Claudie</td>
<td>Postdoctoral Research Fellow</td>
<td>Sarmiento</td>
</tr>
<tr>
<td>Bonachela Fajardo, Juan</td>
<td>Postdoctoral Research Associate</td>
<td>Levin</td>
</tr>
<tr>
<td>Chien, Diana M.</td>
<td>Undergraduate</td>
<td>Ward</td>
</tr>
<tr>
<td>Dybzinski, Ray</td>
<td>Postdoctoral Research Associate</td>
<td>Hedin</td>
</tr>
<tr>
<td>Gerber, Stefan</td>
<td>Associate Research Scholar</td>
<td>Hedin</td>
</tr>
<tr>
<td>Golaz, Ni-Zhang</td>
<td>Environmental Modeler &amp; Analyst</td>
<td>Sarmiento</td>
</tr>
<tr>
<td>Hervieux, Gaelle</td>
<td>Postdoctoral Associate</td>
<td>Curchitser</td>
</tr>
<tr>
<td>Jayakumar, Amal</td>
<td>Sr. Professional Specialist</td>
<td>Ward</td>
</tr>
<tr>
<td>Jeong, Su-Jong</td>
<td>Postdoctoral Research Associate</td>
<td>Medvigy</td>
</tr>
<tr>
<td>Kearney, Kelly</td>
<td>Graduate Student</td>
<td>Sarmiento</td>
</tr>
<tr>
<td>Key, Robert M.</td>
<td>Research Oceanographer</td>
<td>PI</td>
</tr>
<tr>
<td>Lin, Xiaohua</td>
<td>Senior Research Specialist</td>
<td>Key</td>
</tr>
<tr>
<td>Majkut, Joseph</td>
<td>Graduate Student</td>
<td>Sarmiento</td>
</tr>
<tr>
<td>Oey, Lie-Yauw</td>
<td>Research Oceanographer</td>
<td>PI</td>
</tr>
<tr>
<td>Palter, Jaime</td>
<td>Associate Research Scholar</td>
<td>Sarmiento</td>
</tr>
<tr>
<td>Rodgers, Keith</td>
<td>Associate Research Scholar</td>
<td>Sarmiento</td>
</tr>
<tr>
<td>Smith, K. Allison</td>
<td>Postdoctoral Research Associate</td>
<td>Sarmiento</td>
</tr>
<tr>
<td>Ward, Bess</td>
<td>Professor</td>
<td>Ward</td>
</tr>
<tr>
<td>Wright, Daniel</td>
<td>Graduate Student</td>
<td>Smith</td>
</tr>
<tr>
<td>Wurzburger, Nina</td>
<td>Postdoctoral Research Associate</td>
<td>Hedin</td>
</tr>
<tr>
<td>Yau, Siu Chung</td>
<td>Graduate Student</td>
<td>Vanmarcke</td>
</tr>
<tr>
<td>Yeung, June</td>
<td>Graduate Student</td>
<td>Smith</td>
</tr>
<tr>
<td>Zhang, Yan</td>
<td>Graduate Student</td>
<td>Smith</td>
</tr>
</tbody>
</table>
### Shadow Awards: Individual Research Projects Supported Personnel

<table>
<thead>
<tr>
<th>Name</th>
<th>Rank</th>
<th>Advisor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hedin, Lars</td>
<td>Faculty</td>
<td>-</td>
</tr>
<tr>
<td>Keel, Sonja</td>
<td>Postdoctoral Research Associate</td>
<td>Hedin</td>
</tr>
<tr>
<td>Roundy, Joshua</td>
<td>Graduate Student</td>
<td>Wood</td>
</tr>
<tr>
<td>Yuan, Xing</td>
<td>Associate Research Scholar</td>
<td>Wood</td>
</tr>
<tr>
<td>Category</td>
<td>Number</td>
<td>B.S.</td>
</tr>
<tr>
<td>------------------------------</td>
<td>--------</td>
<td>------</td>
</tr>
<tr>
<td>Faculty</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Research Scientist</td>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>Visiting Scientist</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Postdoctoral Research Associate</td>
<td>25</td>
<td>-</td>
</tr>
<tr>
<td>Professional Technical Staff</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>Associate Research Scholar</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>Administrative</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total (≥ 50% support)</strong></td>
<td><strong>40</strong></td>
<td><strong>1</strong></td>
</tr>
<tr>
<td>Undergraduates</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Graduate Students</td>
<td>17</td>
<td>7</td>
</tr>
<tr>
<td>Employees that receive &lt; 50% NOAA funding (not including graduate students)</td>
<td>13</td>
<td>-</td>
</tr>
<tr>
<td>Located at the Lab (include name of lab)</td>
<td>GFDL-36</td>
<td>4</td>
</tr>
<tr>
<td>Obtained NOAA employment within the last year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amount</td>
<td>PI</td>
<td>Project Title</td>
</tr>
<tr>
<td>------------</td>
<td>---------------------------</td>
<td>-------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>$ 41,919*</td>
<td>Jorge L. Sarmiento</td>
<td>Administration (Task I) GFDL-Brian Gross</td>
</tr>
<tr>
<td>$ 159,575*</td>
<td>Robert M. Key</td>
<td>Global Carbon Data Management and Synthesis Project (Task III) COD-Joel Levy</td>
