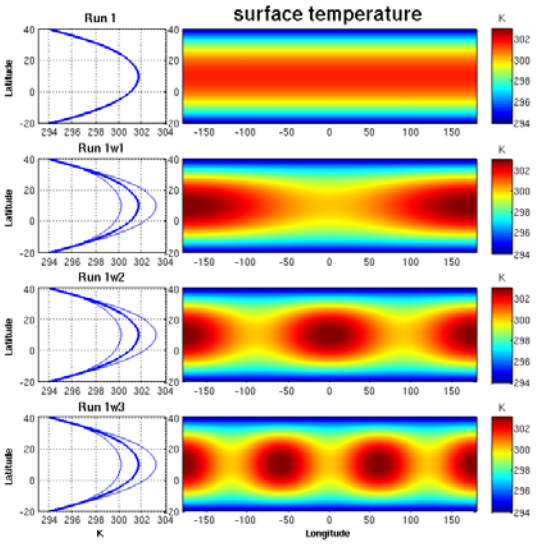
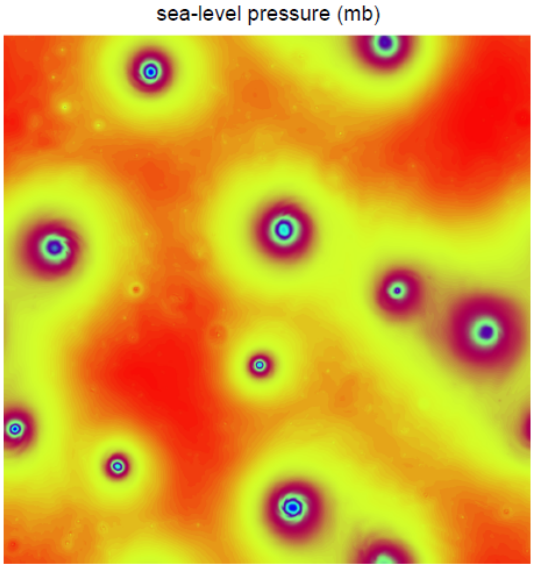


Annual Progress Report
April 1, 2011 – March 31, 2012

Cooperative Institute for Climate Science
at Princeton University
NOAA Cooperative Agreement NA08OAR4320752
Shadow Award NA08OAR4320915



CICS

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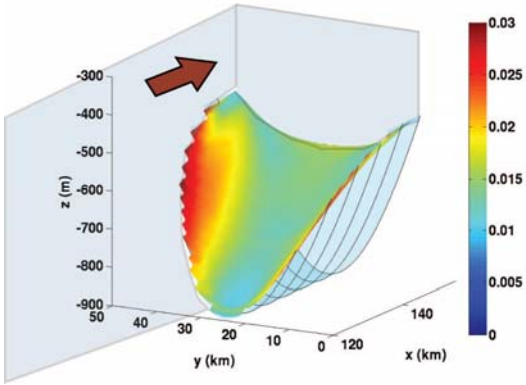

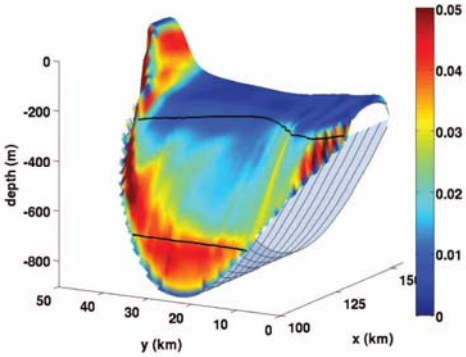

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Cooperative Institute for Climate Science
Princeton University

Annual Progress Report under cooperative agreement NA08OAR4320752
including Shadow Award NA08OAR4320915

For the period April 1, 2011 – March 31, 2012

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, CO_2, CH_4, 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 CO_2, CH_4, 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 are 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

Advancing Land-use Modeling and Analysis for Carbon Cycling Studies Workshop

In collaboration with GFDL and the Princeton Environmental Institute (PEI), CICS co-hosted a workshop from May 17-18, 2011, focused on land-use changes -- past and future. The workshop brought together global experts in land-use/management data, modeling, and analysis with the objective of developing a strategy for understanding and reducing uncertainty in the characterization

of the past effects of land-use changes, including secondary forests, and for improving projections of land C fluxes and their implications for climate change. In response to the need to understand future changes in the carbon cycle, climate models used for making future projections of climate changes over this century and beyond have become progressively more sophisticated. Models have begun to incorporate components to simulate the carbon changes due to direct human activities (e.g., land-use changes) and those that result from climate changes. In support of the fifth IPCC assessment, the goal of the workshop was to organize the land-use analysis activity (model and observations). The analysis activity has three components. The first is to compare the model results to observations over the historical period. This activity will lead to an understanding of what the model can, and cannot, simulate and what new observations are needed to assist in this evaluation. A second component involves the comparison of models to each other to understand why they are producing different results. This activity will help quantify the uncertainty associated with the projection of future changes. The third component entails the comparison of these model results to simpler models used to make the future emission projections. It is worth noting that errors in simple models can lead to very important implications for establishing any future emission targets or goals, for example, limiting the future warming below some threshold.

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:

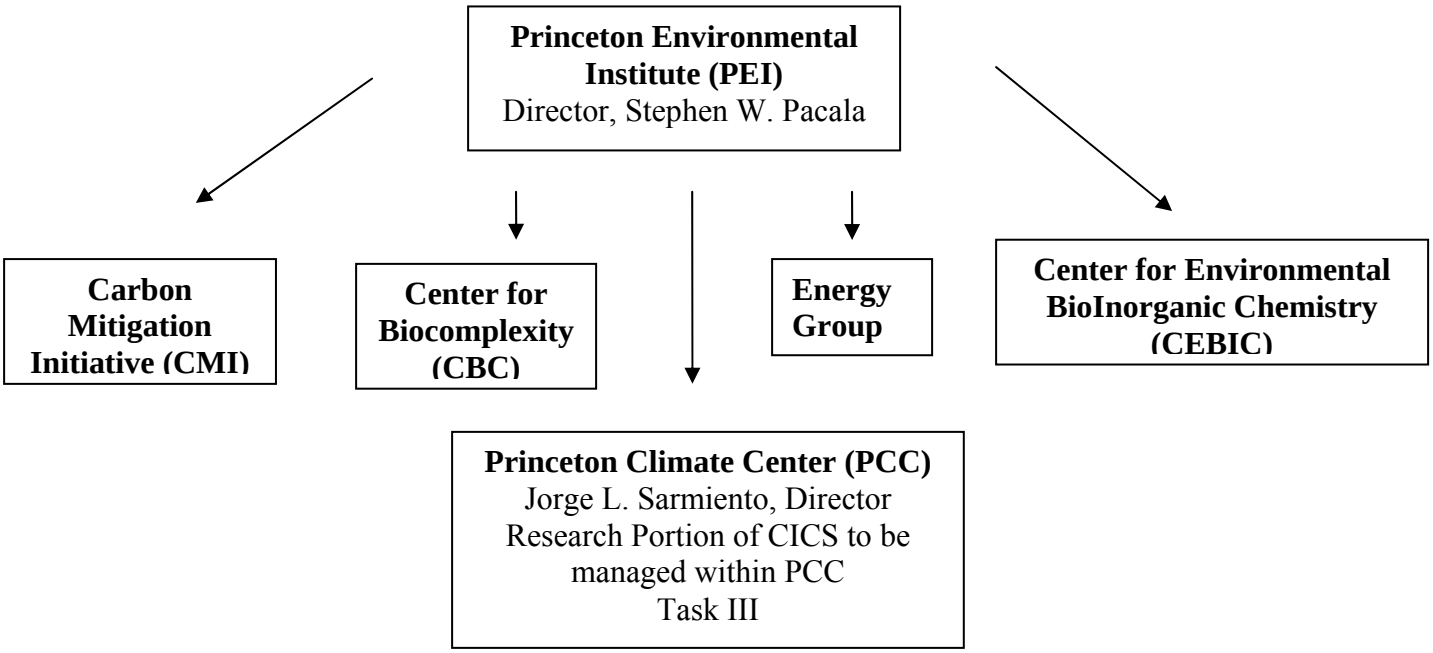
I. Administrative Activities including outreach efforts are carried out jointly by the AOS Program and Princeton Environmental Institute (PEI).

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.

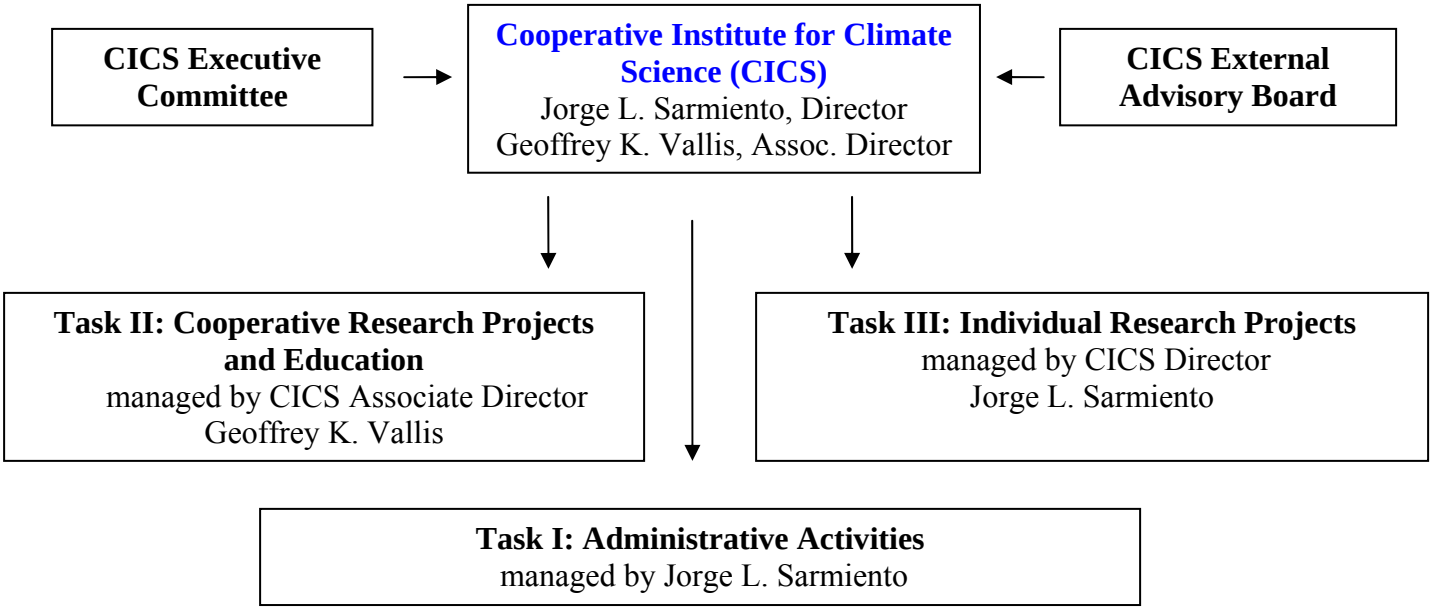
III. Principal Investigator led research projects supported by grants from NOAA that comply with the themes of CICS. These all occur within AOS and the Princeton Environmental Institute (PEI), and may also include subcontracts to research groups at other institutions on an as needed basis.

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.

Princeton Environmental Institute Structure



Cooperative Institute for Climate Science Structure



CICS Committees and Members

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

Executive Committee
Jorge L. Sarmiento – Director of CICS and Professor of Geosciences
Geoffrey K. Vallis – Associate Director of CICS and Senior Research Oceanographer
Isaac Held – GFDL Senior Research Scientist
Denise Mauzerall – Associate Professor of Public and International Affairs, WWS
Michael Oppenheimer – Professor Geosciences and Public and International Affairs, WWS
Stephen W. Pacala – Director of PEI, Professor of Ecology and Evolutionary Biology
V. Ramaswamy – Director of GFDL, GFDL Senior Research Scientist
James Smith – Director, Program in Geological Engineering, Chair and Professor of Civil and Environmental Engineering

Executive Summary of Important Research Activities

Given the range of activities in CICS, it is difficult to highlight just a few in a fair fashion. The following selection should therefore be regarded primarily as a small representative selection of ongoing research in the major research areas; space does not permit us to do more. We organize these highlights by the major themes of the cooperative institute.

EARTH SYSTEM MODELING: DEVELOPMENT and ANALYSIS

In the paragraphs below, we summarize and highlight some of the activities going on in the area of Earth System Modeling. The spectrum of activities stretches from the fundamental to quite applied, in so far as these labels have meaning. These activities both 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.

Radiation in the Atmosphere

On the atmospheric side of the climate system, it is crucial to have a good quantitative model of the representation of the radiative effects of well-mixed greenhouse gases. David Paynter and V. Ramaswamy have performed detailed line by line calculations of the radiative budget, using calculations that account for over one million water vapor spectral lines, and have expanded the empirical continuum code to include gases other than water vapor. They find that there is a much stronger contribution by the water vapor continuum in mid-latitudes than previously thought, implying that the continuum may increase the effectiveness of water vapor as an absorber of solar radiation by up to 20%. Such calculations are a key component in obtaining quantitative estimates of the water vapor feedback in global warming.

Internal Waves and Mixing in the Ocean

The representation of ocean mixing processes continues to be an important task in ocean model development. A number of CICS and GFDL scientists, including Sonya Legg, Max Nikurashin, Angelique Melet, Maarten Buijsman, Robert Hallberg, and Steve Griffies continue to investigate mixing in the interior and near the bottom boundary. This is a key activity in ocean model development, albeit one that does not lend itself easily to sudden breakthroughs or splashy results. One effort over the past year has focused on understanding and parameterizing the mixing generated by tidal flows over rough topography. One aspect of this is understanding the role of multiple steep ridges in leading to constructive interference which can enhance the total mixing. A complimentary aspect is to better understand the role of mixing generated by tidal flow over smaller amplitude rough topography. Significant progress has been made in both areas, necessary precursors for improved parameterizations for global ocean climate models.

Land Use

The LM3 vegetation dynamics component of GFDL's Earth System model, developed with major input from CICS scientists, is one of the few earth system models in the world that includes an explicit simulation of land use scenarios including wood harvesting. CICS Scientists Sergey Malyshev and Elena Shevliakova have collaborated with GFDL Scientist Ronald J. Stouffer to examine how land use affects micro- and macro- climate as well as the carbon budget. One finding from this work is that the impacts on macro-climate are largely confined to the regions of major land use disturbance, with little teleconnection. Because of the tiling structure of the land model, and its ability to calculate water and energy balance separately for each of the tiles, it is also possible to use the model to examine how small scale land use change around the world affects the local climate. Over most of the world, the conversion of land from natural vegetation to cropland leads to a summertime warming despite the increase in albedo. This summertime warming is due largely to reduced evapotranspiration, and in the wintertime, the albedo effect becomes dominant and these areas cool. This model is also being used to study the impact of land use on atmospheric CO_2.

EARTH SYSTEM MODELING: APPLICATIONS

Aerosols and Climate

Understanding the aerosol-induced regional circulation and hydroclimate changes is a key aspect of the general problem of understanding and predicting climate variability and change. In collaboration with GFDL Scientist Yi Ming, Massimo Bollasina has investigated the pathways by which key physical processes influence the regional climate, with particular emphasis on the South Asian monsoon system and the tropical region. The investigators find that the widespread drying of the South Asian summer monsoon during the second half of the twentieth century is most likely to be of anthropogenic origin and, furthermore, can be attributed almost entirely to aerosols. The drying is associated with a slowdown of the tropical meridional overturning circulation which in turn is driven by the need to counteract the aerosol-induced energy imbalance between the northern and southern hemispheres. This result (published in Science magazine) is an important step in increasing our understanding of how regional climates are likely to change in global warming scenarios.

Tropical Cyclone Prediction

The prediction of tropical cyclones remains a daunting challenge, of importance both as a problem in 'weather forecasting' and in climate prediction, for it is crucial to understand whether the strength and frequency of tropical cyclones is likely to increase as the climate warms. To this end, Jan-Huey Chen, in collaboration with GFDL Scientist S-J Lin, has performed retrospective seasonal predictions of tropical cyclones from 1990 to 2010 over all three major ocean basins, in the Northern Hemisphere where such cyclones are more prevalent. They show, using a 5 member ensemble, that the storm counts of tropical storms and hurricanes are highly predictable in the North Atlantic during this period. The skill in the North Pacific is still high, but not nearly as high as in the Atlantic. As well as the scientific value of the results, the feasibility of the numerical model – a 25 km resolution model called HiRAM designed initially as a climate model – has been demonstrated.

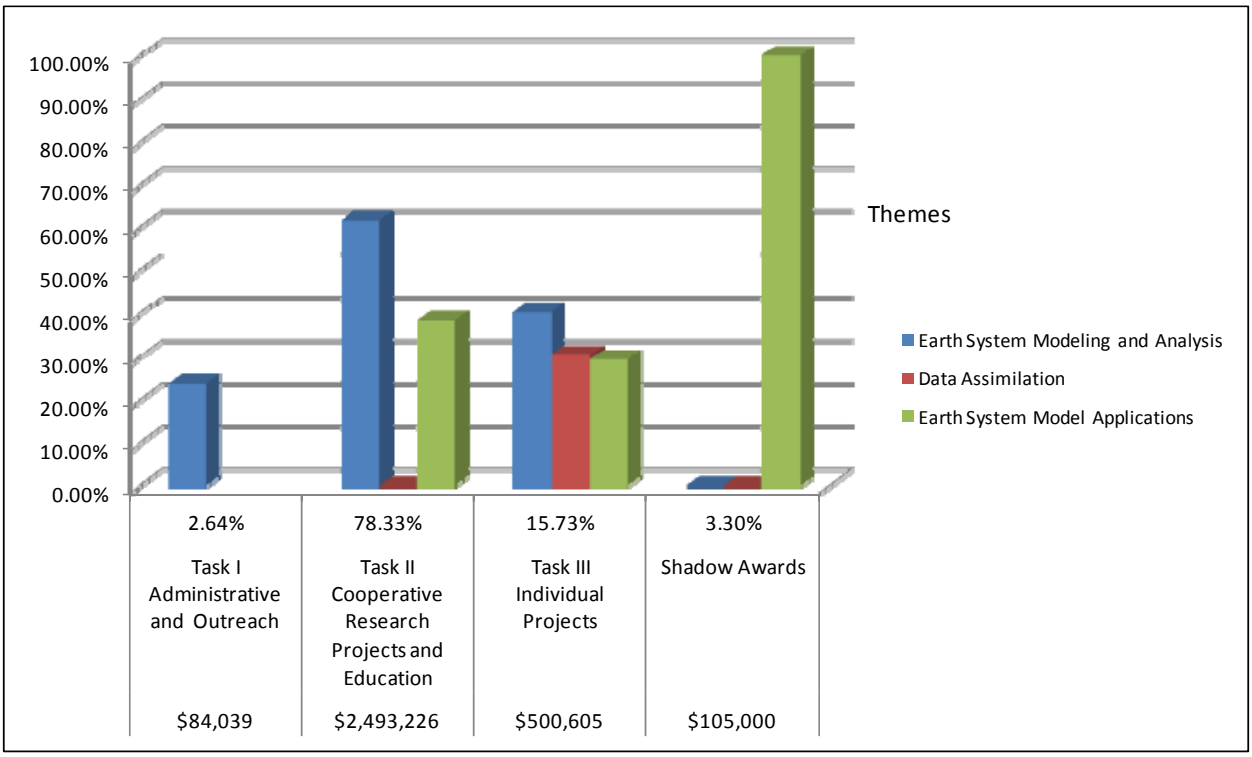
Quantifying the Source of Ozone Pollution

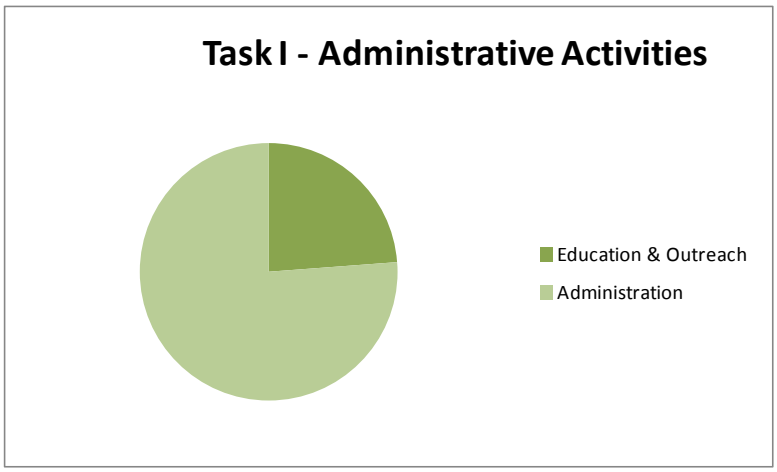
Understanding and quantifying the global sources of ozone pollution over the western United States is manifestly an important topic for the quality of life in the United States. A number of studies have shown that spring winds can carry Asian pollution into the atmosphere above North America. In a recent study, CICS Scientist Meiyun Lin, in collaboration with GFDL Scientist Larry Horowitz and former GFDL Scientist Arlene Fiore, has shown that some of this pollution can descend to the surface where it affects ground-level ozone levels. Indeed, Lin finds that Asian emissions can add 8 to 15 parts per billion of ozone to the air at the surface, comprising up to 20% of the total. The work also suggests how satellite data could be used to predict when incoming plumes of polluted air might affect air quality in the Western USA. These important findings have been highlighted as a Research Spotlight in the American Geophysical Union and featured in Science and Nature magazines, as well as a New York Times blog.

Climate Change Impacts on Biology

Prediction of the impact of climate change on terrestrial and oceanic ecosystems and diversity requires a skillful combination of empirical as well as modeling approaches as illustrated by several recent studies carried out by CICS scientists. Vincent Saba in collaboration with GFDL Scientists Charles Stock and John Dunne developed a model of climate impacts on leatherback turtles based on historical information on mature female foraging success as a function of ENSO variability, and correlations between nest success and hatchling sex ratios and local air temperature and precipitation. Forcing of this empirical model with future climate projected for 2000 to 2100 shows that air temperature in the nesting areas causes a major decline in nesting population which is difficult to compensate for by latitudinal movement. Meanwhile, CICS Scientists David Medvigy and his postdoc Su-Jong Jeong and collaborators, have examined a large terrestrial data set at Harvard Forest to determine the causes of variability in the timing of the springtime emergence of leaves (budburst). They found that budburst models including wintertime exposure to cold temperatures are favored over models based on the assumption that budburst is driven by the accumulation of warm temperature. Forcing their empirical model with 21st century climate showed an advance of up to 17 days in budburst over the US due primarily to warmer spring temperatures.

NOAA Funding by Task and Theme





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 Associate Director. Educational outreach activities included funding for MPOWIR supported graduate students. Princeton University matching funds also supported the Advancing Land-use Modeling and Analysis for Carbon Cycling Studies Workshop.

Research funds will be carried over to the next fiscal year 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

- Advancing Land-use Modeling and Analysis for Carbon Cycling Studies Workshop (Elena Shevliakova)

Task II Projects

- Assessing the Hydroclimate in a High-Resolution Global Coupled Model Framework Phase I: Annual Means and Seasonal Cycle (Sarah Kapnick)
- Bottom-up Forcing, Climate Variability, and Climate Change Impacts on Leatherback Turtles (Vincent Saba)
- Brewer-Dobson Circulation and Stratospheric Water Vapor (Martin Jucker)
- Climatic Impacts of Internal-Wave Driven Mixing in the Ocean (Angelique Melet)
- Controlling Factors in Atmospheric Oxidation Capacity (Jingqiu Mao)
- CODism (Daniel Goldberg)
- Comparison of GFDL's Atmospheric Models Against Observations during El Niño Events (Claire Radley)
- Design and Development of GFDL Data Portal Infrastructure and Publishing IPCC AR5 Simulation Data on GFDL Data Portal (Sergey Nikonov)
- Development of an Ice-Sheet Model (Olga Sergienko)
- Dynamical Mechanisms for the Teleconnection between ENSO and NAO in Late Winter (Ying Li)
- Eddy-Mean Flow Interaction in a Double Jet (Amanda O'Rourke)
- Effects of Historic Land Use and Vegetation Regrowth on 20th Century Climate Change and Terrestrial Carbon Sinks (Elena Shevliakova)
- Flexible Modeling System (FMS) (V. Balaji)
- Global-to-Regional Nesting in the GFDL Finite-Volume Atmosphere Dynamical Core (Lucas Harris)
- Hybrid Ocean Model Development (Alistair Adcroft)
- Improving the Representation of Well Mixed Greenhouse Gases in the GFDL Radiation Code (David Paynter)
- Influence of Land Surface Heterogeneity in GFDL LM3 on Micro- and Macro-Climate (Sergey Malyshev)
- Influence of Small Scale Processes in the Ocean on the Large Scale Circulation (Mehmet Ilicak)
- Investigating Tropical Cyclones using the HIRAM Aquaplanet (Andrew Ballinger)
- Modeling the Effects of Climate Change and Ocean Acidification on Global Coral Reefs (Cheryl Logan)
- Ocean, Atmosphere and Climate Dynamics (Geoffrey Vallis)
- Ocean Heat and Carbon Uptake in Transient Climate in Idealized Eddying and Non-eddying Ocean Circulation Models (Yu Zhang)
- Ocean Mixing Processes and Parameterization (Sonya Legg)

Task II Projects continued

- Offsetting and Complementary Characteristics of Sulfate and Soot Direct Radiative Forcings and Climate Responses (Ilissa Ocko)
- Processes that Control Climate Change over the Southern Hemisphere (Isidoro Orlanski)
- Properties of Convection at High Resolution (Caroline Muller)
- Quantifying the Global Sources of Local Ozone Pollution over the Western United States (Meiyun Lin)
- Seasonal Prediction of Tropical Cyclones Using the 25-km Resolution GFDL High-Resolution Atmospheric Model (HiRAM) (Jan-Huey Chen)
- The Asymmetry of the Duration and Sequencing of El Nino and La Nina (Kityan Choi)
- The Dependency of Tropical Cyclone Scale on Domain Size and Larger Scale Environment (Wenyu Zhou)
- The Effect of Surface Gravity Waves on Short-term Tropical Cyclone Forecasts and Long-wave Climatology and its Impact on Climate Variability (Yalin Fan)
- Tropical Atlantic Variability for a Coarse and High-resolution Climate Model (Takeshi Doi)
- Tropical Modes of Dry Dynamical Cores (Samuel Potter)
- Understanding Aerosol-Induced Regional Circulation and Hydroclimate Changes with Climate Model Simulations and Observations (Massimo Bollasina)
- Variability of the Nordic Seas Overflows (He Wang)

Task III Projects

- Biophysical Models and the Spatial Ecology of Temperature and Oxygen in the Mesopelagic Zone of the Global Ocean (K. Allison Smith)
- Cross-shelf Exchange Processes in the Bering Sea: Downscaling Climate Models and Ecosystems Implications (Enrique Curchitser – Rutgers)
- Data Processing for Atmospheric Observations, Land Model Parameterizations, and Data-Model Comparisons (Jorge Sarmiento)
- Detection and Attribution of Abrupt and Gradual Changes in the Carbon System (Claudie Beaulieu)
- Developing Methods for Fast Spin-up of Ocean Biogeochemical Models (Joseph Majkut)
- Global Carbon Data Management and Synthesis Project (Robert Key)
- 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 CO_2 Fluxes in an Earth System Model (Keith Rodgers)
- Top-down Controls on Marine Microbial Diversity and its Effects on Primary Productivity in the Oceans (Simon Levin)

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 CO_2 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), Robert Hallberg (GFDL), John Dunne (GFDL), Stephen Griffies (GFDL), Matthew Harrison (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 (30%)
Climate Goal: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond (70%)

Objectives: Contribute to the development of GFDL's climate models and the next generation ocean models

Methods and Results/Accomplishments:

The most important result this year was the publication of a quantification of spurious mixing in a suite of ocean-climate models. Working with Mehmet Ilicak, we use the unavailable potential energy of a system to diagnose the rate of unintended (spurious) mixing and then used this to measure numerical mixing rates in both idealized experiments and three of the GFDL ocean models. The bottom line is that at one quarter-degree horizontal resolution, a height based coordinate model such as CM2.4 has as much unintended numerical mixing as explicitly parameterized mixing. Although this is a significant error from an energetic point of view, it is not yet clear whether this has ramifications for the usefulness of the solutions and indeed we suspect not for short time-scale applications (decadal).

We have also begun the development of the one-quarter degree GOLD ocean model which, as anticipated, appears to avoid the excessive heat uptake of other models. This work is still in progress and yet to be published.

Publications:

Spurious dianeutral mixing and the role of momentum closure. Ilicak, M., Adcroft, A., Hallberg. R. and Griffies S., 2012: Ocean Modelling, 45-46 (1-2), doi:10.1016/j.ocemod.2011.10.003.

Simulated Climate and Climate Change in the GFDL CM2.5 High-Resolution Coupled Climate Model. Delworth, T.L., Rosati, A., Anderson, W., Adcroft, A., Balaji, V., Benson, R., Dixon, K., Griffies, S.M., Pacanowski, R.C., Vecchi, G.A., Wittenberg, A.T., Zeng, F. and Zhang, R., 2011. J. Climate, doi:10.1175/JCLI-D-11-00316.1.

GFDL''s ESM2 global coupled climate-carbon Earth System Models Part I: Physical formulation and baseline simulation characteristics. Dunne, J. P., John, J.G. , Adcroft, A., Griffies, S.M., Hallberg, R.W., Shevliakova, E.N., Stouffer, R.J., Cooke, W., Dunne, K.A., Harrison, M.J., Krasting, J.P., Levy, H., Malyshev, S.L., Milly, P.C.D., Phillipps, P.J., Sentman, L.A., Samuels, B.L., Spelman, M.J., Winton, M., Wittenberg, A.T., Zadeh, N., 2012. J. Climate, submitted.

Influence of Ocean and Atmosphere Components on Simulated Climate Sensitivities. Winton, M., Adcroft, A., Griffies, S.M., Hallberg, R.W., Horowitz, L.W., Stouffer, R.J., 2012: J. Climate, submitted.

Progress Report: **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), S-J Lin (GFDL), Jorge Sarmiento (Princeton)

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

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

NOAA's Goal
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). I was appointed to the National Academies Panel on 'A National Strategy for Climate Modeling' and the Science Advisory Board, Oak Ridge Climate Change Science Institute. Additionally, I was appointed as a World Climate Research Program representative to the Advisory Board of the Climate Code Foundation, 2011-2015.

Other notable developments include: grant award from DOE ($1M 2011-2013, co-PIs Held and Feuglistaler); G8 international grant award from NSF ($300k 2011-2013); co-editor, special issue of *IEEE Software*. 2011, "Climate Change: Science and Software"; and invited talk at AGU on G8 ExArch project.

References:

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

Publications:

Balaji, V., 2012: Code parallelisation on massively parallel machines. Earth System Modelling - Volume 2, L.Bonaventura, R.Redler, and R.Budich, Eds., Springer Berlin Heidelberg, Springer Briefs in Earth System Sciences, Vol.1, 77--88.

Balaji, V., 2012: The Flexible Modeling System. Earth System Modelling - Volume 3, S.Valcke, R.Redler, and R.Budich, Eds., Springer Berlin Heidelberg, Springer Briefs in Earth System Sciences, 33--41.

Balaji, V. and A.Langenhorst, 2012: ESM workflow. Earth System Modelling - Volume 5, R.Ford, G.Riley, R.Budich, and R.Redler, Eds., Springer Berlin Heidelberg, Springer Briefs in Earth System Sciences, 5--13.

DeLuca, C., G.Theurich, and V.Balaji, 2012: The Earth System Modeling Framework. Earth System Modelling - Volume 3, Springer Berlin Heidelberg, Springer Briefs in Earth System Sciences, 43--54.

Delworth, T.L., etal., 2011: Simulated climate and climate change in the GFDL CM2.5 high-Â-resolution coupled climate model. J. Climate, in advance online publication.

Easterbrook, S., P.Edwards, V.Balaji, and R.Budich, 2011: Guest editors' introduction: Climate change-science and software. Software, IEEE, 28(6), 32--35.

Guilyardi, E, and Ventakramani Balaji, et al., May 2011: The CMIP5 model and simulation documentation: A new standard for climate modelling metadata. Clivar Exchanges, 16(2), 42-46.

Progress Report Title: **Investigating Tropical Cyclones using the HIRAM Aquaplanet**

Principal Investigator: Andrew Ballinger (Princeton Graduate Student)

CICS/GFDL Collaborator: Isaac Held (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
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 large-scale controls on tropical cyclogenesis using high-resolution climate model simulations on an aquaplanet

Methods and Results/Accomplishments:

Cyclogenesis frequency with variations in SST – zonal asymmetries: GFDL's High Resolution Atmospheric Model (HIRAM) version 2.1 (on a C180 grid) has been run in an aquaplanet configuration forced with various idealized patterns of SST (Fig 1). The resulting variation in genesis frequency has been linked to changes in the large-scale fields associated with the particular SST pattern.

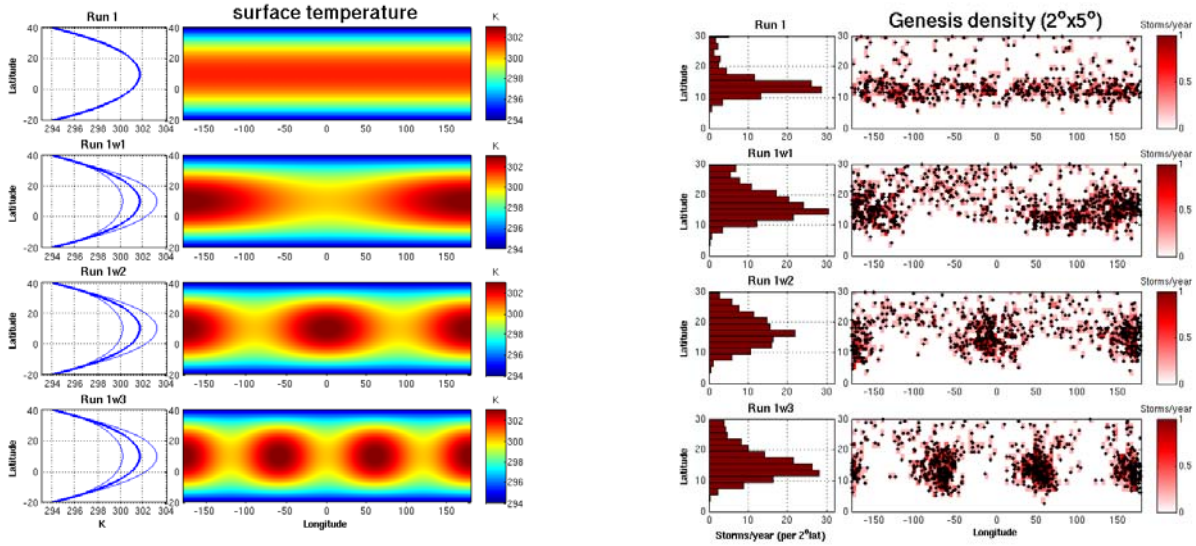


Figure 1: Left: The patterns of SST forcing (shading) for the various aquaplanet experiments, along with the meridional profiles of zonal-mean (thick blue line) and range (thin blue lines) of SSTs. Right: The corresponding genesis frequency density (shading, cyclones/year per 2°x5° grid box), along with histograms of cyclone frequency, computed by summing cyclones within each 2° latitude strip.

Tracking pre-cyclone 'pouches': 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 our preliminary results it seems that the marsupial pouch theory could well describe one of the (major) genesis pathways apparent in our aquaplanet simulations. A methodology has been developed which detects pouch-like disturbances in the HIRAM fields, allowing compositing of the pre-cyclone storm environment in a frame of reference moving with the velocity of the disturbance's critical layer.

Influence of tropical cyclones on the extratropical circulation: As a tropical cyclone (TC) moves poleward and recurves into the midlatitude westerlies, interaction occurs between the 'local' vortex and the broader stormtrack region. Observational studies, both those looking at individual events as well as those compositing over many storms, along with idealized modeling studies, have shown that these TCs can often (but not always) excite or amplify existing Rossby wave trains. Accompanying downstream development can exert influence far away from the initial TC, and linkages have been made to episodes of high-impact weather downstream in several case-studies.

By employing a storm compositing technique, we have attempted to characterize the large-scale environment associated with the poleward-moving TCs. For simplicity the compositing was made (over time and longitude) about an individual TCs northward passage through 40°N, with no initial distinction being made with respect to the storms' extratropical status. We have started to attempt to shed some further light on the interaction of poleward-moving storms with the extratropical circulation.

References:

Dunkerton, T. J., M. T. Montgomery, and Z. Wang, 2009: Tropical cyclogenesis in a tropical wave critical layer: easterly waves. Atmos. Chem. Phys., 9, 5587-5646.

Zhao, M., I. M. Held, S.-J. Lin, and G. A. Vecchi, 2009: Simulations of global hurricane climatology, interannual variability, and response to global warming using a 50-km resolution GCM. J. Climate, 22, 6653-6678.

Zhao, M., I. M. Held, and G. A. Vecchi, 2010: Retrospective forecasts of the hurricane season using a global atmospheric model assuming persistence of SST anomalies. Mon. Wea. Rev., 138, 3858-3868.

Progress Report Title: **Understanding Aerosol-Induced Regional Circulation and Hydroclimate Changes with Climate Model Simulations and Observations**

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

CICS/GFDL Collaborator: Yi Ming (GFDL), 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 understanding of the mechanisms and physical processes underpinning changes in regional hydroclimate and atmospheric circulation, especially in response to aerosol forcing. The pathways by which key physical processes influence the simulated regional climate are also investigated. Particular focus is placed on the South Asian monsoon system and the tropical region.

Methods and Results/Accomplishments:

Aerosol footprint on the long-term precipitation change over South Asia - A series of CM3 historical experiments is used to study the widespread drying of the South Asian summer monsoon during the second half of the twentieth century. The response to changes in natural and anthropogenic forcing, especially aerosols and greenhouse gases, is examined. The observed precipitation decrease, realistically simulated by the model, is found to be very likely of anthropogenic origin, and can be attributed almost entirely to aerosols. The drying is associated with 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.

Precipitation Bias over the western Indian Ocean in an atmospheric GCM: role of the meridional SST gradient - The AM3 is used to comprehensively characterize the spatio-temporal evolution of the positive precipitation bias over the southwestern equatorial Indian Ocean (SWEIO) found in most coupled and uncoupled GCMs. The oceanic bias is part of a consistent precipitation and circulation pattern over the whole Indian region. An anomalous Hadley-type circulation subsiding over India affects the monsoon evolution, as also supported by experiments with the GFDL dry dynamical core model. By means of observations and AM3 sensitivity experiments, this study makes the case that the precipitation bias over the SWEIO is forced by the model excess response to the local meridional SST gradient through enhanced near-surface meridional wind convergence. This mechanism highlights the important role of the SWEIO in simulations and future predictions of the South Asian summer monsoon.

The South Asian monsoon onset in an idealized setting: unsteady response driven by land-atmosphere processes - Perpetual (i.e., with solar radiation and SST fixed) experiments with AM3 are conducted to investigate the existence of equilibrium between the land-atmosphere system and the "external" slowly-evolving forcing over India as the monsoon evolves. In May precipitation and winds undergo a rapid northward migration and vigorously intensify compared to a control run in which insolation and SSTs are free to follow their annual cycle. The equilibrium is reached after about 250 days, and closely resembles June climatological conditions. The land-atmosphere system in May is thus far from being in equilibrium, highlighting the important role of land-atmosphere processes (of surface hydrology, in particular) in driving the transition to the monsoon regime. Minor changes are found for

other months. From a climate change perspective, aerosol-induced changes in the land-surface energy balance in late spring may be crucially amplified by the non-linear mediation of land-surface processes.

Publications:

Bollasina, M., Y. Ming, and V. Ramaswamy, 2011: Anthropogenic aerosols and the weakening of the South Asian summer monsoon. Science**,** 334, 502-505.

Bollasina, M., and Y. Ming, 2012: The general circulation model precipitation bias over the southwestern equatorial Indian Ocean and its implications for simulating the South Asian monsoon. Climate Dyn. (Accepted).

Bollasina, M., and Y. Ming, 2012: The South Asian monsoon onset in an idealized setting: unsteady response driven by land-atmosphere processes. To be submitted to Climate Dyn**.** (April 2012).

Bollasina, M.: Anthropogenic aerosols and the weakening of the South Asian summer monsoon, Institute for Terrestrial and Planetary Atmospheres, School of Marine and Atmospheric Sciences, Stony Brook University, NY, 29 February 2012 (invited).

Bollasina, M.: The South Asian monsoon onset in an idealized setting: unsteady response driven by land-atmosphere processes, 24th Conference on Climate Variability and Change, 92nd American Meteorological Society Annual Meeting, New Orleans, LA, 22-26 January 2012.

Bollasina, M.: Precipitation bias over the western Indian Ocean in an atmospheric GCM: role of the meridional SST gradient, WCRP Open Science Conference: Climate Research in Service to Society, Denver, CO, 24-28 October 2011.

Bollasina, M.: Anthropogenic Aerosols and the Weakening of the South Asian Summer Monsoon, WCRP Open Science Conference: Climate Research in Service to Society, Denver, CO, 24-28 October 2011.

Bollasina, M.: Anthropogenic Aerosols and the Weakening of the South Asian Summer Monsoon, Gordon Research Conference: Clouds, Aerosols, Precipitation and their Role in Climate and Climate Change, Waterville, ME, 10-15 July 2011.

Bollasina, M.: Multi-faceted forcing on the South Asian monsoon, GFDL Informal Lunchtime Seminars, Princeton, 19 May 2011.

Bollasina, M.: The expanding Thar Desert: a modeling study of its impact on the South Asian monsoon, AOS Monday Lunch Seminars, Princeton, 9 May 2011.

Progress Report Title: **The Asymmetry of the Duration and Sequencing of El Nino and La Nina**

Principal Investigator: Kityan Choi (Princeton Graduate Student)

CICS/GFDL Collaborator: Gabriel Vecchi (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 validate and understand the cause and effect of the overall asymmetric behaviors of El Nino and La Nina in terms of their durations, sequencing and strength

Methods and Results/Accomplishments:

With the 4000-year record of CM2.1 control run, the likelihood of finding a La Nina following an El Nino is found to be systematically higher than the other way round, despite the multi-decadal variability that exists (Wittenberg 2009). The time it takes for the transition of an El Nino to a La Nina is also systematically shorter. Such behavior is noticeable in the latest observational records (Larkin and Harrison 2002, McPhaden and Zhang 2009, Ohba and Ueba 2009, Okumura and Deser 2010). Together with the duration and sequencing, the skewness in the surface temperature anomalies between El Nino and La Nina has long been recognized and studied (Burgers and Stephenson 1999).

We are aiming at explaining all of these first-order asymmetries of the El Nino-Southern Oscillation (ENSO) using a conceptual model as simple as possible yet can be validated with the use of fully coupled numerical models, single-component numerical models and observations.

We first note that the strength of the surface wind response over the western equatorial Pacific is more sensitive to the temperature departures over the eastern equatorial Pacific during warm episodes than during the cold ones, as is discernible from the FSU wind pseudostress analysis and the CM2.1 control run aforementioned. Using a modified Battisti and Hirst delay-oscillator model imposed by white noise, we are able to simulate oscillations in which the time it takes to transit from a cold event to a warm event is longer than that for transitions from warm to cold events, by allowing the proportionality constant between the western Pacific wind anomaly and the eastern Pacific temperature anomaly be larger during warm events. The likelihood of having an El Niño being followed by a La Nina is also higher. For certain parameter regimes, in particular, when the negative oceanic feedback is weaker than the positive oceanic feedback, warm anomalies are systematically larger than the cold ones, consistent with the observed tendency that El Niño's tend to be stronger.

References:

Gerrit Burgers and David B. Stephenson, "The 'normality' of El Niño," Geophysical Research Letters 26, no. 8 (n.d.): PP. 1027-1030.

Narasimhan K. Larkin and D. E. Harrison, "ENSO Warm (El Niño) and Cold (La Niña) Event Life Cycles: Ocean Surface Anomaly Patterns, Their Symmetries, Asymmetries, and Implications," Journal of Climate 15, no. 10 (May 2002): 1118-1140.

Michael J. McPhaden and Xuebin Zhang, "Asymmetry in zonal phase propagation of ENSO sea surface temperature anomalies," Geophysical Research Letters 36 (July 3, 2009): 6 PP.

Masamichi Ohba and Hiroaki Ueda, "An impact of SST anomalies in the Indian Ocean in acceleration of the El Niño to La Niña transition," Journal of the Meteorological Society of Japan 85, no. 3 (n.d.): 335-348.

Yuko M. Okumura and Clara Deser, "Asymmetry in the Duration of El Niño and La Niña," Journal of Climate 23, no. 21 (November 2010): 5826-5843.

Andrew T. Wittenberg, "Are historical records sufficient to constrain ENSO simulations?," Geophysical Research Letters 36 (June 23, 2009): 5 PP.