</tr>
<tr>
<td>$ 60,000*</td>
<td>Keith Rodgers</td>
<td>Using Models to improve our ability to monitor ocean uptake of anthropogenic carbon (Task III) COD-Joel Levy</td>
</tr>
<tr>
<td>$ 28,000*</td>
<td>Lie-Yauw Oey</td>
<td>Collaborative Research: Modeling sea ice-ocean-ecosystem responses to climate changes in the Bering-Chukchi-Beaufort Seas with data assimilation of RUSALCA Measurements (Task III) ARO-John Calder</td>
</tr>
<tr>
<td>$ 76,155*</td>
<td>James A. Smith</td>
<td>Regional Climate Studies Using the Weather Research and Forecasting Model (Task III) GFDL-Brian Gross</td>
</tr>
<tr>
<td>$ 18,515*</td>
<td>Erik Vanmarcke</td>
<td>Improved Hurricane Risk Assessment, with Links to Earth Systems Models (Task III) GFDL-Brian Gross</td>
</tr>
<tr>
<td>$ 97,624*</td>
<td>Simon Levin</td>
<td>Top-down controls on marine microbial diversity and its effects on primary productivity in the oceans (Task III) GFDL-Brian Gross</td>
</tr>
<tr>
<td>$ 35,484*</td>
<td>Joseph Majkut</td>
<td>Developing Methods for Fast Spin-up of Ocean Biogeo-chemical Models (Task III) GFDL-Brian Gross</td>
</tr>
<tr>
<td>$ 42,337*</td>
<td>Claudie Beaulieu</td>
<td>Detection and Attribution of shifts in the carbon system (Task III) GFDL-Brian Gross</td>
</tr>
<tr>
<td>$ 38,552*</td>
<td>K. Allison Smith</td>
<td>Competitive interactions between bacteria and zooplankton along oxygen concentration gradients in global ocean models (Task III) GFDL-Brian Gross</td>
</tr>
<tr>
<td>$ 115,656*</td>
<td>David Medvigy</td>
<td>A mechanistic framework for predicting land-atmosphere carbon fluxes (Task III) GFDL-Brian Gross</td>
</tr>
<tr>
<td>$ 36,758*</td>
<td>Jorge L. Sarmiento</td>
<td>Unallocated (Task III) GFDL-Brian Gross</td>
</tr>
<tr>
<td>$3,473,612*</td>
<td>Jorge L. Sarmiento</td>
<td>Cooperative Research Projects and Education (Task II) GFDL-Brian Gross</td>
</tr>
<tr>
<td>Amendment No./PI</td>
<td>Amount</td>
<td>Project Title</td>
</tr>
<tr>
<td>-----------------</td>
<td>--------</td>
<td>---------------</td>
</tr>
<tr>
<td>Amendment #10:</td>
<td>$60,000</td>
<td>Using Models to Improve our Ability to Monitor Ocean Uptake of Anthropogenic Carbon</td>
</tr>
<tr>
<td>PI: Keith Rodgers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amendment #11:</td>
<td>$159,575</td>
<td>Global Carbon Data Management and Synthesis Project</td>
</tr>
<tr>
<td>PI: Robert Key</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amendment #12:</td>
<td>$3,976,612</td>
<td>CICS-Princeton: Year 3</td>
</tr>
<tr>
<td>PI: Jorge Sarmeinto</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Co-PI: Geoff Vallis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Task I:</td>
<td>$41,919</td>
<td></td>
</tr>
<tr>
<td>Task II:</td>
<td>$3,473,612</td>
<td></td>
</tr>
<tr>
<td>Task III:</td>
<td>$461,081</td>
<td></td>
</tr>
<tr>
<td>Amendment #13:</td>
<td>$28,000</td>
<td>Collaborative Research: Modeling sea ice-ocean-ecosystem responses to climate changes in the Bering-Chukchi-Beaufort Seas with data assimilation of RUSALCA measurements</td>
</tr>
<tr>
<td>PI: Lie-Yauw Oey</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## CICS FY’11 List of Awards for Shadow Award NA08OAR4320915

<table>
<thead>
<tr>
<th>Amendment No./PI</th>
<th>Amount</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amendment # 5:</td>
<td>$137,153</td>
<td>Improving climate predictions by reducing uncertainties about CO2 fertilization in the terrestrial biosphere <em>CPO-Ken Mooney</em></td>
</tr>
<tr>
<td>PI: Lars Hedin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amendment #6:</td>
<td>$102,000</td>
<td>Development of an experimental national hydrologic prediction system <em>CPO-Kendra Hammond</em></td>
</tr>
<tr>
<td>PI: Eric Wood</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amendment #7:</td>
<td>$63,000</td>
<td>Ensemble Hydrologic Forecasts over the Southeast in Support of the NIDIS Pilot <em>NCEP/NWS-Kingtse C. Mo</em></td>
</tr>
<tr>
<td>PI: Eric Wood</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>