Progress Report Title: **The Effect of Surface Gravity Waves on Short-term Tropical Cyclone Forecasts and Long-wave Climatology and its Impact on Climate Variability**

Principal Investigator: Yalin Fan (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Shian-Jiann Lin, Stephen Griffies (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 (50%)
Weather & Water Goal: Serve Society's Needs for Weather and Water Information (50%)

Objectives: Improve global model forecasts on tropical cyclones; Evaluate global wave climatology from wave coupled high-resolution atmospheric model (HiRAM); Develop wave coupling for GFDL coupled model (CM2.1)

Methods and Results/Accomplishments:

A fully coupled global atmosphere-wave simulation system with sea state dependent momentum flux parameterization has been developed early last year. Its performance on 5-day hurricane forecasts has been evaluated for the 2008 and 2009 season.

The simulated global wave climatology for a 29-year period shows strong response to climate variability (i.e. NAO and SOI) and has very good agreements with observations and reanalysis (in situ buoys, satellite altimeter measurements, and ERA-40 reanalysis) in terms of magnitude, spatial distribution, and scatter. The comparisons with satellite altimeter measurements indicate that our model has improved the significant wave height low bias in ERA-40 reanalysis. A manuscript has been submitted to the Journal of Climate on this work.

The wave model (WAVEWATCH III) has been incorporated into the GFDL coupled model, CM2.1 (Figure 1). To our knowledge, this is the first global coupled model in the world that has two-way coupling with a wave model. This newly coupled system is evaluated using the 1990 control run following Delworth et al (2006) and shows improvement on surface wind climatology (Figure 2).

References:

Delworth, T., and Coauthors, 2006: GFDL's CM2 global coupled climate models. Part I: Formulation and simulation characteristics. J. Climate, 19, 643–674.

Publications:

Fan, Y., S. Lin, I. M. Held, Z. Yu, and H. L. Tolman, 2012: Global Ocean Surface Wave Simulation using a Coupled Atmosphere-Wave Model. J. Clim, in press.

Fan, Y. and S. Griffies, 2012: Ocean Surface Gravity Wave Effects On Global Climate Simulations. Ocean Science Meeting, Salt Lake City, UT.

Fan, Y., S. Lin, I. M. Held, Z. Yu, and H. L. Tolman, 2011: Global Ocean Surface Wave Simulation using a Coupled Atmosphere-Wave Model, AGU, San Francisco, CA.

M. Hemer, Y. Fan, N. Mori, A. Semedo, V. Swail, and X. Wang, 2011: Global wave climate change from a community ensemble of wind-wave projections. 12th International Workshop on Wave Hindcasting and Forecasting and 3rd Coastal Hazards Symposium (WAVES 2011), Hilo, HI.

Fan, Y., 2011: Coupling of WAVEWATCH III to GFDL Atmospheric model, and its applications on global wave climate change research and hurricane predictions. NCEP/EMC, Camp Springs, MD.

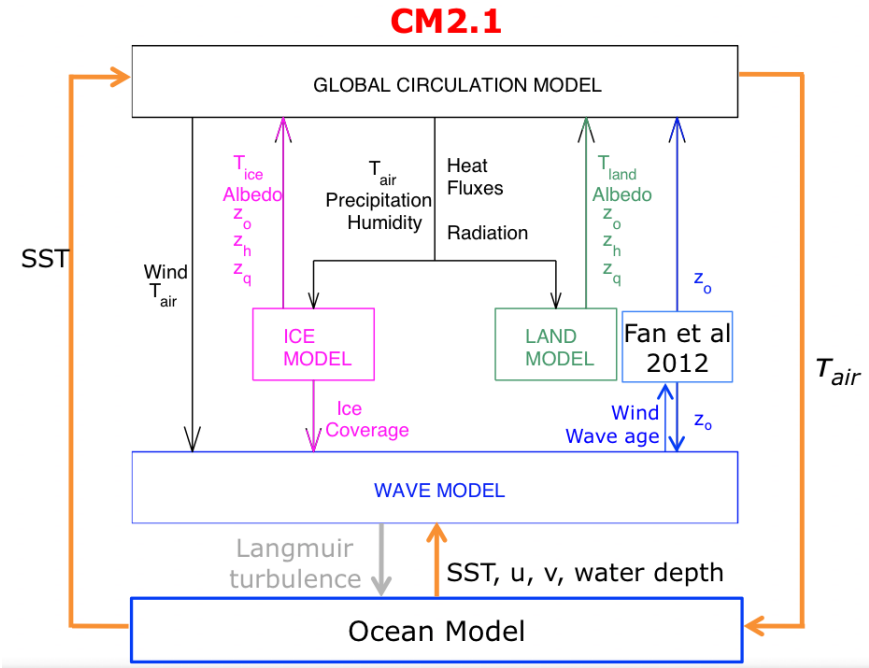


Figure 1. A schematic diagram of the atmosphere-land-ice-ocean-wave coupled model. The arrows indicate the prognostic variables that are passed between the model components. In the diagram, z_o, z_q, and z_h, are momentum, latent heat, and sensible heat roughness lengths. T_{air}, T_{ice}, and T_{land} are air, ice, and land temperatures at the surface.

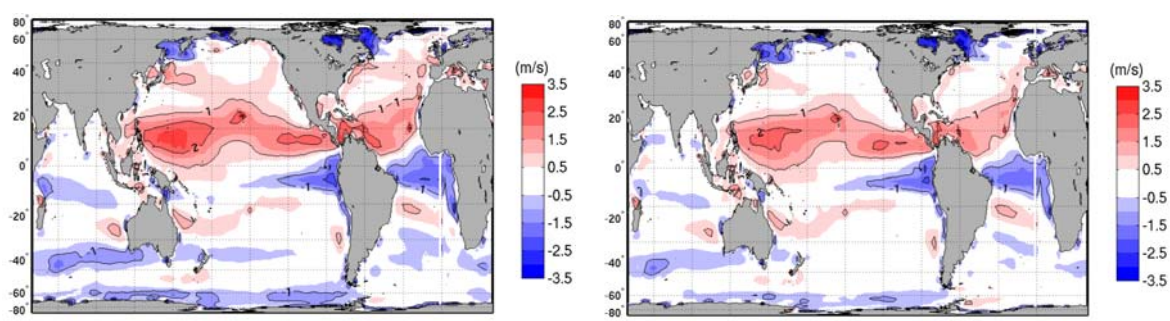


Figure 2. Maps of errors in simulations of annual-mean 10-m wind speed. The errors are computed as model minus observations, where the observations are from ERA-40 reanalysis data averaged from 1981 to 2001. The left panel is the original CM2.1 results and the right panel is the atmosphere-land-ice-ocean-wave coupled model results. Both model results are 100 year means.

Progress Report Title: **CODism**

Principal Investigator: Daniel Goldberg (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Olga Sergienko (Princeton), Robert Hallberg (GFDL)

Other Participating Researchers: Chris Little (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: Develop code for an ice sheet/ice shelf component in GOLD (or FMS) for purposes of coupling with ocean

Methods and Results/Accomplishments: Achieved. Model was successfully run in parallel, source code in CVS.

Publications:

Goldberg, D.N., C.M. Little, O.V. Sergienko, A. Gnanadesikan, R. Hallberg, M. Oppenheimer, Investigation of land ice-ocean interaction with a fully coupled ice-ocean model, Part 1: Model description and behavior. Submitted to JGR-Earth Surface.

Goldberg, D.N., C.M. Little, O.V. Sergienko, A. Gnanadesikan, R. Hallberg, M. Oppenheimer, Investigation of land ice-ocean interaction with a fully coupled ice-ocean model, Part 2: Sensitivity to external forcings. Submitted to JGR-Earth Surface.

Progress Report Title: **Global-to-Regional Nesting in the GFDL Finite-Volume Atmosphere Dynamical Core**

Principal Investigator: Lucas Harris (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Shian-Jiann Lin (GFDL), Zhitao Yu (UCAR), Zhi Liang (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 (30%)
Weather & Water Goal: Serve Society's Needs for Weather and Water Information (70%)

Objectives: Develop a global-to-regional nested version of the atmosphere dynamical core for use in GFDL HiRAM for hurricane forecasting, regional climate simulation, and other applications requiring locally-enhanced model resolution

Methods and Results/Accomplishments:

We have developed an efficient two-way grid nesting for the dynamical core and for dynamically-passive tracers. This includes a simple mass-conservative coupling for air mass, and a more sophisticated flux-form boundary condition to conserve tracer mass while preventing non-physical negative masses. A means to simultaneously run the coarse and nested grids ("concurrent nesting") was also developed, which could allow very efficient nested simulations in environments with many available processors (such as Gaea). Tests with the dynamical core indicate that a two-way nested simulation could be performed with as little as a 10% increase in integration time compared to running the coarse grid alone, and much faster than a single global grid with the same resolution globally as the nested grid. Work has been underway to merge the nesting code into the full-physics HiRAM, and would also be available to the other GFDL atmosphere models.

Research is also underway for seasonal prediction of severe winter storms. This uses the same HiRAM configuration and simulation technique as the highly successful seasonal predictions of Atlantic hurricanes of Chen and Lin (2011), but instead for the winter season (December--February). An efficient cyclone tracker was written to identify Northern Hemisphere storms over the season, to identify the maximum winds and six-hour snowfall rates in each storm, and to produce the number of storms of certain intensities affecting particular regions (such as the central US Atlantic coast or the Pacific Northwest) over the season.

References:

Chen, J H., and Shian-Jiann Lin, June 2011: The remarkable predictability of inter-annual variability of Atlantic hurricanes during the past decade. Geophysical Research Letters, 38, L11804, DOI:10.1029/2011GL047629.

Publications:

Harris, L M, and S.-J. Lin: A two-way nested global-regional dynamical core on the cubed-sphere grid. In review at Monthly Weather Review.

Harris, L M: A two-way nested global-regional dynamical core on the cubed-sphere grid. Workshop on Global-to-Regional Climate Simulation. http://public.lanl.gov/ringler/BDBS/BDBS.html Santa Fe, NM, 3--5 August 2011.

Harris, L M: A two-way nested global-regional dynamical core on the cubed-sphere grid. AMP Lunchtime seminar, National Center for Atmospheric Research, Boulder, CO, 9 August 2011.

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

Principal Investigator: Mehmet Ilicak (Associate Research Oceanographer)

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 models.

Methods and Results/Accomplishments:

Spurious diapycnal mixing is one of the most challenging problems in geo-potential coordinate ocean models. We investigate numerical mixing using idealized experiments with four different ocean general circulation models (GOLD, MOM, ROMS and MITgcm). The results show that only GOLD, an isopycnic model, has zero numerical cross isopycnal mixing. Terrain following coordinate ocean model, ROMS, has the second least spurious mixing. The reason behind this is that ROMS employs a dissipative momentum scheme. When we employ similar schemes in MOM and MITgcm, the numerical mixing decreases significantly.

We also perform global simulations using GFLD's GOLD and MOM ocean codes. It is shown that ¼ degree z-coordinate model, MOM, has more spurious mixing than 1 degree MOM and GOLD. This is very important for the future of climate modeling since nowadays higher resolution climate models are being used in the climate community.

Some idealized simulations have been also employed to study the horizontal convection. There is a still debate in the community if the ocean can have a strong deep circulation with stratification by only cooling and warming at the surface (i.e. horizontal convection). We perform very high resolution non-hydrostatic simulations and show that at high Rayleigh numbers, the circulation cannot be maintained.

Publications:

Ilıcak, M., Adcroft, A., Griffies, S. M., Hallberg, R., Spurious dianeutral mixing and the role of momentum closure, Ocean Modelling , 45-46, 37-58, 2012.

Ilıcak, M., and Vallis, G. K., Simulations and Scaling of Horizontal Convection, Tellus A. accepted March, 2012.

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

Principal Investigator: Sonya Legg (Princeton Research Oceanographer)

CICS/GFDL Collaborator: Robert Hallberg, Steve Griffies, (GFDL), Alistair Adcroft, Mehmet Ilicak, Maxim Nikurashin, Maarten Buijsman, He Wang, Angelique Melet (Princeton)

Other Participating Researchers: 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 due to oceanic overflows. In collaboration with Jody Klymak at University of Victoria, a parameterization of tidal mixing at tall steep topography has been developed. Efforts in the past year have focused on exploring the logistics of implementing this parameterization into global circulation models, and the sensitivity of the estimated dissipation to the implementation approximations. Preliminary results were presented at the recent Internal Wave-Driven Mixing Climate Process Team workshop at Scripps in January 2012. A second aspect of tidal mixing, being explored in collaboration with Maarten Buijsman and Jody Klymak, is the role of multiple steep ridges in leading to constructive interference which can enhance the total mixing. Two manuscripts describing theoretical aspects and applications of this phenomena to the South China Sea respectively are submitted or in press (Klymak et al, 2012; Buijsman et al, 2012).

A complementary problem, mixing generated by tidal flow over smaller amplitude rough topography, has been considered in collaboration with postdoc Maxim Nikurashin (Nikurashin and Legg, 2011). This study identified nonlinear wave-wave interaction as a mechanism for transferring internal wave energy to small scales, and Legg's efforts in the past year have focused on establishing a theoretical framework for parameterizing the mixing due to this process. A further topic of investigation has been the fate of large-scale internal waves on reflection from sloping topography, and a manuscript describing the dependence of dissipation on the topographic parameters is in progress. Finally, CICS postdoc Angelique Melet, funded by the Internal Wave-Driven Mixing CPT, has been working under the supervision of Robert Hallberg and Legg to implement a new, more physically based parameterization of tidal mixing, developed by Kurt Polzin at WHOI, into the GOLD ocean climate model, and evaluate the sensitivity of the large-scale stratification to the change in mixing distribution introduced by this new parameterization. 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.

With regard to overflows, collaboration with CICS postdoc Mehmet Ilicak led to a publication in Ocean Modeling (Ilicak, Legg, Adcroft and Hallberg, 2011), and AOS student He Wang is continuing work under Legg's supervision to investigate the behavior of overflows in the climate models, in particular their variability and role in the climate system. Of particular interest is the difference in Atlantic Overturning Circulation variability between CM2M and CM2G which may result from the difference in overflow representation between the two models, a hypothesis which He Wang will test more thoroughly in the next few months.

Publications:

Buijsman, M.C., S. Legg and J. Klymak, 2012: Double ridge internal tide interference and its effect on dissipation in Luzon Strait. J. Phys. Oceanogr., in press.

Ilicak, M., S. Legg, A. Adcroft and R. Hallberg, 2011: Dynamics of a dense gravity current flowing over a corrugation. Ocean Modelling, v38, 71-84.

Klymak, J.M., M. Buijsman, S. Legg and R. Pinkel, 2012: Parameterizing baroclinic internal tide scattering and breaking on supercritical topography: the one- and two-ridge cases. J. Phys. Oceanogr., submitted.

Nikurashin, M., and S. Legg, 2011: A mechanism for local dissipation of internal tides generated at rough topography. J. Phys. Oceanogr., v41, 378-395.

Legg, S., J. Klymak and M. Nikurashin, 2011: Mixing in a rotating stratified fluid by breaking internal tides, Keynote lecture, Proceedings of 7th International symposium on stratified flows.

Legg, S., 2011: Mixing generated by tidal flow over topography and its parameterization for climate modeling. Plenary lecture, Swedish society for marine sciences, Visions of the Sea 2011 conference.

Melet, A.V., R.W. Hallberg, S. Legg, K. Polzin, 2012: Sensitivity of the Pacific ocean state to the formulation of the vertical profile of internal-tide driven mixing, TOS/ASLO/AGU 2012 Ocean Sciences Meeting, Abstract ID 10208.

Wang, H., S. Legg, R. Hallberg, 2012: The contribution of atmospheric forcing to decadal variations of the Nordic Overflows. TOS/ASLO/AGU 2012 Ocean Sciences Meeting, Abstract ID 11521.

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)

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

Other Participating Researchers: Juan A. Bonachela (EEB, Princeton), Michael Raghib (Los Alamos National Laboratory), Miguel A. Muñoz (University of Granada, Spain)

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 contributes to generate and maintain diversity in different regimes of nutrient availability. Both goals are closely related (see below).

Methods and Results/Accomplishments:

In the last twelve months, we have finished the development of an individual-based model (IBM) describing phytoplankton nutrient uptake (see [P1]). This model allows the cell to acclimate to changes in its environment by altering the number of transporters that incorporate nutrient ions into the cytoplasm. By using simple but mechanistically justified equations, this model predicts important ecological consequences associated with the addition of this acclimation ability that can be relevant especially in oligotrophic areas of the ocean, areas where earth system models have special difficulties to make reliable predictions on primary productivity and community structure. We also have scaled up the IBM to the level of the population (population-level model, PLM), which has allowed us to simplify the approach above and make it easier to be used as a tool, embedded in more complicated frameworks (see below). The use of both versions of the model allowed us to conclude that the extreme values for the cell quota of a nutrient, as well as the maximum photosynthetic rate, the maximum rate of uptake-protein production, and the affinity of the protein for that nutrient, are the main traits determining the growth and uptake of the organism (see [P1] and first goal presented in objectives).

Concerning the second goal, we are using both levels of description to investigate how the presence of viruses affects the uptake and growth of a single species (IBM), and how it affects to the diversity of a community formed by N different phytoplankton species (PLM). Our uptake model, focused on the ecological timescale, proves to be an essential tool to tackle these questions. For the first task, we use an explicit description of the individual interactions between the nutrient and the phytoplankton cells, and between the virus cells and the phytoplankton uptake proteins (gateways for viral infection); by using the latent period of the virus as degree of freedom, we have studied how that delay between infection and final lysis affects population-level observables such as uptake and growth. The preliminary results indicate that if lysis is considered to be instantaneous (i.e. negligible latent period), the effect of the pool of virus can be represented at the population level with a mortality term proportional to the burst size, density of virus and plankton density; this is equivalent to the standard term regularly used in population-level models. However, a non-vanishing latent period modifies non-trivially this term. We are currently

working on the deduction of a population-level term able to describe this phenomenology in a synthetic way. On the other hand, as detailed in the "Future Work" report, we are using the PLM mentioned above in a chemostat environment, with one single nutrient, one single virus species and N species of phytoplankton, to investigate how the presence of viruses affects community structure. With no viruses, the competition between the different species in such conditions will result in one single species outcompeting the rest. We are researching how a pool of viruses changes this outcome, first by using the standard mortality term to represent the interactions with the pool of viruses, and in the near future, by using the new mortality term deduced when the latent time is different from zero.

Also, delving further into top-down controls on phytoplankton community structure, we have investigated the role that demographic stochasticity (noise at the level of the population associated with birth and death events at the level of the individual) plays in the ecological interactions between zooplankton and phytoplankton (see [P2]). We have shown that it is possible to modify classic deterministic models (like the Levin-Segel model, see [1]) in a simple way to add this stochasticity and still be able to keep essential features such as phytoplankton and zooplankton patchiness (see the "Future Work" report for further details on this).

As a last note, to further assess how our flexible description can help improve the predictability of earth system models, we have modified a one-dimensional version of M.I.T.'s Darwin model within which to embed our PLM. This adds flexibility and realism to the Darwin model, which has to be combined with the fact that, as our model is based on a quota-based description, the modifications to the Darwin can help take it from its original Monod-based description to a quota-based description (under development). The plots in Figure 1 can give an idea of how much these models can benefit from using our approach. We performed the theoretical exercise of running simulations in a chemostat environment with a Monod-like approach (similar to Darwin) and our dynamic, quota-based approach. We measured the relative error in growth rate, Δ_μ, and in the break-even concentration (concentration of the most limiting nutrient in the stationary state for the population), Δ_{R^*}, in order to assess the possible ecological differences between approaches. As we can see, for the parametrization used in this example, the organism described by our approach would always outcompete the one described with the Darwin model, due to its larger growth rate and smaller break-even concentration. We are in close contact with Mick Follows and Stephanie Dutkiewicz (M.I.T.) for discussions on the relevance and further development of this approach.

References:

S. A. Levin and L. A. Segel, Hypothesis for Origin of Planktonic Patchiness. Nature 259, 659 (1976).

Publications:

[P1] J. A. Bonachela, M. Raghib, and S. A. Levin, Acclimation or Starvation: A Dynamic Model of Flexible Phytoplankton Nutrient Uptake, Proc. Natl. Acad. Sci. USA 108(51), 20633 (2011).

[P2] J. A. Bonachela, M. A. Muñoz, and S. A. Levin, Patchiness and Demographic Noise in Three Ecological Examples, submitted to J. Stat. Phys. (2012).

Figures:

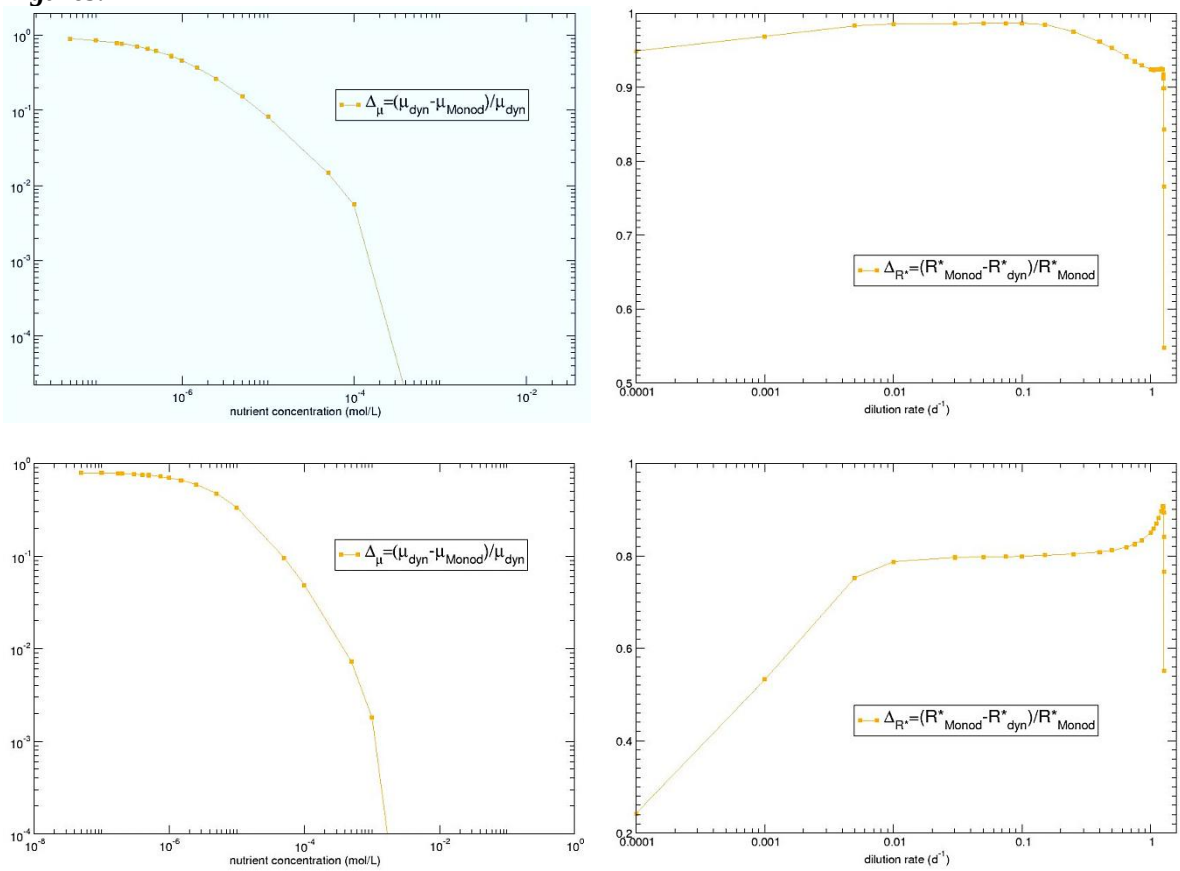


Figure 1: Relative distance in terms of growth rate, μ, and break-even concentration, R*, between the Monod-based approach followed by Darwin and the dynamic approach introduced in [P1]. Top: Without considering the physical limitations to the uptake emerging when nutrient is scarce (diffusion limitation). Bottom: With the diffusion-limitation correction for the uptake rate explained in [P1]. See [P1] and references therein for further details on that correction.

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

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 understand the linkages between ENSO and the Northern Hemisphere atmospheric circulation

Methods and Results/Accomplishments:

We use a variety of observational datasets (reanalyses) and numerical experiments (two coupled general circulation models developed at GFDL, CM2 and CM3), and an extensive array of diagnostic techniques, to examine the ENSO/NAO link from both tropospheric and stratospheric pathways.

For the tropospheric pathway, we found that ENSO forcing in the tropical Pacific modulates the large-scale background circulation pattern in the North Pacific-North America-North Atlantic sector, which alters the location and strength of the storm tracks. The disturbances embedded in these storm tracks in turn influence the background flow through eddy-induced tendencies associated with vorticity transports. Such eddy forcing in the North Atlantic sector is seen to play a substantial role in determining the phase of the local NAO.

For the stratospheric pathway, particular attention is devoted to the role of ENSO in modifying the tropospheric planetary-scale waves (zonal wavenumbers one and two), which propagate upward, and then change the stratospheric polar vortex through eddy-mean flow interaction. The effect on the modified polar vortex could in turn descend back into the troposphere and affect the NAO. In addition, the effects of planetary wave refraction in the upper troposphere on the eddy-driven circulation cells in the troposphere, and the linkage between the lower branches of these cells and the near surface wind patterns has also been examined.

Publications:

Li, Y, and N.-C. Lau, January 2012: Impact of ENSO on the atmospheric variability over the North Atlantic in late winter – Role of transient eddies. J. Climate, 25(1), doi:10.1175/JCLI-D-11-00037.1.

Li, Y, and N.-C. Lau: Contributions of Downstream Eddy Development to the Teleconnection between ENSO and the Atmospheric Circulation over the North Atlantic. J. Climate. doi:10.1175/JCLI-D-11-00377.1, in press.

Li, Y. and N.-C. Lau,: Stratospheric role in the teleconnection between ENSO and the NAO. to be submitted to J. Climate.

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, 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 that we considered 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, we have found it difficult to satisfactorily implement the TMM in the GFDL MOM4p1 ocean model. Previous uses of the method (Khatiwala et al., 2008) applied the TMM to ocean models that had grid cells of constant volume. The new generation of models used by GFDL includes parameterizations of the free surface and bottom cells that do not have constant volume. Likewise, the vertical coordinates are often cast in pressure space instead of in depth. In testing our implementation of the TMM, we found that mass conservation was difficult to achieve with this newer generation of models. Significant changes to the methodology would be required to implement the TMM in the MOM4p1 model. We have halted current work on developing this method for the time being while other methods of accelerating biogeochemical simulations are being investigated, including flux accumulation and coarse graining physical models.

References:

Khatiwala, S. 2008. "Fast spin up of Ocean biogeochemical models using matrix-free Newton–Krylov." Ocean Modelling 23 (3-4): 121-129. doi:10.1016/j.ocemod.2008.05.002. http://linkinghub.elsevier.com/retrieve/pii/S1463500308000589.

Progress Report Title: **Influence of Land Surface Heterogeneity in GFDL LM3 on Micro- and Macro-Climate**

Principal Investigator: Sergey Malyshev (Princeton Professional Specialist)

CICS/GFDL Collaborator: Elena Shevliakova (Princeton), Ronald J. Stouffer (GFDL)

Other Participating Researchers: Stephen W. 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

Objectives: To understand the direct influence of land surface properties change due to human land use on the microclimate within each grid-cell, as well as possible influence on larger-scale climate, in the framework of GFDL's earth-system model ESM2M.

Methods and Results/Accomplishments:

Land cover changes can affect regional climate through changes in the surface properties, such as albedo, surface roughness, and rooting depth and, therefore, water available for transpiration (Pitman et al. 2009, Findell et al., 2007). Changes in surface properties shift the partition between components of the land surface energy balance, resulting in changes of near-surface air temperature. Additionally, change of the land surface properties may change the local balance of water and potentially affect precipitation and other climate variables on larger scale.

However, sign and the magnitude of the effect are uncertain and largely model-dependent (Pitman et al. 2009). Also, it is not clear if the fully-coupled ocean-land-atmosphere can exhibit some large-scale response to the local land properties change that the simulations with prescribe sea surface temperature would miss.

To examine those questions, we looked at the output of IPCC AR5 historical simulation performed with the GFDL's Earth System Model ESM2M. The tiling structure of the land model LM3, and its unique ability to calculate water and energy balance separately for each of the tiles makes it highly suitable for this purpose.

Upper left-hand panel of Figure 1 shows the summer-time difference of near-surface temperature between cropland and natural vegetation, averaged over the last 20 years of ESM2M historical simulation (1986-2005). Note that these are the differences between the tiles within the same grid cell within the same model run: the atmospheric forcing acting on each tile within the grid cell is the same, but differences in land surface properties result in different response.

The summer-time temperatures are higher for all human-disturbed land tiles (crops, pastures, and secondary vegetation), but the largest changes occur on the cropland. This is because the harvesting policy adopted in the model maintains much smaller biomass of crops compared to other human-disturbed land and to natural vegetation, and therefore the difference in surface properties between croplands and natural vegetation is the largest.

The fluxes shown in Figure 1 show that the land use increases the surface albedo, reducing the short-wave radiation input. However, reduction of evaporation and associated latent heat exchange overwhelms the albedo effect and results in overall warming. It is interesting to note that the water in the

upper 0.3 m of soil is higher on croplands, but despite that the evapotranspiration is smaller because of the lower biomasses and consecutively lower ability to uptake water from the soil.

In the winter time, the micro-climate effect of the land use change is opposite (not shown): cooling over the most of the land-disturbed surface, with changes on crops being the largest. The analysis of fluxes demonstrate that in mid- and high-latitudes the major factor is the reduction of the net surface short-wave radiation due to direct albedo change due to land use, and increased snow-albedo effect.

To examine whether the land use impact on the near-surface climate is limited to the regions of the land use, or can be expected to have some long-range effects, we compare two fully-coupled runs of the ESM2M. One is the concentration-driven historical simulation, where all anthropogenic forcings were specified according the AR5 input data. The other is the same, except there was no land use (potential vegetation run). Figure 2 shows December-January-February (DJF) and June-July-August (JJA) differences in near-surface temperature and precipitation between those two runs. Statistically significant changes occur mostly in the regions of intense land use, and teleconnection patterns do not seem to exist. This is consistent with the results shown in Pitman et al. 2009, except that this result was obtained with fully-coupled model and seems to contradict their hypothesis that including fully-coupled ocean may expand the regions of land use influence.

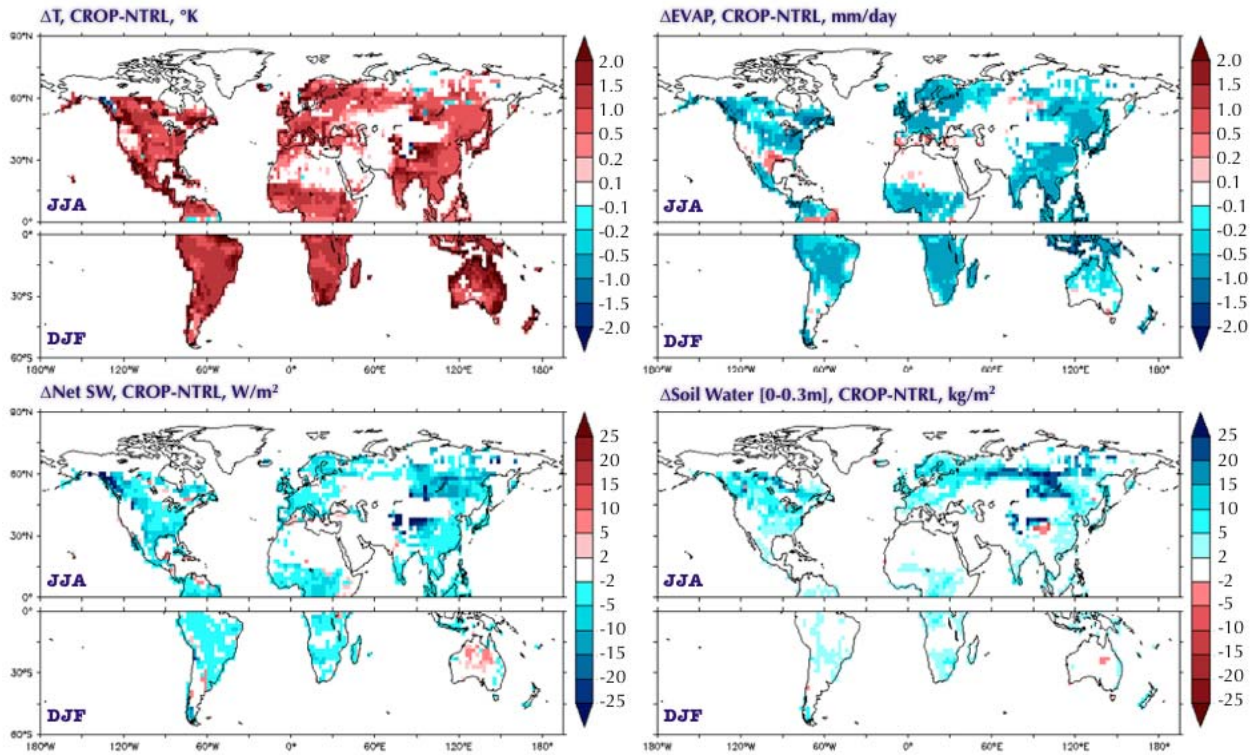


Figure 1. Summer-time differences between crop land and the natural vegetation, 1986-2005 average. From upper-left hand, counter-clockwise: near-surface temperature; total evaporation rate; water in the upper 0.3 m of soil; net short-wave radiation.

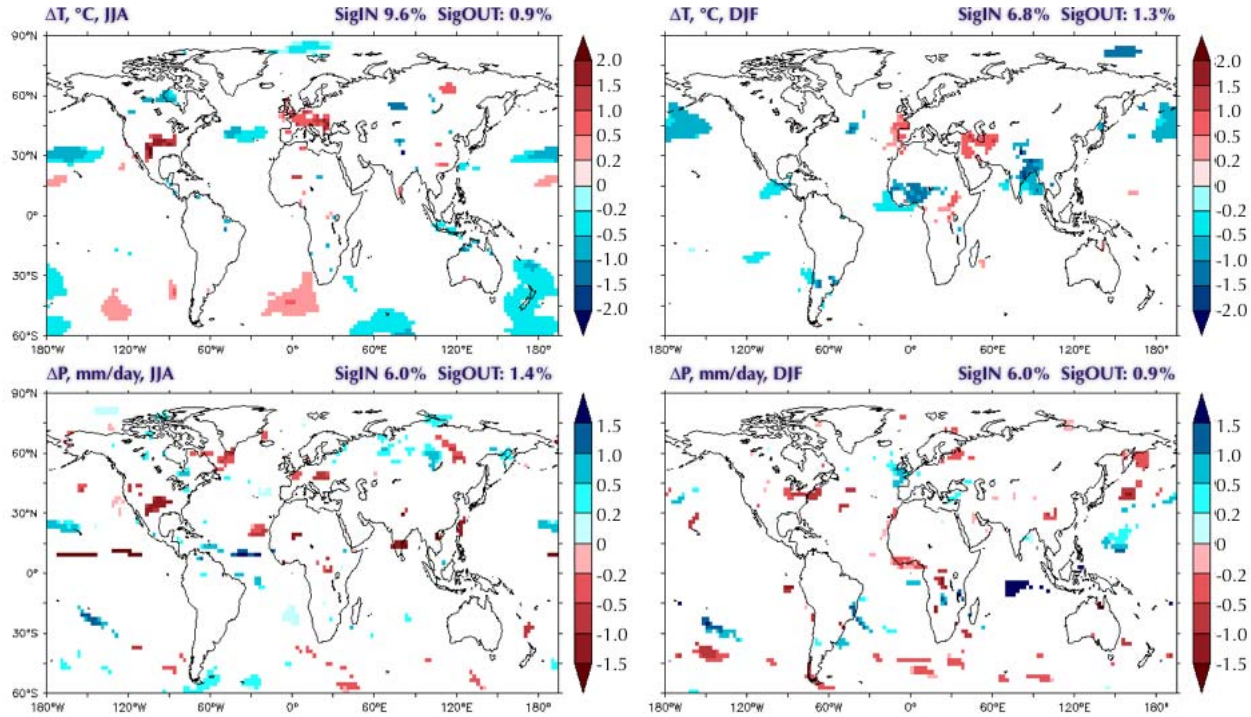


Figure 2. Changes in near-surface temperature and precipitation between full land-use run of ESM2M and respective no-land-use simulation (potential vegetation). 1986-2005 average; only regions with statistically significant at 95% confidence level are shown. SigIN: percent of land area that exhibits significant change within the regions of intense land use. SigOUT: percent of land area that exhibits significant change outside of the regions of intense land use. Intense land use regions are defined as those where change in leaf area index are larger than 0.5 (Pitman et al. 2009)

References:

Findell, K. L., Shevliakova, E., Milly, P. C. D., and Stouffer, R. J. (2007): Modeled impact of anthropogenic land cover change on climate. Journal of Climate, 20, 3621–3634, doi:10.1175/JCLI4185.1**.**

Pitman, A. J., de Noblet-Ducoudré, N., Cruz, F. T., Davin, E. L., Bonan, G. B., Brovkin, V., Claussen, M., Delire, C., Ganzeveld, L., Gayler, V., van den Hurk, B. J. J. M., Lawrence, P. J., van der Molen, M. K., Reick, C. H., Seneviratne, S. I., Strengers, B. J., and Voldoir, A. (2009): Uncertainties in climate responses to past land cover change: First results from the LUCID intercomparison study. Geophysical Research Letters, 36, L14814, doi:10.1029/2009GL039076.

Publications:

Malyshev, S., Shevliakova, E., Stouffer, R. J., and Pacala, S. W. (2011): Land Use and Land Surface Heterogeneity in GFDL LM3 (Invited), Abstract B51R-08 presented at 2011 Fall Meeting, AGU, San Francisco, Calif., 5-9 Dec.

Koster, R D., C Tony Gordon, and Sergey Malyshev, et al., October 2011: The second phase of the global land-atmosphere coupling experiment: Soil moisture contributions to subseasonal forecast skill. Journal of Hydrometeorology, 12(5), DOI:10.1175/2011JHM1365.1.

Sentman, Lori T., Elena Shevliakova, Ronald J Stouffer, and Sergey Malyshev, October 2011: Time scales of terrestrial carbon response related to land-use application: Implications for initializing an earth system model. Earth Interactions, 15(30), DOI:10.1175/2011EI401.1.

Progress Report Title: **Controlling Factors in Atmospheric Oxidation Capacity**

Principal Investigator: Jingqiu Mao (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Larry Horowitz (GFDL)

Other Participating Researchers: Songmiao Fan (GFDL), Arlene Fiore (Columbia), Daniel Jacob (Harvard)

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 controlling factors in atmospheric oxidation capacity

Methods and Results/Accomplishments:

Methods: We developed a new box model to study the role of aerosol uptake in oxidant chemistry. I have implemented a complete set of heterogeneous process into GFDL AM3 model. I also implemented a state-of-the-art isoprene oxidation mechanism into AM3 model. We are currently using AM3 model with different emission scenarios to study the controlling factors in atmospheric oxidation capacity.

Accomplishments: We discovered a major and previously unrecognized role of aerosol in atmospheric oxidant chemistry. We have submitted one paper to Nature (currently in review). We have one paper on biomass burning in progress. We submitted one proposal on organic nitrates to NOAA (not funded due to budget cut, but very high scores).

Publications:

Mao et al., Radical loss in the atmosphere from Cu-Fe redox coupling in aerosols, submitted to Nature.

Mao et al., Insights into hydroxyl measurements and atmospheric oxidation in a California forest, Atmos. Chem. Phys. Discuss., 12, 6715-6744, doi:10.5194/acpd-12-6715-2012, 2012.

Mao et al., oral presentation, "Reducing the leaking rate of surface NOx", The 5th International GEOS-Chem meeting, Cambridge, MA, April, 2011.

Marais et al., Isoprene emissions in Africa inferred from OMI observations of formaldehyde columns, Atmos. Chem. Phys. Discuss., 12, 7475-7520, doi:10.5194/acpd-12-7475-2012, 2012

Fischer et al., The role of the ocean in the global atmospheric budget of acetone, Geophys. Res. Lett., 39, L01807, doi:10.1029/2011GL050086, 2012.

Wang et al., Sources of carbonaceous aerosols and deposited black carbon in the Arctic in winter–spring: implications for radiative forcing, Atmos. Chem. Phys., 11, 12453-12473, doi:10.5194/acp-11-12453-2011, 2011.

Barkley et al., Can a "state of the art" chemistry transport model simulate Amazonian tropospheric chemistry? J. Geophys. Res., 116, D16302,.

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carbon oxidation processing, Atmos. Chem. Phys., 11, 11867-11894, doi:10.5194/acp-11-11867-2011, 2011.

Browne et al., Global and regional effects of the photochemistry of CH3O2NO2: evidence from ARCTAS, Atmos. Chem. Phys., 11, 4209-4219, doi:10.5194/acp-11-4209-2011, 2011.

Wolfe et al., The Chemistry of Atmosphere-Forest Exchange (CAFE) Model – Part 2: Application to BEARPEX-2007 observations, Atmos. Chem. Phys., 11, 1269-1294, doi:10.5194/acp-11-1269-2011, 2011.

Progress Report Title: **Climatic Impacts of Internal-Wave Driven Mixing in the Ocean**

Principal Investigator: Angelique V. Melet (Princeton Postdoctoral Research Associate)

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

Other Participating Researchers: Kurt Polzin (WHOI)

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: This work is part of the Climate Process Team (NOAA/NSF) on internal-wave driven mixing. The overall goal of this work is (1) to implement physically-based parameterizations of internal-wave driven mixing in GFDL's climate models in order to (2) study their climatic impacts.

Methods and Results/Accomplishments:

The breaking of internal tides is a major source of diapycnal mixing, which plays a key role in maintaining the ocean stratification and meridional overturning circulation. Many recent climate models parameterize internal-tide breaking using the scheme of St Laurent et al. (2002). While this parameterization dynamically accounts for internal-tide generation, the vertical distribution of the resultant mixing is ad hoc, prescribing energy dissipation to decay exponentially above the ocean bottom with a fixed length scale. Recently, Polzin (2009) formulated a dynamically-based parameterization in which the vertical profile of dissipation decays algebraically with a varying decay scale, accounting for variable stratification using WKB stretching. We compare two simulations using the St Laurent and Polzin formulations in the GOLD-SIS ocean-ice coupled model, with the same formulation for internal-tide energy input at the bottom. Focusing mainly on the Pacific ocean, where numerous internal-tide generation sites are found, we show that the ocean state shows modest but robust and significant sensitivity to the vertical profile of internal-tide driven mixing. Therefore, not only the energy input to the internal-tide matters, but also where in the vertical it is dissipated.

References:

The Climate Process Team on internal-wave driven mixing can be found at :
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Publications:

Melet, A.; Hallberg, R.; Legg, S. and K. Polzin. "Sensitivity of the Pacific Ocean state to the vertical distribution of internal-tide driven mixing". Submitted to the Journal of Physical Oceanography in March 2012.

Melet, A.; Hallberg, R.; Legg, S. and K. Polzin. "Sensitivity of the Pacific Ocean state to the vertical distribution of internal-tide driven mixing". Oral presentation at the Ocean Science Meeting, Salt Lake City, Feb. 2012.

Progress Report Title: **Properties of Convection at High Resolution**

Principal Investigator: Caroline Muller (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Isaac Held (GFDL)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

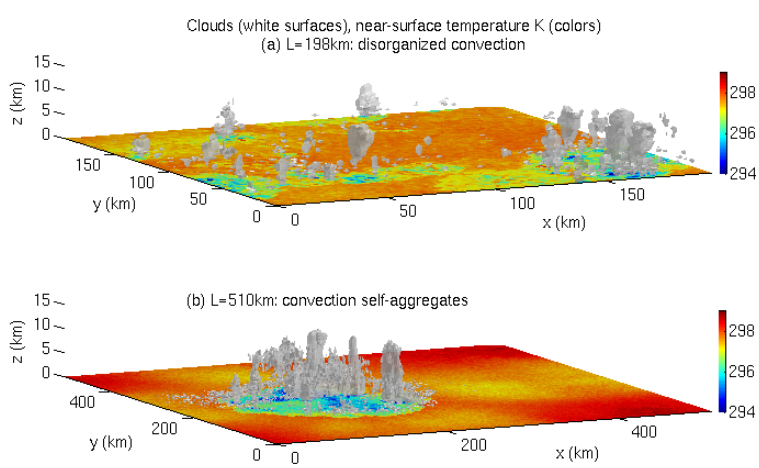
NOAA Goals:
***Climate Goal*:** Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objectives: Investigate the properties of tropical convection in models with high resolution, in order to help guide and improve current convective parametrizations

Methods and Results/Accomplishments:

It is well known that convection can organize on a wide range of scales. Current convective parametrizations used in global climate models typically do not account for convective organization, although the latter has been shown to strongly impact large-scale properties in models with intermediate resolution or using superparametrizations (two-dimensional cloud-resolving models embedded in coarse global climate model). High-resolution simulations can be used to better understand convective organization, its impact on large-scale properties, and its dependence on the subgrid-scale closure, boundary layer, ocean surface, and radiative scheme used. The ultimate goal is to help guide and improve current convective parametrizations.

Project 1: Self-aggregation of convection: One type of convective organization that we studied in detail is the spontaneous aggregation of convection in high-resolution cloud-resolving models that are forced homogeneously. In such models, it is well known that convection can self-aggregate into one single localized moist region if the domain is large enough (see Figure).



We use a cloud-resolving model (SAM) to investigate in detail the onset of self-aggregation and the physical mechanism responsible for the aggregation. The large changes in the mean climate state and radiative fluxes accompanying self-aggregation raise questions as to what simulations at lower resolutions with parametrized convection, in similar homogeneous geometries, should be expected to produce to be considered successful in mimicking a cloud-resolving model.

Project 2: Impact of convective organization on the amplification of precipitation extremes with warming: Simulations of tropical precipitation extremes with current coarse-resolution global climate models are unreliable. Therefore progress on the problem of changing tropical precipitation extremes must rely on either theory, observations, or simulations that resolve the convective-scale processes. In simulations that resolve the convective-scale processes, modeled precipitation extremes are known to increase in magnitude in response to an increase in sea surface temperature, at least in idealized settings.

In this project, we investigate how convective organization impacts these results. We use the cloud-resolving model (SAM) utilized in the previous project, and impose a background shear in order to organize the convection along lines or curves, depending on the strength of the shear imposed. We find much larger amplification of precipitation extremes with warming when convection is organized, particularly at the highest precipitation percentiles. A scaling introduced in earlier work can explain this behavior, and how it relates to the behavior of thermodynamic and dynamic variables.

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Muller, C. J. 2012: Impact of convective organization on the response of precipitation extremes with warming. J. Climate, in preparation.

Publications:

Muller, C. J. and I. M. Held, 2011: Detailed investigation of the self-aggregation of convection in cloud-resolving simulations. J. Atmos. Sci., in press.

Muller, C. J. 2012: Impact of convective organization on the response of precipitation extremes with warming. J. Climate, in preparation.

Muller, C. J. and I. M. Held, 2011: Self-aggregation in a cloud resolving model. Oral Presentation, 18th Conference on Atmospheric and Oceanic Fluid Dynamics, American Meteorological Society.

Muller, C. J. 2011: Intensification of Precipitation Extremes with Warming in a Cloud-Resolving Model. Invited seminar, Stony Brook University.

Progress Report Title: **Processes that Control Climate Change over the Southern Hemisphere**

Principal Investigator: Isidoro Orlanski (Princeton Senior Meteorologist)

CICS/GFDL Collaborator: Isaac Held, 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 and quantify the atmosphere extra-tropical climate changes due to Polar and/or Equatorial changes

Methods and Results/Accomplishments:

A Frontal Activity Index (FAI) as a good indicator for extreme climate events: It is well known that atmospheric fronts are the major trigger of extreme events from polar to sub-tropical latitudes; gust winds, squall lines, flush floods, severe thunderstorms, and tornadoes are some of these extreme mesoscale events that could be associated with fronts. Most of these severe phenomena are of scales smaller than the present climate models could resolve with some confidence. However, since atmospheric fronts are surface manifestations of developing cyclones, present models do reasonably well describing the scale of these cyclones, and their associated frontal systems. In a recent article, Solman and Orlanski (2010, J. Atmos. Sci, 67) have shown a very good correlation of the frontal activity with intense precipitation over a region of South America.

It is suggested that FAI could be a very important indicator of extreme events in model simulations of climate variability and climate change. Our study shows frontal activity, FAI, consistent with other findings, shifting poleward in the last decades of the southern hemisphere (SH) in the spring/summer seasons. It also provides an explanation on why it is possible that precipitation patterns could also be shifting poleward, as is shown by IPCC models results due to global warming scenarios. Also, a less reported high anomaly occurs over the South Eastern Pacific Ocean in winter of the SH; the FAI also tends to show a consistent diminution of fronts over the area underneath the high anomaly (shown in Fig 1) . A paper summarizing these results is in preparation.

What controls the seasonal climate change over the southern hemisphere: Global Ocean Warming or the Ozone Depletion?: A considerable number of articles appeared recently in the literature about the observed climate change experienced on the Southern Hemisphere for the last 50 years. Storm tracks have been displaced poleward, as well as the zonal westerlies; the expansion of the Hadley cell and the warming of western Antarctica are examples of the evidence of climate change. It is not yet clear what physical process produced such a change. Although the evidence seems quite robust, the source for such change is not that clear. Some studies suggest that the global ocean warming could be the cause of such change; other studies point to the decrease of the stratospheric ozone as the main cause.

We recently initiated a study that focuses on the seasonal variability of climate change. In the study, we tried to assess which source -- the stratospheric ozone or the ocean warming-- has the most impact on different periods of the year. We have used data from the ERA40 reanalysis, results of two ensemble runs,

all forcing "Bens" (from AM2.1_1870_2004_HGlob-SST-ICE-AllForc_B) and Non-forcing Aens (from AM2.1_1870_2004_HGlob-SST-ICE-1860RAD), and a member of the B runs (B1) that show a higher sensitivity of stratospheric temperatures due to the ozone depletion.

The results suggest by measuring how much the regression of the surface wind (10m) with a) stratospheric polar temperature (150hPa, hereafter UPTDC) or b) low level equatorial zonal temperature (850hPa, hereafter EQTDC) explain the observed surface wind (10m) differences of the two decades 1991-1999 minus 1973-1981. The results seem consistent between the reanalysis and the runs that include ozone depletion (runs B). The sharp stratospheric temperature decrease (UPTDC) in the decade 1991-1999 explains better than the (EQTDC), the observed changes in the surface wind for the period Sep-Dec (SOND), where as the equatorial changes (EQTDC) seem to explain the changes foremost of the rest of the year (see Fig 2). These results suggest being cautious to extrapolate the climate change over the South Hemisphere in the last decades, as a proxy for possible changes in the future, because it is expected that climate ocean warming may continue over the next decades, but the decrease of ozone may recuperate.
A paper is in preparation.

References:

Solman, S A., and Isidoro Orlanski, May 2010: Subpolar high anomaly preconditioning precipitation over South America**.** Journal of the Atmospheric Sciences, 67(5)**,** doi:10.1175/2009JAS3309.1.

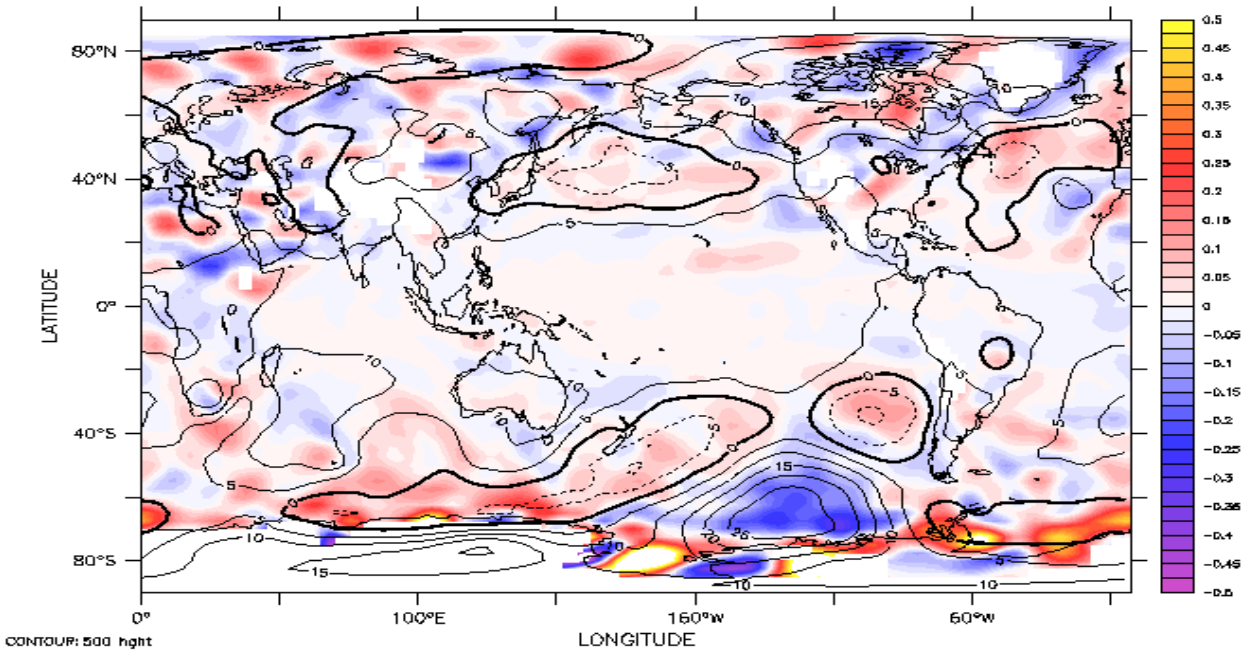


Fig 1. The difference of the Frontal Activity Index for the decade 1990-1999 minus the 40 years climatology (winter of the South Hemisphere) is shown in color and the difference for the same decade of the 500hPa heights are the black contours. Note the large void area (blue) of FAI over the Southern Pacific Ocean and the corresponding height anomaly over the region.

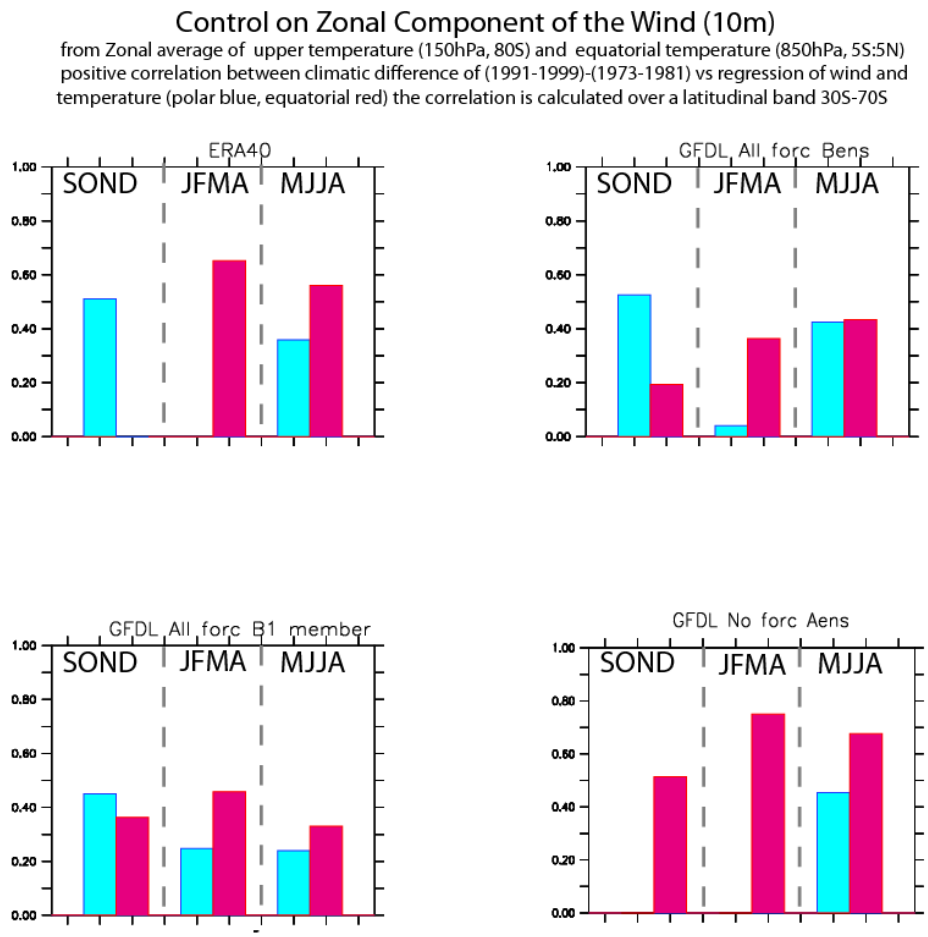


Fig 2. Quantify the control exert on the decade changes of the surface wind U(10m), due to the stratospheric Ozone depletion (blue bars) and the increase of equatorial ocean temperatures (red bars). The control is simple the correlation between the decade change and the pattern from the regression on both zonal averaged temperatures, Tozone(150hPa, 80S) and the Tequatorial(850hPa, -5S to 5N).

Progress Report Title: **Eddy-Mean Flow Interaction in a Double Jet**

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

CICS/GFDL Collaborator: Geoff Vallis (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: We investigate the interaction of the subtropical and eddy-driven jets using an idealized model in order to better understand how the zonal mean atmospheric circulation influences eddy propagation, breaking, and reflection.

Methods and Results/Accomplishments:

The feedback between eddy phase speed and the background flow composed of a gradually separated stirred and relaxed jet, representing an idealization of the eddy-driven and subtropical jets respectively, is investigated in a barotropic β-plane model. A minimum bound on eddy phase speed that is dependent on zonal wavenumber, latitude, and the background potential vorticity gradient is proposed. Cospectral analysis of eddy momentum flux convergence shows that the eddy activity is well confined between the maximum and minimum eddy phase speeds from linear theory for varying background states. This minimum phase speed represents a turning line for meridionally propagating waves and its presence can influence the development of a double-jet state.

A series of background zonal mean winds are created by varying the separation distance between the relaxation and stirring regions is considered. We find that waves propagate from the center of stirring through the region of relaxation for relatively large separation distances relative to a superposition of the winds generated by each forcing mechanism independently. The propagation of eddies through the relaxed jet waveguide results in a merged, single jet state relative to a superposition of the eddy-driven and relaxed jets. A sustained double jet state is achieved when either a critical or turning latitude forms between the centers of stirring and relaxation.

Publications:

O'Rourke, A. K. and Vallis, G. K., (June 2011) Interaction of the subtropical and eddy-driven jets in idealized models. Presented at the 18th Conference on Atmospheric and Oceanic Fluid Dynamics in Spokane, Washington.

Progress Report Title: **Improving the Representation of Well Mixed Greenhouse Gases in the GFDL Radiation Code**

Principal Investigator: David Paynter (Princeton Associate Research Scholar)

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 better understand and model the impact of non-CO_2 greenhouse gases upon Earth's radiation budget

Methods and Results/Accomplishments:

The potential for weak water vapor lines to increase the absorption of solar radiation has been investigated. We have carried out line by line calculations using the new UCL theoretical line database, which contains over 1 million water vapor spectral lines, compared to the 68,000 present in the HITRAN database (the additional lines in the UCL database are weak lines). Our research shows that these weak lines result in globally an additional 0.6 Wm^{-2} clear sky absorption, with up to 1 Wm^{-2} occurring in tropical regions. However, in a global warming scenario the weak lines increased the effectiveness of water vapor as an absorber of solar radiation by only 2%.

We have expanded our empirical continuum code (called BPS) to include gases other than water vapor. This involved incorporating collision induced absorption measurement data of nitrogen, oxygen and other trace non-CO2 GHGs. In addition, ozone cross-section data from the GEISA database has also been put into the BPS formulation. We have also updated our water vapor continuum model using the latest continuum measurement data. The inclusion of the additional absorbers and improved coverage of the water vapor spectra means that the BPS continuum is now a variable alternative to the commonly used MT CKD continuum. It also has the benefit of being based upon the most up-to-date measurement data.
Our research into the fundamental causes behind the water vapor continuum has continued. The latest results suggest that the temperature dependence of the water vapor continuum, as presently measured, is too strong to be explained by either the water dimer or far-wings theories. We have explored the possible atmospheric implications of this stronger temperature dependence, and have concluded that it leads to a far larger contribution by the water vapor self-continuum at mid-latitudes than previously thought. This means that in a global warming scenario, the water vapor continuum may increase the effectiveness of water vapor as an absorber of solar radiation by up to 20%.

Using the GFDL AM2.1 GCM, we have started to investigate the impact upon the Earth's radiation budget of using different continuum models (including the BPS continuum). So far our results show that the continuum plays a significant role in determining the strength of the water vapor feedback in the model. In addition it also alters both the latent heat and sensible heat. We are presently in the process of quantifying the impact that the choice of continuum model has upon these metrics and others.

Publications:

Paynter, D.J., and V. Ramaswamy (2011). "An assessment of recent water vapor continuum measurements upon longwave and shortwave radiative transfer", J. Geophys. Res., 116, D20302.

Paynter, D. J., Poster: The Royal Society Theo Murphy Meeting on Water Vapor in the Gas Phase. 13th-14th June 2011. Milton Keynes, UK.

Progress Report Title: **Comparison of GFDL's Atmospheric Models Against Observations during El Niño Events**

Principal Investigator: Claire Radley (Princeton Graduate Student)

CICS/GFDL Collaborator: Leo Donner (GFDL), Stephan Fueglistaler (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: Comparing GFDL's atmospheric models, AM2 and AM3, against satellite observations in order to evaluate how well they simulate the atmospheric response during an El Niño event

Methods and Results/Accomplishments:

I have compared the model runs of AM2 and AM3 against the observations by the International Satellite Cloud Climatology Project (ISCCP). These models are atmosphere only models and are forced by prescribing historical sea surface temperature values. A new feature of AM3 is the inclusion of the ISCCP simulator, which allows us to directly compare ISCCP observations with model output. This comparison has shown us that, on average, AM3 has 40% too much high cloud in the Western Pacific. During an El Niño event the anomaly in AM3 is also significantly larger than that in ISCCP. This bias in high cloud is partially compensated for by the mid cloud amounts, as AM3 has 20% less than observations. As one might expect, this bias carries through to the top-of-atmosphere radiation budget and in the climatology we see a difference of 30W/m^2 between the model and Earth Radiation Budget Experiment (ERBE) observations. We also see significant differences in the low clouds, which have a strong affect on the shortwave radiation budget.

We have also analyzed the response of the atmosphere during El Niño events. In particular we have looked at how the tropically and globally averaged outgoing longwave radiation (OLR) and shortwave (SW) vary as a function of the El Niño 3.4 Index. OLR has a strong positive correlation with this index (i.e. there is an increase in OLR during an El Niño event), but there is a very weak relationship (if any) between the SW and El Niño events. From these results we concluded that El Niño could be thought of primarily in terms of OLR. We also found that within the tropics there are very large anomalies locally (up to 40 W/m^2), which end up cancelling with each other to a large extent, so that the tropically averaged anomalies are only of order 1W/m^2. This result is robust across all observations and models studied; however we are yet to understand it fully.

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

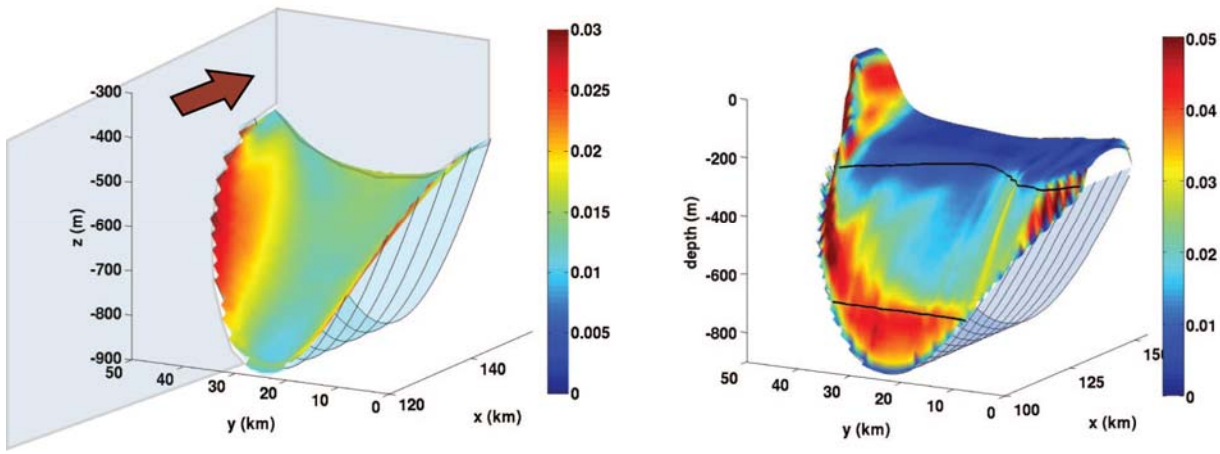
Objectives: Improve understanding of the role of ice sheets in climate system, their interaction with other components of the climate system by means of numerical modeling and incorporation of the field and remote sensing observations into models. A primary tool to achieve these goals is a continental-scale ice-sheet model coupled to the GFDL Earth System model.

Methods and Results/Accomplishments:

In collaboration with Robert Hallberg, Daniel Goldberg and Christopher Little the fully coupled, dynamical regional ice stream/shelf/ocean model has been developed. The idealized geometry model simulations show that, the ice stream/shelf/cavity system is inherently coupled with strong feedbacks between sub-ice shelf cavity circulation and ice flow. The ice shelf cavity configuration (Figure 1), which is shaped by the melting that results from the thermodynamic ice-ocean interaction, affects sub-ice shelf cavity circulation, and as a result melting rates (Figure 2).

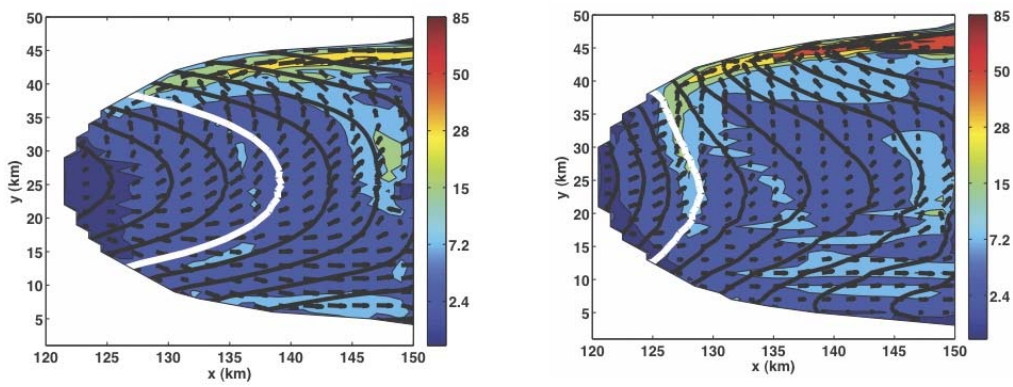
Ice-shelf/ocean interaction strongly affects thermodynamic regimes of the shelf. Using a coupled ice shelf/ocean plume model and a newly derived expression for temperature distribution in ice shelves, we (myself, Daniel Goldberg and Christopher Little) have found that ice shelves floating in hot ocean waters (dominated by Circumpolar Deep Waters) are significantly colder than those floating in warm waters (dominated by High Salinity Shelf Waters). This result has significant implication on stability of ice shelves. Colder ice is stiffer and more brittle. Fractures in cold ice, once initiated, continue to develop and propagate through the ice shelf, in contrast to those in warm ice that can be arrested and healed.

Presence of active subglacial lakes (filling and draining on decadal time scale) affect ice flow, however, direct measurements of the lakes' effects are logistically impossible on the scale of Antarctic continent. Results of a collaborative study with a group of Prof. Hulbe from PSU show that formation of these subglacial lakes is controlled by basal conditions under ice streams. Numerical simulations show that such lakes form preferably in the vicinity of locations with enhanced basal traction. Ice flow over such locations form favorable conditions for subglacial water ponding (Sergienko and Hulbe, 2011).



(a) (b)

Figure 1. Sub-ice shelf cavity shape at the beginning (a) and end (b) of the simulations. Color indicates slope of the cavity. The point of view is from upstream interior of the shelf. Red arrow shows direction of ice flow.



(a) (b)

Figure 2. Melt rates (m/yr) at the beginning (a) and end (b) of the simulations.

References:

Sergienko O. V. and C. L. Hulbe. 2011. 'Sticky spots' and subglacial lakes under ice streams of the Siple Coast, Antarctica. Annals of Glaciology. Vol. 52(58), 18-24.

Publications:

Sergienko O. V. and C. L. Hulbe. 2011. 'Sticky spots' and subglacial lakes under ice streams of the Siple Coast, Antarctica. Annals of Glaciology. Vol. 52(58), 18-24.

MacAyeal D. R., D. S. Abbot and O. V. Sergienko. 2011. Iceberg capsize tsunamigenesis. Annals of Glaciology. Vol. 52(58) Featured in Nature 472, 43–44

D. N. Goldberg and O. V. Sergienko. 2011. Data assimilation using a hybrid ice flow model. The Cryosphere, 5, 315-327.

Goldberg D. N., C. M. Little, O.V. Sergienko, A. Gnanadesikan, R. Hallberg and M. Oppenheimer Investigation of land ice-ocean interaction with a fully coupled ice-ocean model, Part 1: Model description and behavior, in revision.

Goldberg D. N., C. M. Little, O.V. Sergienko, A. Gnanadesikan, R. Hallberg and M. Oppenheimer Investigation of land ice-ocean interaction with a fully coupled ice-ocean model, Part 2: Sensitivity to external forcings, in revision.

Sergienko O.V. and D. R. MacAyeal. 2011, Are there preferred numerical approaches to modeling ice flow over an undulated bed? Abstract C31C-04 presented at 2011 Fall Meeting, AGU, San Francisco, Calif., 5-9 Dec. 2011.

Sergienko O. V. 2011, Bumpy beds, what to do about them. 18th Annual WAIS Workshop, Sylvan Dale Guest Ranch, Loveland, Co, Sept 21 - 23, 2011.

Sergienko O. and D. R. MacAyeal. 2011, Basal control of supraglacial lakes Geophys. Res. Abstracts Vol. 13, EGU2011-11073, EGU General Assembly 2011, Vienna.

Nowicki S. and O. Sergienko. 2011, The effect of ice rheology on contact problems Geophys. Res. Abstracts Vol. 13, EGU2011-13553, EGU General Assembly 2011, Vienna.

Progress Report Title: **Variability of the Nordic Seas Overflows**

Principal Investigator: He Wang (Princeton Graduate Student)

CICS/GFDL Collaborator: Sonya Legg (Princeton), Robert Hallberg (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: Understand the decadal variability of the Nordic Seas overflows, their forcing mechanism, how and why they influence on the Atlantic Meridional Overturning Circulation and climate in the climate models

Methods and Results/Accomplishments:

The Nordic Seas are regions of deep convection and where the dense water of the ocean is formed. The dense water flowing out from the Nordic Seas through the Denmark Strait (DS) and the Iceland-Scotland (IS) Channels are called the overflows. They provide the major portion of the Deep Western Boundary Current (DWBC), which is the lower limb of the Atlantic Meridional Overturning Circulation (AMOC). Thus the variability of the Nordic overflows may influence the AMOC, especially on the time scale of decades.

Analysis of the output from the GFDL climate model CM2G shows that the DS overflow transport is very barotropic and it has a prominent variability with the time scale of around 10 yrs; while the IS overflow is very baroclinic, and the decadal variability is only seen in its barotropic component. In previous works, it has been shown that two mechanisms are responsible for the variation and variability of the overflows: wind forcing and the upstream region convection. It is shown that in CM2G, these two mechanisms both exist and apply for the overflows' barotropic and baroclinic variation, respectively. In another climate model CM2M, the Denmark Strait overflow also has a similar decadal variability, but with the time scale of around 15 yrs. The barotropic forcing mechanism also applies in CM2M.

The influences of the overflows on the downstream regions and AMOC are different, however, in the two models. In CM2M, the overflow has a statistically significant correlation with AMOC, with a leading time of 3-5 yrs. This correlation does not exist in CM2G. Further analysis shows that this difference might be caused by the different mixings in the two models. In CM2G, the dense water transport formed in the Labrador Sea dominates the variability of DWBC and AMOC. The Labrador Sea dense water transport has a similar variability as the overflows, but in the opposite phase. The net effect is that the correlation between overflow and the AMOC is almost cancelled out by the Labrador Sea water. This is not the case in CM2M, in which, the overflow water and the Labrador Sea water is not well separable as in CM2G.

Progress Report Title: **Ocean Heat and Carbon Uptake in Transient Climate in Idealized Eddying and Non-eddying Ocean Circulation Models**

Principal Investigator: Yu Zhang (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Geoffrey K. 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: To investigate impacts of transient climate change on ocean heat and carbon uptake, to understand basic mechanisms driving ocean heat and carbon uptake, and to understand roles of eddies in uptake

Methods and Results/Accomplishments:

Stage: I: The primary focus of my research since March 2011 has been to investigate ocean heat uptake in transient climate. Using GFDL Modular Ocean Model version 4p (MOM4p1), we studied the ocean heat uptake in an idealized ocean domain, an inter-hemispheric basin with a re-entrant channel along the southern boundary representing the Antarctic Circumpolar Current. Under control climate, the model ocean is forced at the surface by constant wind and a heat flux that acts to restore temperature to a prescribed profile. In perturbation climate, an anomaly is abruptly added to the surface restore temperature mimicking climate warming.

With a suite of experiments having different geographical distribution of the surface restore temperature anomaly, we found two mechanisms that make the ocean absorb heat from the atmosphere. One is related to the Meridional Overturning Circulation (MOC), inducing heat absorption in the mid-depth and the abyssal ocean, in relation to the mid-depth and the abyssal MOC cell. The heat uptake lasts on millennial time scales. In addition, heat enters the ocean through Ekman pumping along ventilated thermocline, and is meanwhile slowly diffused across the base of the main thermocline into the deep ocean. The upper ocean quickly equilibrates with the atmosphere within a few decades, leaving the deep ocean largely intact. The ocean heat uptake in high-resolution models that resolve explicitly mesoscale eddies doesn't show qualitative differences with coarse-resolution models that using Gent-MacWilliam eddy parameterization in at least a few hundred of years in the perturbed climate.

Main results of this part of the work were documented in our manuscript "Ocean heat uptake: driving mechanisms and role of eddies", which will be submitted soon.

Stage II: We are now working on coupling the ocean model with a biogeochemical model of GFDL: Ocmip2, to investigate the carbon uptake and the associated mechanism in transient climate, which is represented by an increase of the atmospheric CO2 concentration.

Publications:

Zhang, Y., J. Pedlosky, and G. R. Flierl, 2011: Shelf Circulation and Cross-Shelf Transport out of a Bay Driven by Eddies from an Open-Ocean Current. Part I: Interaction between a Barotropic Vortex and a Step-like Topography. J. Phys. Oceanogr., 41, 889–910.

Zhang, Y., J. Pedlosky, and G. R. Flierl, 2011: Cross-shelf and out-of-bay transport driven by an open-ocean current. J. Phys. Oceanogr., 41, 2168-2186.

Zhang, Y. and R. Ferrari, 2012: Mixed-layer eddy diffusivity: effects of surface relaxation and turbulent mixing. In prep.

Zhang, Y., and G. K. Vallis, 2012: Ocean heat uptake: driving mechanisms and role of eddies. In prep.

Progress Report Title: **The Dependency of Tropical Cyclone Scale on Domain Size and Larger Scale Environment**

Principal Investigator: Wenyu Zhou (Princeton Graduate Student)

CICS/GFDL Collaborator: Isaac Held (GFDL), Geoff Vallis (Princeton)

Other Participating Researchers: Steve Garner (GFDL), Ming Zhao (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 dependency of tropical cyclone scale on domain size and large scale environment

Methods and Results/Accomplishments:

GFDL's High Resolution Atmospheric Model (HiRAM 2. 1) has been used in Zhao et al., 2009 to study global tropical cyclone statistics. As it simulates well the observed climatology and interannual variability, we would like to study this model carefully in an idealized geometry, that is, double period domain with fixed sea surface temperature.

Different domain sizes are tested. A smaller domain cannot sustain an intense storm, while in a much larger domain a set of closely-packed rotating storms are observed. The critical size of a domain where an intense storm could happen depends on the background rotation. The difficulty for a small domain to sustain an intense storm may result from its relatively small reservoir, which could not provide enough energy.

The closely-packed structure in a much larger domain could be a good case to study dependency of the tropical cyclone scale on large scale environment parameters, such as sea surface temperature and the background rotation. Earlier work (Held IM, Zhao M. 2008) shows the number of storms increases with larger f and smaller sea surface temperature. We show that the radius of maximum wind increases with f, though the statistical significance is still under investigation.

A snapshot of sea level pressure field in a large domain (12500x12500km) with the background rotation at 20˚N and a fixed sea surface temperature at 301K is shown below.

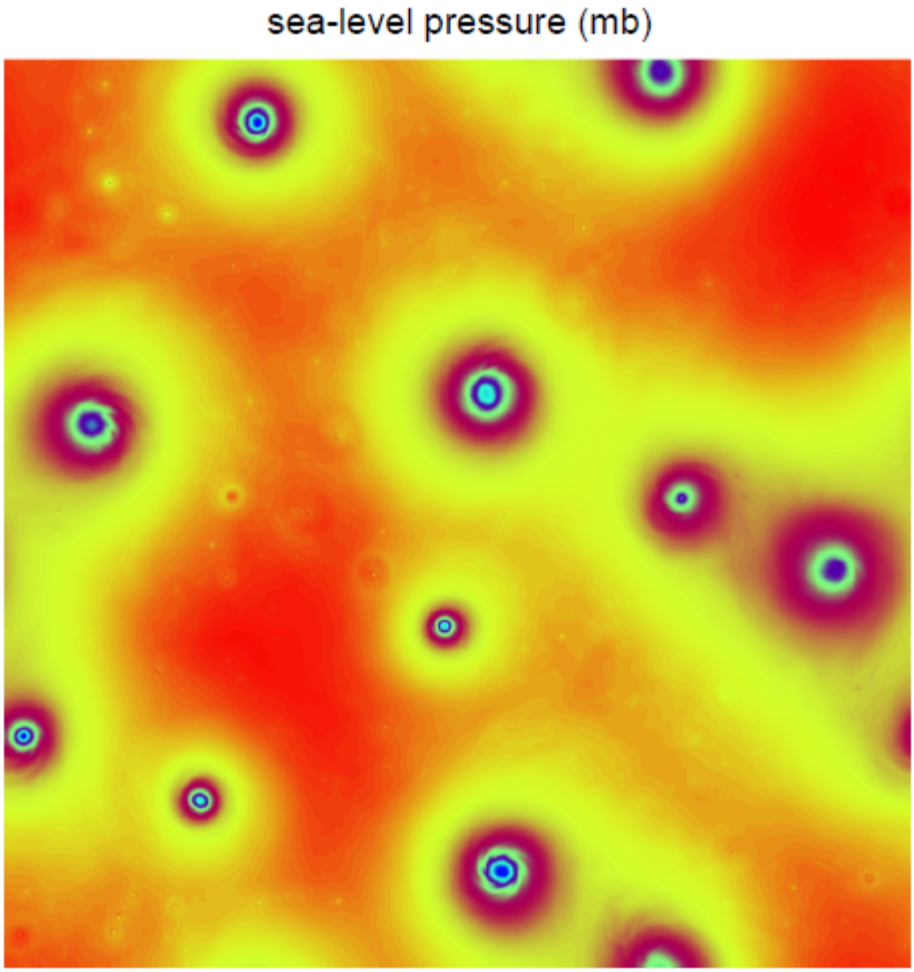


Figure 1 Sea level pressure field with the background rotation at 20˚N and a fixed sea surface temperature at 301K

References:

Zhao, M., I. M. Held, S.-J. Lin, and G. A. Vecchi, 2009: Simulations of global hurricane climatology, interannual variability, and response to global warming using a 50-km resolution GCM. J. Climate, 22, 6653-6678.

Held IM, Zhao M. 2008. Horizontally homogeneous radiative–convective equilibria at GCM resolution. J. Atmos. Sci. 65:2003–2013.

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, Richard Feely, Steve Hankin (PMEL), Rik Wanninkhof (AOML), Alex Kozyr (CDIAC), Frank Millero (Miami), Andrew Dickson (UCSD-Scripps)

Task III: Individual Projects

NOAA Sponsor: David Legler and 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:

Over the past two and a half centuries, the surface oceans have absorbed approximately 30% of the total anthropogenic carbon dioxide emissions from the atmosphere, equaling >550 billion tons of carbon dioxide (Canadell et al., 2007). This absorption of CO_2 from the atmosphere has reduced the accumulation of greenhouse gases in the atmosphere, thus slowing the rate of climate change (IPCC, 2007; Sabine and Feely, 2007). The details of this uptake and storage as well as the mechanisms controlling them are still not fully understood. Continued monitoring and scientific analysis of the ocean carbon cycle is critical for understanding how this important sink for anthropogenic CO_2 is functioning and how ocean carbon storage might change in the future.

Recognizing the need to constrain the oceanic uptake, transport, and storage of anthropogenic CO_2 for the anthropocene and to provide a baseline for future estimates of oceanic CO_2 uptake, two international ocean research programs, the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS), jointly conducted a comprehensive survey of inorganic carbon distributions in the global ocean in the 1990s (Wallace, 2001). After completion of the US field program in 1998, a five year effort called the Global Ocean Data Analysis Project (GLODAP) was begun to compile and rigorously quality control the US and international data sets including a few pre-WOCE data sets in regions that were data limited (Key et al., 2004). These data have greatly improved our understanding of the spatial distributions of natural and anthropogenic carbon in the ocean and are being used to examine the mechanistic controls on ocean carbon distributions.

The single snapshot of the ocean provided by the GLODAP data product is not ideal for understanding the temporal patterns of variability in ocean uptake and storage. The most important component of an assessment of ocean biogeochemical change, whether of natural or anthropogenic origin, is high-quality observations. The WOCE/JGOFS data set provides an important point of reference for ocean carbon studies, but many other useful data sets exist or are being collected which have not been analyzed in such a context because there has not been a coordinated effort to bring these data together and no data management system to make navigation and exploitation of these data convenient. For example, the NOAA Climate Observations and Monitoring (COM) Program's Carbon Network (hydrographic sections, underway pCO_2, and CO_2 moorings) is a valuable contribution to the Global Ocean Observing System (GOOS) and Global Climate Observing System (GCOS). It is not sufficient, however, simply to

collect and archive the data if we expect the data to improve our understanding of the global carbon cycle and the role of the ocean in climate change. Although carbon scientists are the primary direct users of ocean carbon data, these scientists are working to produce meaningful products from these observations that a wide range of decision makers and the public can use to make informed decisions about current and future CO_2 emissions.

The goal of the Global Carbon Data Management and Synthesis Project is to work together with the COM carbon measurement projects as well as other national and international colleagues with high-quality ocean carbon data to take the fundamental carbon observations and turn them into products that are useful for scientists and the public for understanding the ocean carbon cycle and how it is changing over time. This effort ranges from ensuring that the observations are of the highest quality and are mutually consistent with each other to combining the observations into a common data set that is available and easy for the community to use and explore to evaluating the time rate of change in global ocean carbon uptake and storage. This project brings together ocean carbon measurement experts, information technology experts and data managers to ensure the most efficient and productive processing possible for the COM carbon observations.

Scientific Accomplishments: The COM ocean carbon network makes two basic types of observations: surface CO_2 observations (with ships of opportunity and moorings) and water column carbon observations (with repeat hydrography cruises). The surface observations are aimed at understanding the exchange of CO_2 across the air-sea interface (i.e. ocean carbon uptake and release). The interior ocean observations help quantify the ocean carbon inventory and how it is changing with time (i.e. ocean carbon storage). Uptake is not necessarily the same as storage, because ocean transport can move carbon that is removed from the atmosphere in one place and store that carbon in another place. Although the spatial and temporal patterns of carbon uptake may be different from the storage patterns, these two measures of the ocean carbon cycle are closely related to each other. Integrated over large enough time and space domains, the net uptake should be reconcilable with the storage.

The Global Carbon Data Management and Synthesis Project addresses both observational approaches for understanding the role of the oceans in the global carbon cycle. Princeton is involved only in the water column observation and data synthesis portion of this project.

While the COM ocean carbon network is primarily aimed at understanding the uptake and storage of ocean carbon, it also provides information on the consequences of that carbon on the chemistry of the oceans. When anthropogenic CO_2 is absorbed by seawater chemical reactions occur that reduce both seawater pH and the concentration of carbonate ions in a process known as "ocean acidification". The pH of ocean surface waters has already decreased by about 0.1 units since the beginning of the industrial revolution (Caldeira and Wickett, 2003; Caldeira and Wickett, 2005), with a decrease of ~0.0018 yr^{-1} observed over the last quarter century at several open ocean time-series sites (Bates, 2007; Bates and Peters, 2007; Santana-Casiano et al., 2007).

The COM ocean carbon observations and subsequent synthesis efforts through this project have played a significant role in highlighting to the scientific community and the general public the importance of ocean acidification and its consequences on marine life. The advancements in our understanding in ocean acidification made through this project are discussed below.

Ocean Interior Carbon: The ocean interior component of the Global Carbon Data Management and Synthesis Project involves continued processing and assessment of the CLIVAR/CO_2 Repeat Hydrography data, an international synthesis of high-quality carbon data for the period from GEOSECS to CLIVAR, and a global assessment of decadal changes in ocean carbon inventories. As with the surface data, an important component of the effort is national and international outreach and coordination to improve data quality, and assemble data into coherent unified datasets. As described below the participants of the ocean carbon synthesis efforts have been active participants and leaders of efforts such as CARINA, PACIFICA and RECCAP that provide critical data products for interpretation and testing/verification of models of ocean carbon dynamics and change. Each of these is very briefly discussed below.

Processing Repeat Hydrography Data: In FY2011, the NOAA DIC data from the S4P cruise, from Lyttelton-Punta Arenas along 67°S, were finalized and submitted to CDIAC. Data from the A10 cruise across the South Atlantic are currently being finalized and will be submitted to CDIAC shortly. PIs Millero and Dickson are finalizing the total alkalinity data collected on the CLIVAR S4P and A10 cruises. These data will be submitted to CDIAC and final cruise reports written and made publically available. Over the past year CDIAC made DIC data from the following datasets available to the general public: I05_2009, P06_2009, P21_2009, P15_2009, A13.5 (except for pH).

We have constructed an Atlantic, Pacific and Indian Ocean "CLIVAR" data product similar to GLODAP and CARINA. This data product is composed of very high quality cruise data collected since 1998. We have not distributed this data product because it includes several "preliminary" carbon data sets, a few proprietary data sets, and because several of these cruises have been included in other collections. We are using this product for in-house carbon change calculations (see below).

Ocean Interior Data Synthesis: With the completion of CARINA in 2010, the synthesis effort was shifted to the Pacific with a project led by PICES called PACIFICA. This is a data synthesis effort that is scientifically similar to CARINA in all aspects except that the data are primarily from the North Pacific. Over the past year the PACIFICA group, which includes several of the Global Carbon Data Management and Synthesis Project PIs collected and began assessing the quality of approximately 250 new cruises not previously available to the public. Princeton's involvement in PACIFICA has been much less than it was for the prior data collection efforts primarily due to funding. Japanese scientists have assembled all of the data for the collection. They have also had the primary responsibility for 1st QC of the data. R. Key's involvement has been limited to attending the data QC meetings and offering guidance. X. Lin (P.U.) has imported all of the PACIFICA data into the Princeton data system and has been checking 1st QC in collaboration with the PACIFICA group. Feely and Sabine are regional leaders in the QC process.

Global Assessment of Decadal Changes in Ocean Carbon Storage: An important component of the Global Carbon Data Management and Synthesis Project is the analysis of decadal changes in ocean carbon storage. These analyses are initially conducted along specific lines occupied as part of the CLIVAR/CO_2 Repeat Hydrography program. During the WOCE program, east-west cruise line S4P in the South Pacific along ca. 67°S was occupied in Feb-March 1992 and repeated this year in Feb. – April 2011 as part of the CLIVAR/CO_2 Repeat Hydrography program to investigate the temporal changes in total dissolved inorganic carbon (DIC) from 1992 to 2011 along this cruise line, The results are shown in Figure 1. The estimated DIC increases over the 19-year interval vary from about 0 µmol kg^{-1} below 800 m to values greater than 40 µmol kg^{-1} near 138°W with the main concentrations increases between the surface and 300m. Similar analyses using the extended multiple linear regression (eMLR) approach along the P06 line along 32ºS by C. Sabine indicate that ocean carbon storage in this region has increased 30-50% over the last decade relative to the previous decade.

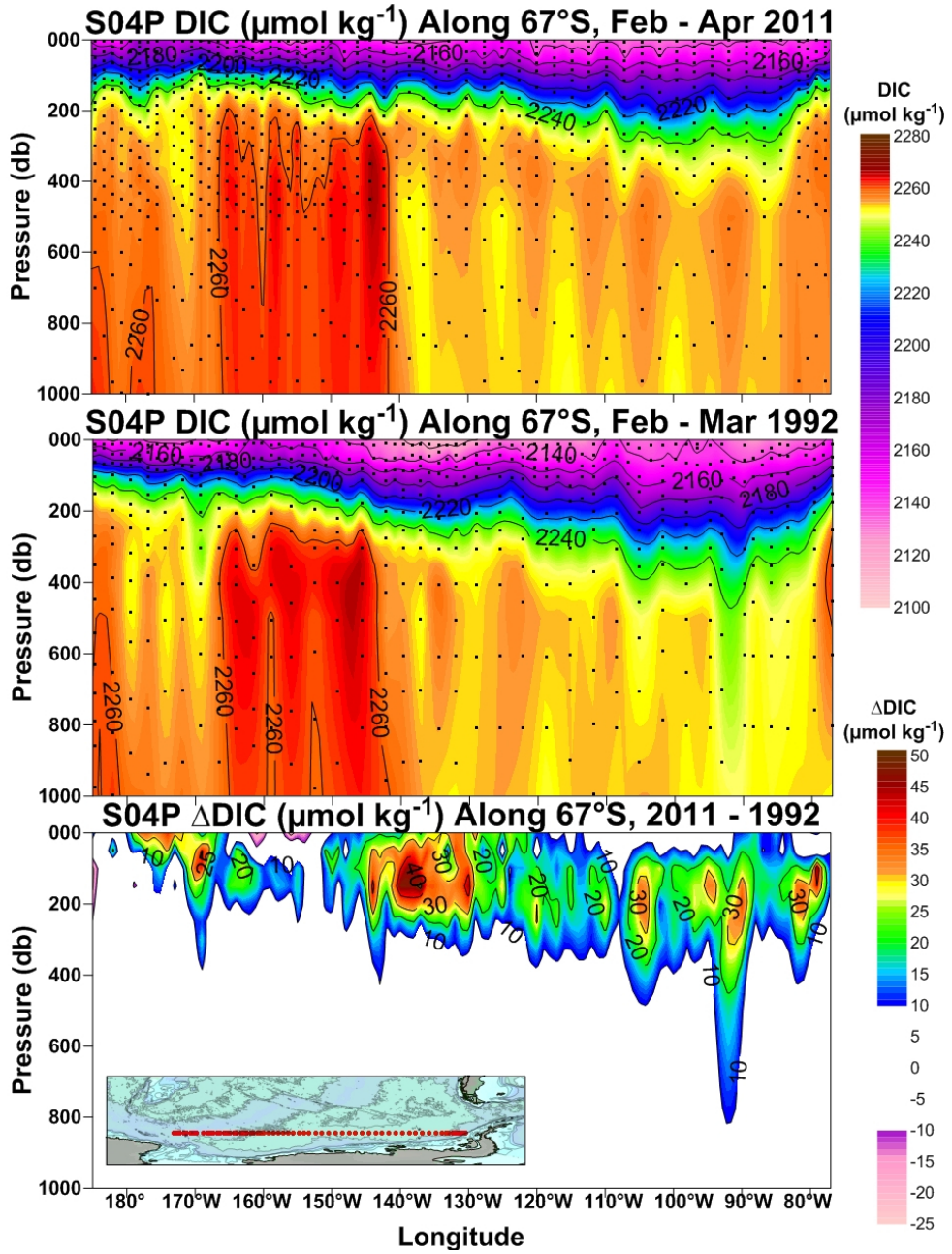


Figure 1. Sections of total dissolved carbon in Feb-April 2011 (top); Feb-Mar. 2092 (middle); and the 2011-1992 difference (bottom) in units of µmol kg^{-1}.

Ocean Interior Carbon in the Regional Carbon Cycle Assessment and Processes (RECCAP): RECCAP is an international activity coordinated through the Global Carbon Project (GCP) with the goal of producing global and regional assessments of the sources and sinks of CO_2. An important component of this effort is the evaluation of the global carbon inventories and how they are changing with time. Several of the COM carbon project PIs (Sabine, Feely, Wanninkhof, Key, Kozyr) are a part of this effort and are taking the lead on different aspects of the project. For example, as part of this project Sabine will be summarizing the various techniques for assessing natural and anthropogenic carbon inventories and their results. Initial work along these lines was recently published by Sabine and Tanhua (2010).

Detection and attribution of hydrographic and biogeochemical changes in the deep ocean (≈> 2000 m) is challenging due to limited accurate data. There are indications that anthropogenic and climate change signals are starting to manifest themselves at depth. During the performance period we determined the changes in deep water inorganic carbon content along meridional transects in the Atlantic and Pacific Ocean on decadal time scales using observations from the World Hydrographic Program in the 1980s and 1990's, and the CLIVAR/CO_2 repeat hydrography effort in the past decade. Decadal changes of DIC in deep water cannot currently be measured with confidence in the ocean interior removed from the outcrop regions. Changes based on discrete pCO_2 (20) measurement show appreciable rates of inventory change that are in general agreement with the age of water masses. The cruises in the Atlantic central basin show deep water changes at a rate of changes of 0.5 mol m^{-2} yr^{-1}, the South eastern South Atlantic basin shows changes of 0.12 mol m^{-2} yr^{-1} (Figure 2) and the Southeastern Pacific at 0.07 mol m^{-2} yr^{-1}. The changes are appreciably higher than the output of the NCAR CCSM-1 model but this model also shows less CFC11 at depth than measured CFC11 (Figure 3). The CFC11 ages based on the measured CFC11 concentrations indicate that the dissolved inorganic carbon (DIC) changes based on pCO_2(20) measurements are plausible and from anthropogenic origin. The results indicate that appreciably more anthropogenic CO_2 is entering the ocean interior than several current observation based techniques indicate. However, the paucity in pCO_2(20) data and largely uniform specific inventory changes ΔDIC_{pCO2} with latitude (Figure 2) make the quantification of this signal tentative.

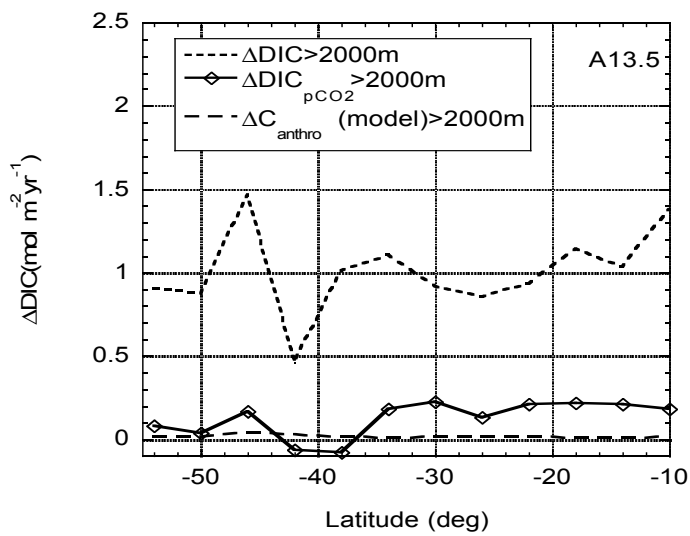


Figure 2. Specific inventory changes of ΔDIC, ΔDIC_{pCO2}, and ΔC_{anthro} (model) below 2000 m versus latitude for the A13.5 line from 54˚ S to 10˚ S between 1983 and 2010. The measured change in DIC is unrealistically large and attributed to offsets in the older data. The calculated DIC change based on pCO2(20), ΔDIC_{pCO2}, is plausible.

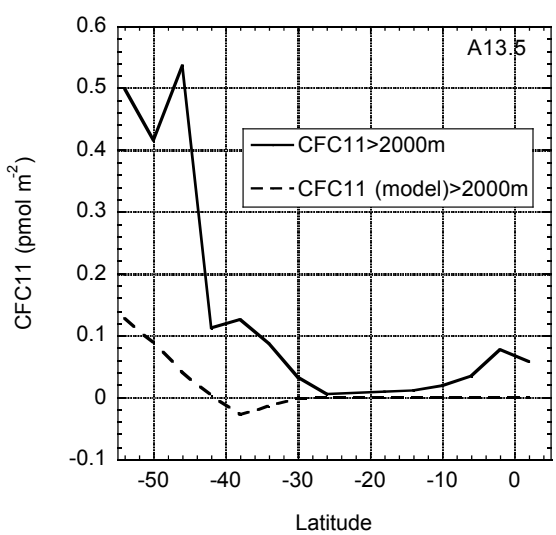


Figure 3. Specific inventory for measured CFC11 and modeled CFC11 greater than 2000m for 2010 for the A13.5 line. The model data is systematically lower suggesting issues in (some) models with deep ventilation processes.

In related work R. Key has been working with M. Manizza to better understand the carbon system in the Arctic Ocean. This research is grounded with data assembled as part of the CARINA project and more recent cruises, and results from a numerical ocean model. The model suggests a regional uptake of 59TgC/a in agreement with the estimate from very limited data (29-199TgC/a). Because of limited circulation, broad shelf areas and numerous rivers, the carbon chemistry of this region is particularly interesting (Manizza et al. 2012). Later this year we plan to submit a proposal to NSF to develop an "ocean

carbon state estimation" for the Arctic Ocean using a new regional adjoint model.

Ocean Acidification: The uptake of anthropogenic CO_2 by the global ocean induces fundamental changes in seawater chemistry that could have dramatic impacts on biological ecosystems in the upper ocean. Based on measurements from the WOCE/JGOFS global CO_2 survey, the CLIVAR/CO_2 Repeat Hydrography Program in the Pacific Ocean, we have observed an average 0.34% yr^{-1} decrease in the saturation state of surface seawater with respect to aragonite and calcite. The upward migrations of the aragonite and calcite saturation horizons, averaging about 1 to 2 m yr^{-1}, are the direct result of the uptake of anthropogenic CO_2 by the oceans and regional changes in circulation and biogeochemical processes. The shoaling of the saturation horizon is regionally variable, with more rapid shoaling in the South Pacific where there is a larger uptake of anthropogenic CO_2. In some locations, particularly in the North Pacific Subtropical Gyre and in the California Current, the decadal changes in circulation can be the dominant factor in controlling the migration of the saturation horizon. If CO_2 emissions continue as projected over the rest of this century, the resulting changes in the marine carbonate system would mean that many coral reef systems in the Pacific would no longer be able to sustain a sufficiently high rate of calcification to maintain the viability of these ecosystems as a whole and perhaps could seriously impact the thousands of species that depend on them for survival.

In the surface mixed layer (depths to ~100 m), the extent of pH change is consistent with that expected under conditions of seawater/ atmosphere equilibration, with an average rate of change of -0.0017 yr^{-1}. Future mixed layer changes can be expected to closely mirror changes in atmospheric CO_2, with surface seawater pH continuing to fall as atmospheric CO_2 rises.

Education and Outreach: Synthesis Project investigators have been very active in educating the public about ocean carbon changes. Several of the PIs regularly teach graduate and undergraduate classes in ocean carbon chemistry. These classes incorporate the scientific results coming from this work. Several of the PIs have graduate students or post-docs that are exposed to the work accomplished through this project. Several of the Synthesis Project PIs also serve on a number of national and international science committees that help guide and coordinate ocean carbon research. Interactions with the general public include presentations to local schools, open public lectures (both in the US and abroad), public "webinars" (seminars broadcast as streaming video onto the web e.g. for World Oceans Day), laboratory tours for groups ranging from school kids to Congressional Representatives, and official congressional testimonies. We have also given numerous press interviews and have been quoted in printed and online media, radio, and television.

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Manizza, M., M.J. Follows, S. Dutkiewciz, D. Menemenlis, J.W. McClelland, C.N. Hill, B.J. Peterson, R.M. Key, 2011. Modeling the Arctic Ocean carbon cycle, J. Geophys. Res., 116,C12020, doi:10.1029/2011JC006998.

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Progress Reports:

Earth System Model Applications

Progress Report Title: **Detection and Attribution of Abrupt and Gradual Changes in the Carbon System**

Principal Investigator: Claudie Beaulieu (Princeton Postdoctoral Research Associate)

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

Other Participating Researchers: Elena Shevliakova (GFDL), David Medvigy (Princeton), Wolfgang Buermann (UCLA), Sara Mikaloff-Fletcher (National Institute of Water and Atmospheric research, New Zealand) , Joe Majkut (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

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

Methods and Results/Accomplishments:

Previous results from this project suggested an abrupt change in the net land uptake of carbon of approximately 1 Pg C/year in 1988 (Beaulieu et al., 2012a). Following Sarmiento et al. (2010), the net land uptake was estimated as a balance of different components of the carbon budget: observed atmospheric growth rate of CO_2, fossil fuel emissions, and the ocean uptake estimated from a suite of state of the art ocean models. Furthermore, a general and flexible methodology was developed in order to detect gradual and abrupt changes in climate and carbon time series and to distinguish the signal from the noise (Beaulieu et al., 2012b). In the past year, my research focused on refining this analysis by using additional ocean uptake estimates and investigating abrupt changes in the terrestrial carbon cycle.

Additional evidence for an abrupt shift in the mean net land uptake in 1988 was found by using three new ocean uptake estimates to calculate the land sink. These ocean uptake estimates were obtained using the GFDL Modular Ocean Model (MOM4p1) and the Biogeochemistry with Light, Iron, Nutrients and Gases (BLING) model forced with CORE, ERA-40 and NCEP-1 re-analyses data products (Majkut et al., 2012, in prep.). By conducting similar analyses as those performed in Beaulieu et al. (2012a), a similar shift in the mean net land uptake computed using the new ocean uptake estimates was found at the same time.

In order to investigate whether this shift is really occurring in the land, satellite data of gross primary production, terrestrial respiration and net ecosystem exchange fluxes for the region North of 45°N were analyzed in collaboration with researchers at UCLA. A simultaneous shift in annual and spring fluxes of gross primary production and respiration in this region was detected using the methodology of Beaulieu et al. (2012b). The sign of the net shift detected in satellite data agrees with the shift in the net land uptake of carbon, but the magnitude is smaller (the net shift is approximately 0.2 Pg C/yr). As a visual support, figure 1 presents the gross primary production and terrestrial respiration fluxes. Ongoing work is focusing on analyzing these fluxes at the grid cell level to identify the specific regions where the change comes from.

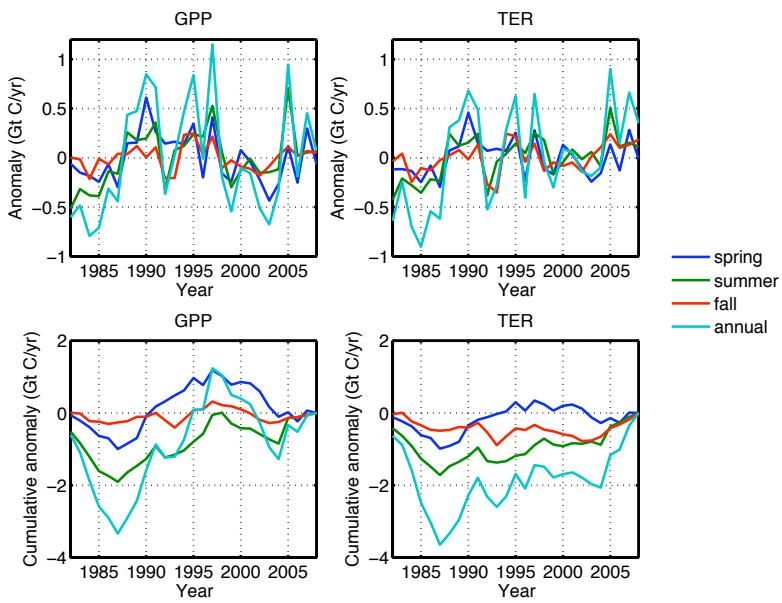

Figure 1: Total fluxes of gross primary production (GPP) and terrestrial respiration (TER) above 45° North anomalies and cumulative anomalies. The change of slope in 1987 in the cumulative anomaly shows the possibility for a shift.

We have applied the methodology developed in Beaulieu et al. (2012b) to a high-resolution global dataset of meteorological forcings for land surface modeling (Sheffield et al., 2006) to investigate specific regions where similar changes in the climate are occurring at the same time. The variables analyzed are mean, minimum and maximum air temperature, total precipitation, specific humidity, downward short- and longwave radiation, surface air pressure and wind speed from 1948-2008. The spatial patterns of the timing of the shifts detected are very noisy and consequently, it is very difficult to identify any spatial patterns. Hence, we have assumed that there will be at most one shift to perform this analysis, but this assumption seems unreasonable for representing climate change since over a sixty years period. Ongoing work is focusing on implementing a new methodology to relax the hypothesis of having at most one shift.

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Beaulieu, C., Sarmiento, J.L., Mikaloff Fletcher, S., Chen, J., Medvigy, D. (2012a) Identification and characterization of abrupt changes in the land uptake of carbon. Global Biogeochemical Cycles, 26, GB1007.

Beaulieu, C., Chen, J., Sarmiento, J.L. (2012b) Change point detection as a tool to describe past climate variations, Philosophical Transactions of the Royal Society Series A special issue : Climate predictions: the influence of nonlinearity and randomness, 370, 1228-1249.

Medvigy, D., and Beaulieu, C. (2012) Trends in daily solar radiation and precipitation coefficients of variation since 1984. Journal of Climate, 25, 1330-1339.

Progress Report Title: **Seasonal Prediction of Tropical Cyclones Using the 25-km Resolution 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: Retrospective seasonal predictions of tropical cyclones (TCs) in the three major ocean basins of the Northern Hemisphere are evaluated from 1990 to 2010 using the Geophysical Fluid Dynamics Laboratory (GFDL) High-Resolution Atmospheric Model (HiRAM) at 25-km resolution.

Methods and Results/Accomplishments:

The GFDL HiRAM at 25-km resolution which is designed for both weather forecast and climate-change studies is used for retrospective seasonal predictions of TCs in the three ocean basins of the Northern Hemisphere (the NA, the ENP and the WNP) during 1990-2010. Atmospheric states are initialized for each forecast, with the sea surface temperature anomaly (SSTA) persisted from that at the starting time during the 5-month forecast period (July-November). By using a 5-member ensemble, it is shown that the storm counts of both tropical storm (TS) and hurricane categories are highly predictable in the North Atlantic basin during the 21-year period. The correlations between the 21-year observed and model predicted storm counts are 0.88 and 0.89 for hurricanes and TSs, respectively. The skill is significantly higher during the second decade (2000-2010), which yields correlations above 0.92 for both categories. The prediction in the eastern North Pacific is skillful, but it is not as outstanding as that in the North Atlantic. The use of persisted SSTA assumption appears to be less robust for the western North Pacific, contributing to less skillful predictions in that region.

The research also showed that intensity distribution of TCs can be captured well by our model if the central sea-level pressure were used as the threshold variable instead of the commonly used 10-meter wind speed (Fig. 1). This demonstrated the feasibility of using the 25-km resolution HiRAM, a general circulation model designed initially for long-term climate simulations, to study the impacts of climate-change on the intensity distribution of TCs.

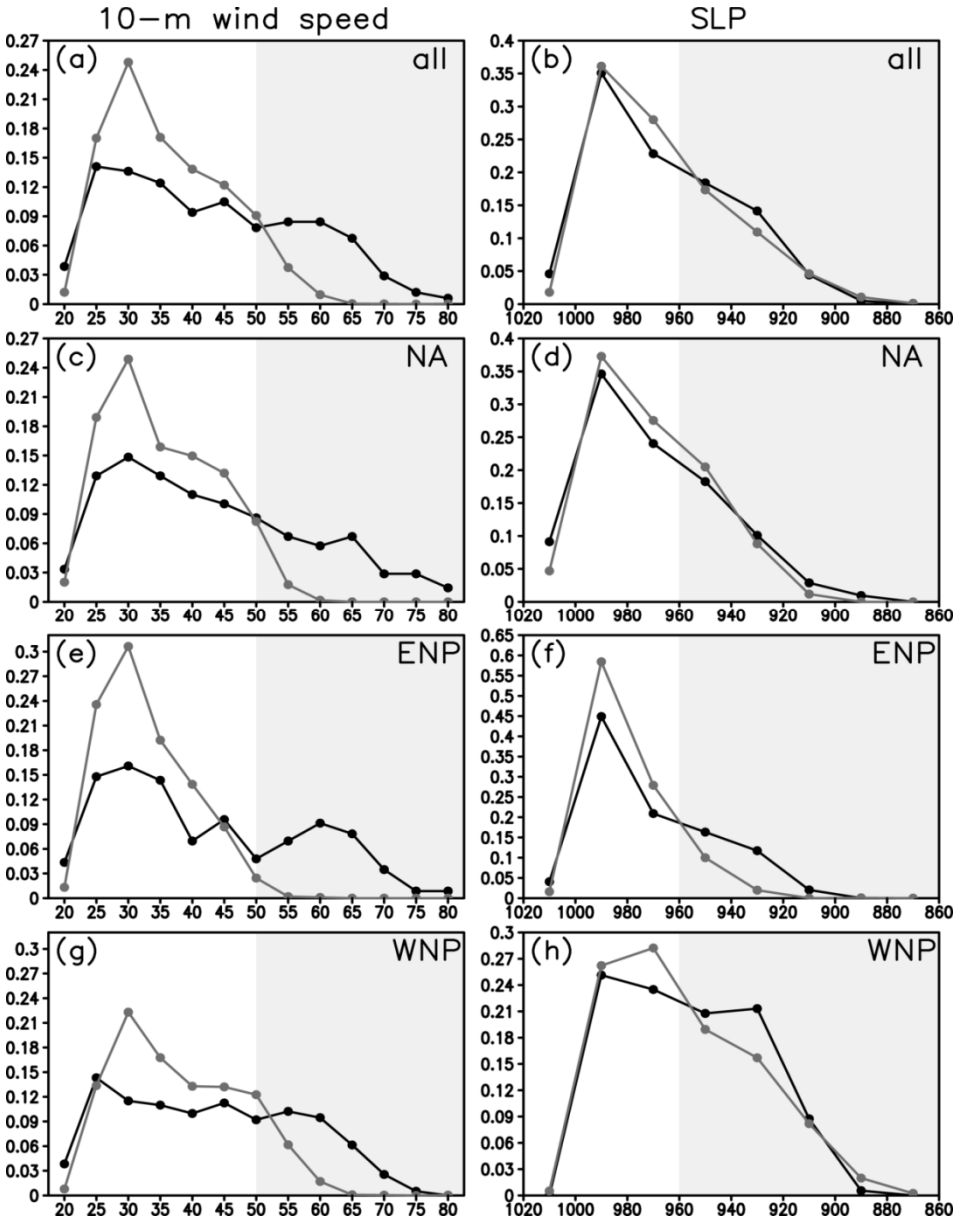

Fig. 1 Distributions of tropical storm intensity based on (a) the maximum 10-m wind speed (unit: ms^{-1}) and (b) the minimum sea-level pressure (hPa) for the three basins during 1990-2010. (c), (e), (f) As in (a), but for the NA, ENP and WNP basins, individually. (d), (f), (h) As in (b), but for the NA, ENP and WNP basins, individually. Observations from IBTrACS data are shown by black lines and circles, and the grey lines and circles represent the ensemble mean of the HiRAM model forecasts. The light-grey shades mark the range above the major hurricane criteria.

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Chen, J.-H., and S.-J. Lin, 2012: Seasonal predictions of tropical cyclones using a 25-km resolution general circulation model. Submitted to J. Clim.

Progress Report Title: **Cross-shelf Exchange Processes in the Bering Sea: Downscaling Climate Models and Ecosystems Implications**

Principal Investigator: Enrique Curchitser (Associate Research Professor, Rutgers, IMCS)

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

Other Participating Researchers: Gaelle Hervieux (Rutgers), Fred Castruccio (Rutgers)

Task III: Individual Projects

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 (50%)
Climate Goal: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond (50%)

Objectives: Understanding the mechanisms that control exchanges of physical and biological properties between ocean basins and continental shelves, where the dominant portion of the biological productivity takes place, and potential linkages between these mechanisms and climate variability and change is a key step toward representing these processes in global climate models. For the eastern Bering Sea, these exchanges provide nutrients that are critical for maintaining high biological production and arise from a combination of currents interacting with topography (e.g. canyons) instabilities of shelf break flows and eddy activity. This study proposes to diagnose the cross-shelf exchanges and the processes governing them for the eastern Bering Sea within a high-resolution (<10 km) regional ROMS simulation and compare these results to GFDL's global ocean simulations.

Methods and Results/Accomplishments:

The proposed workplan was to 1) Complete and analyze a 50-year hindcast simulation of the Bering Sea using ROMS at a 10 km resolution, 2) Perform a small ensemble of downscaled projections using GFDL global model solutions for boundary forcing and 3) Analyze the cross-shelf processes in all these simulations. To date the following have been accomplished in this project: (1) 1958-2008 ROMS hindcast simulation has been completed and extensive model-data validation has taken place and results published in two manuscripts to date. The regional model shows significant skill in reproducing conspicuous features such as the seasonal cold pool, interannual sea ice variability and major circulation features. Capturing these coastal-scale features is essential for understanding the response of the Bering Sea to climate variability and change. (2) Both a passive and an age tracer were developed for this setup and a hindcast simulation is being carried out with them. In particular, we are seeding the tracers along the shelf break and at Unimak Pass that is one of the main connection points between the Bering and the North Pacific ocean. The purpose of these simulations is to study the role of advection in the cross shelf exchange and to determine the relative roles of the off-shelf and N. Pacific waters on the Bering shelf, as well as their residence times. (3) The main activity since the last report was the carrying out and analysis of a coupled physics-NPZD simulation in the Bering Sea. We have modified the NEMURO ecosystem model to include benthic processes (denitrification and burial), which are believed to be important in the region. We have also improved the representation of iron limitation in off-shore waters and improved the treatment of nutrients along the model boundaries to eliminate nutrient drift. We are currently working on a manuscript describing the nutrient fluxes on the Bering shelf and relating the interannual and decadal

variability to North Pacific climate indices. This work was presented as a poster at the Ocean Sciences meeting in Salt Lake City. (4) Work continues on setting up simulations of future scenarios where the regional model is forced by output from GFDL earth system model runs. Lessons learned in the long-term hindcast efforts described in 1-3 will help these efforts. We expect that these simulations to begin during the summer of 2012 and we have obtained funding from NOAAs Integrated Ecosystem Assessment Program to support the continuation of this work (see future plans).

References:

Hervieux, C., Curchitser, E.N., Stock, C.A., Castruccio, F.S. (Poster). A high-resolution regional model for the Bering Sea ecosystem. Presented at the 2012 Ocean Sciences Meeting, Salt Lake City Utah.

Publications:

Hervieux, C., Curchitser, E.N., Stock, C.A., Castruccio, F.S. (in prep). Seasonal and inter-annual nutrient supply and transport on the Bering Sea shelf.

Progress Report Title: **Tropical Atlantic Variability for a Coarse and High-resolution Climate Model**

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 investigate the character and sources of SST and precipitation biases in the tropical Atlantic and improve the simulation and prediction skill of the GFDL climate models; the Climate Model version 2.1 developed at the Geophysical Fluid Dynamics Laboratory (CM2.1) and CM2.5: a new high-resolution climate model based on CM2.1

Methods and Results/Accomplishments:

Many aspects of the simulation (*e.g.,* annual cycle and interannual variability of northern tropical Atlantic SST and precipitation) are significantly improved in CM2.5 relative to CM2.1-yet others persist (Doi et al. 2012a). CM2.5 has an improved simulation of the annual mean and the seasonal cycle of the rainfall over the Sahel and the northern South America, while CM2.1 shows excessive Sahel rainfall and lack of northern South America rainfall in boreal summer. This marked improvement in CM2.5 is mainly due to not only high-resolved orography, but also a significant reduction of some biases in the seasonal meridional migration of the Intertropical Convergence Zone (ITCZ). In particular, the seasonal northward migration of the ITCZ in boreal summer is coupled to the seasonal variation of the SST and a subsurface doming of the thermocline in the northeastern tropical Atlantic, known as the Guinea Dome (Doi et al, 2009; Doi et al, 2010). Improvements in the ITCZ allow for better representation of the coupled processes that are important for an abrupt seasonally phase-locked decay of the interannual SST anomaly in the northern tropical Atlantic. Nevertheless, the differences between CM2.5 and CM2.1 were not sufficient to reduce the warm SST biases in the eastern equatorial region and Angola-Benguela Area. The weak bias of southerly winds along the southwestern African coast may be a key to improve the warm SST biases (e.g. Tozuka et al. 2010).

Next, I explored response of SST in the Atlantic Hurricane Main Development Region (SST_{MDR}) to CO_2 doubling, using the new high-resolution CM2.5 (Doi et al. 2012b). CM2.5 shows better skills on simulation of the northern tropical Atlantic and other tropics (Doi et al. 2012a; Delworth et al. 2012) In the annual mean, the SST_{MDR} warms by about 2°C in the CO_2 doubling run relative to the Control run, the trade winds become weaker in the northern tropical Atlantic, and the rainfall increases over the ITCZ and its northern region. The amplitude of the annual cycle of the SST_{MDR} is not significantly changed by CO_2 doubling. However, we find that the interannual variations show significant responses to CO_2 doubling: the seasonal maximum peak of the interannual variations of the SST_{MDR} moves from boreal spring to early boreal summer, at which time it is about 25% stronger than in the Control run. The enhancement of the interannual variations of the SST_{MDR} is due to changes in effectiveness of the Wind-Evaporation-SST (WES) positive feedback: WES remains a positive feedback until boreal early summer in the CO_2 doubling run. The enhancement of the interannual variation of SST_{MDR} in boreal early summer in a warm climate also seems to appear in observation, although there are some uncertainties among observational

datasets. The large amplitude of the interannual variation of the SST_{MDR} enhances the year-to-year variation of the Atlantic Hurricane count.

I also investigated the simulation skill of CM2.5 for the Indian summer rainfall (Doi et al. 2012c). CM2.5 captures orographic rainfall over the Western Ghats much better relative to CM2.1. Not only coupled models, but also stand-alone atmospheric models have been analyzed to understand how important increasing resolution is for rainfall simulation (Doi et al. 2012d). Those results are very helpful to understand zonal teleconnections among the tropical Atlantic, Pacific and Indian Ocean.

References:

Delworth, T. L., and Coauthors, 2012: Simulated climate and climate change in the GFDL-CM2.5 high-resolution coupled climate model. *J. Climate*, *in press.*

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, J. Geophys. Res., 116, C06010, doi:10.1029/2010JC006717.

Doi, T., T. Tozuka, and T. Yamagata, 2010: The Atlantic Meridional Mode and its coupled variability with the Guinea Dome, J. Climate, 23, 455-475.

Doi, T., T. Tozuka, and T. Yamagata, 2009: Interannual variability of the Guinea Dome and its possible link with the Atlantic Meridional Mode, Climate Dynamics, 33, 985-998.

Publications:

Doi, T., G. A. Vecchi, A. J. Rosati, and T. L. Delworth, 2012a: Tropical Atlantic biases in the mean state, seasonal cycle, and interannual variations for a coarse and a high resolution coupled climate model, J. Climate, in revision.

Doi, T., G. A. Vecchi, A. J. Rosati, and T. L. Delworth, 2012b: Response to CO_2 doubling of the Atlantic Hurricane Main Development Region in a High-Resolution Climate Model, submitted to J. Climate.

Doi, T., G. A. Vecchi, A. J. Rosati, and T. L. Delworth, 2012c: The Indian summer rainfall in a high-resolution climate model, in preparation.

Doi, T., G. A. Vecchi, S. Manabe, B. Wyman, S. Kapnick, A. J. Rosati, and T. L. Delworth, 2012d: Rainfall simulation for a coarse and a high-resolution AGCM, in preparation.

Doi, T., G. A. Vecchi, A. J. Rosati, and T. L. Delworth: “Tropical Atlantic biases in the mean state, seasonal cycle, and interannual variations for a coarse and a high resolution coupled climate model”, 2012 Ocean Sciences Meeting, Salt Lake City (U.S.), Feb. 2012 (Oral).

Doi, T., G. A. Vecchi, A. J. Rosati, and T. L. Delworth: "The Indian summer rainfall in a high-resolution coupled climate model", Bay of Bengal Workshop, Woods Hole (U. S.), Nov. 2011 (Oral).

Doi, T., G. A. Vecchi, A. J. Rosati, and T. L. Delworth: "Tropical Atlantic biases in the mean state, seasonal cycle, and interannual variations in the new GFDL-CM2.5", the Oceanographic Society of Japan (JOS) fall meeting, Fukuoka (Japan), Sep. 2011 (Oral).

Doi, T., G. A. Vecchi, A. J. Rosati, and T. L. Delworth: "Biases in the mean state, seasonal and interannual variations in the tropical Atlantic in GFDL climate models CM2.1 and CM2.5", Workshop on coupled ocean-atmosphere-land processes in the tropical Atlantic, Miami (U. S.), Mar. 2011 (Oral & Poster).

Doi, T., and G. A. Vecchi: "Coupled GCM's bias for the summer decay of the year-to-year SST variation in the northern tropical Atlantic and its coupled link with the Guinea Dome", AGU fall Meeting 2010, San Francisco (U. S.), Dec. 2010 (Poster).

Progress Report Title: **Brewer-Dobson Circulation and Stratospheric Water Vapor**

Principal Investigator: Martin Jucker (Princeton Postdoctoral Research Fellow)

CICS/GFDL Collaborator: Geoffrey K. Vallis (Princeton)

Other Participating Researchers: Stephan Fueglistaler (Princeton)

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: Better understand the relationships between topographic forcing, the stratospheric meridional overturning circulation, and the distribution of water vapor in the stratosphere

Methods and Results/Accomplishments:

Although comprehensive General Circulation Models are extremely useful for general climate change research, it can be difficult to concentrate on only few dynamical details. For this, idealized models are more appropriate, as they allow for diminishing the number of independent variables. For studying the dynamics and distribution of water vapor in the stratosphere, we developed such an idealized model based on previous models of Polvani and Kushner (2002) and Gerber and Polvani (2009). This model includes realistic atmospheric and stratospheric dynamics, but limits both chemical and radiative effects as well as boundary conditions. The most important driving of the Brewer-Dobson circulation comes from wave-two perturbations from surface topography, and we model these by including simplified Gaussian mountains around the geographical positions of the Rockies and the Tibetan Plateau. There is no ocean dynamics. Water vapor is included as a passive tracer advected by wind and transported vertically by ascending or descending air mass. Its source is everywhere on the surface except where mountains reach higher than ten meters altitude, and the sink corresponds to saturation given by the Clausius-Clapeyron relation. Maximum specific humidity then depends on air pressure and temperature, and any excess is removed from the air without precipitation or clouds. We can vary mountain height (i.e. topographic forcing of the circulation), the strength of the polar vortex in the winter hemisphere (i.e. zonal wind strength impacting wave propagation and temperature impacting water vapor content), and the seasonal cycle (e.g. realistic cycle or eternal January) independently. Thanks to this versatile model, we are able to study the impact on the water vapor distribution in the stratosphere of a strengthening/weakening of the polar vortex and strengthening/weakening of the Brewer-Dobson circulation. It is important to increase our knowledge of these relationships, as water vapor is an extremely potent greenhouse gas on one hand and an active chemical agent on the other hand.

So far, we have developed the model and run several consistency checks. These checks concentrated on stratospheric dynamics, with upwelling in the tropics and subsidence in high latitudes, as well as diabatic heating which needs to be equilibrated by diabatic cooling. Furthermore, residual circulation and the downward control mechanism (Haynes et al. (1991)) could be verified. After these successful testing, we are now running scans of water vapor distribution as a function of circulation strength by varying the mountain height.

References:

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Haynes, P, M McIntyre, T Shepherd et al. (1991), On the "Downward Control" of extratropical diabatic circulation by eddy-induced mean zonal forces, J. Atmos. Sc. 48, 651.

Polvani, L and P Kushner (2002), Tropospheric response to stratospheric perturbations in a relatively simple general circulation model, Geophys. Rev. Lett. 29, 40.

Progress Report Title: **Assessing the Hydroclimate in a High-Resolution Global Coupled Model Framework Phase I: Annual Means and Seasonal Cycle**

Principal Investigator: Sarah Kapnick (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Thomas Delworth (GFDL)

Other Participating Researchers: Chris Milly (USGS), Sergey Malyshev (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: My first objective is to assess the variability of snowfall and snowpack in the latest models developed at the GFDL and compare them to previous versions and observations/reanalysis. My second objective is to utilize the models to explore the variability of the winter/spring hydroclimate and its impacts on water supply.

Methods and Results/Accomplishments:

My research centers on output from two models developed at the GFDL: CM2.5 (Delworth et al., 2012) and CM2.1 (Delworth et al., 2006). The CM2.5 model is the latest high-resolution coupled model available at the GFDL. It is updated from previous versions by increasing the resolution of both the atmosphere (50km in the horizontal) and ocean (~25 km horizontal resolution in the tropics, refining to 10km at the poles). This model presents a unique opportunity to look at simulated hydroclimate at the highest resolution possible. For comparison, I am also using output from an older lower-resolution version of the model, CM2.1 (atmospheric resolution of ~200km and ocean resolution of ~100km). The CM2.1 model was developed and used for the 2007 IPCC AR4 report. My research compares output from these two models in the present and future climate simulations to explore the improvements in the simulation of hydroclimate from resolution enhancement. The model output is also compared with various observational data sets and reanalysis for validation and future model improvement work.

I have focused my time developing two main studies. The first uses annual means of snowfall, precipitation, temperature, and runoff to explore the mechanisms controlling snowfall and resulting impact on global water supply as measured by snowfall as a percentage of total runoff (Kapnick and Delworth 2012). The second study explores the seasonal cycle of snowpack as measured by snow water equivalent and hemispheric snow covered area (Kapnick, Delworth, and Milly 2012). Both studies highlight the importance of high-resolution to reproduce the distribution and magnitude of hydrologic variables. Changes in these characteristics are evident when comparing present and future simulations. For example, the magnitude and slope of the seasonal cycle of snow covered area in the Northern Hemisphere is improved with higher resolution (Figure 1). The climate change runs show that snow covered area should reduce in the future climate, with greater differences shown in the high-resolution runs. I am presently writing up these two studies into two separate papers. I will present some of this work as an invited speaker at the end of this month (Kapnick 2012). I have also been accepted to present some of this work at the 2012 NCCR Climate Summer School in Switzerland in September.

References:

Delworth, T. et al., 2012: GFDL's CM2.5 Global Coupled Climate Models. Part I: Formulation and Simulation Characteristics. In Press at J. Climate.

Delworth, T. et al., 2006: GFDL's CM2 Global Coupled Climate Models. Part I: Formulation and Simulation Characteristics, J. Climate, 19, 643-674.

Publications:

Kapnick, S. and T. Delworth, 2012: Global Snowfall Variability: Controlling Mechanisms and Surface Hydrology Implications. In preparation.

Kapnick, S., T. Delworth, C. Milly, and S. Malyshev, 2012: The Seasonal Cycle of Northern Hemisphere Snowpack in the Present and Future Climate. In preparation.

Kapnick, S., 2012: Sierra Nevada snowpack and California's water resources: A regional hydroclimate case study. PIIRS Workshop on Climate Change and Water Cycle, and Communicating Uncertainty, Princeton University, Princeton, NJ.

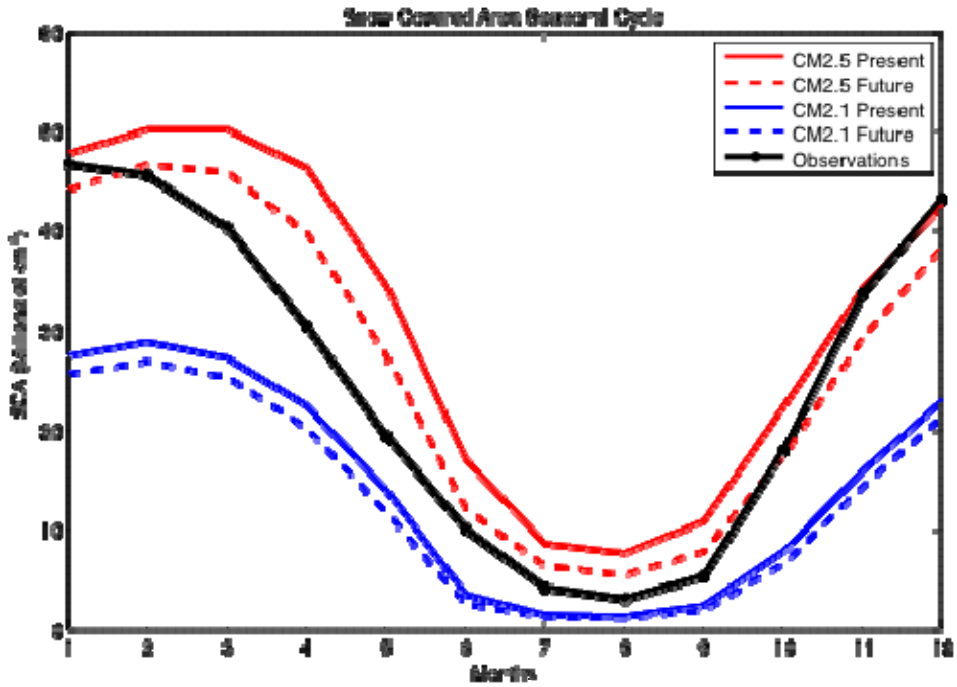

Figure 1: Northern Hemisphere monthly mean snow covered area for 40 years of model simulations in the present and future climate. Observations from the Rutgers Snow Lab (available at: http://climate.rutgers.edu/snowcover/index.php).

Progress Report Title: **Quantifying the Global Sources of Local Ozone Pollution over the Western United States**

Principle Investigator*:* Meiyun Lin (Princeton Associate Research Scholar)

CICS/GFDL Collaborator*:* Larry Horowitz (GFDL)

Other Participating Researchers: Arlene Fiore (Columbia/Lamont), Owen Cooper (NOAA/ESRL), Hiram Levy II (GFDL)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

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

Objectives: Advance knowledge on the global sources of local ozone pollution over the western United States to inform U.S. air quality policy; Quantifying the role of imported Asian pollution, stratospheric exchange, wildfire emissions, and other natural sources

Methods and Results/Accomplishments:

Several recent studies have shown that powerful spring winds can carry Asian pollution into the atmosphere above North America. Our analysis goes further, using high-resolution models and observations to show how some of the imported pollution can descend to the surface, where it affects ground-level ozone, a regulated pollutant. We find that during episodes of high surface ozone in parts of California and the Southwest, Asian emissions added 8 to 15 parts per billion of ozone to air, comprising up to 20 percent of the total. In several areas, about half of the springtime pollution episodes that exceeded federal limits would probably not have occurred without the contribution of Asian pollution. We could use satellite data to predict when incoming plumes of polluted air might affect western air quality, one to three days ahead of time. These new findings were reported in a paper published in the Journal of Geophysical Research – Atmospheres. The paper was selected as a Research Spotlight in American Geophysical Union, featured in Science and Nature Magazines, and covered by public media.

Trans-Pacific transport of Asian pollution plumes to U.S. west coast often coincides with ozone injected from the stratosphere. We find that a newly developed, high-resolution (~50x50 km^2) version of the GFDL AM3 model can reproduce real-world patterns of ozone over California measured by balloon-borne instruments, aircraft, and ground instruments during a NOAA-sponsored field study of air quality and climate in 2010 (CalNex). Building upon model simulations and observations as described in Lin et al. [2012], we will be submitting two additional research papers in a few weeks, focusing on the role of stratospheric ozone intrusions in driving high surface ozone events over the western USA.

References*:*

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ScienceShot: http://news.sciencemag.org/sciencenow/2012/03/scienceshot-imported-air-polluti.html?ref=hp

Nature News: http://www.nature.com/news/emissions-from-asia-put-us-cities-over-the-ozone-limit-1.10161

New York Times: http://green.blogs.nytimes.com/2012/03/06/a-new-east-asian-import-ozone-pollution/?scp=1&sq=ozone&st=cse

Daily Camera: http://www.dailycamera.com/science-environment/ci_20141328/noaa-asian-pollution-contributes-up-20-percent-west

NOAA Research: http://researchmatters.noaa.gov/news/Pages/ozonestudy.aspx

Lin, M., A. M. Fiore, L. W. Horowitz, O. R. Cooper et al, Quantifying stratospheric ozone in surface air: role of model resolution. To be submitted to Geophysical Research Letter, March 2012

Lin, M., A. M. Fiore, O. R. Cooper, L. W. Horowitz et al, Springtime high-surface ozone events over the western United States: Quantifying the role of stratospheric ozone intrusions. To be submitted to J. Geophy. Res, March 2012

Publications:

Lin, M., A.M. Fiore, L.W. Horowitz, O.R. Cooper, V. Naik, J. Holloway, B.J Johnson, A.M. Middlebrook, S.J. Oltmans, I.B. Pollack, T.B. Ryerson, J.X. Warner, C. Wiedinmyer, J. Wilson, B. Wyman (2012) Transport of Asian ozone pollution into surface air over the western United States in spring , J. Geophys. Res. , 117, D00V07, doi:10.1029/2011JD016961.

Progress Report Title: **Modeling the Effects of Climate Change and Ocean Acidification on Global Coral Reefs**

Principal Investigator: Cheryl Logan (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: John Dunne (GFDL)

Other Participating Researchers: Simon Donner (UBC), 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: In the past year, my focus has been on developing a framework for comparing coral bleaching thresholds and making a recommendation to NOAA Coral Reef Watch for an improved bleaching prediction method. This method will be used in combination with SSTs from the GFDL Earth System model to predict coral bleaching frequency through 2100.

Methods and Results/Accomplishments:

Coral reefs are highly vulnerable to elevated sea surface temperatures that induce coral bleaching. Since 2002, NOAA Coral Reef Watch has used an empirically based bleaching threshold based on global sea surface temperatures to provide operational real-time bleaching warnings. Bleaching alerts can prompt coral reef managers to reduce other stressors on reefs (e.g. fishing) during times of thermal stress. Scientists widely use the bleaching prediction method to assess reef resilience and to forecast bleaching rates under different climate change scenarios. Recent studies suggest that modifications to the current global bleaching prediction method may result in higher predictive power. We developed a method for comparing alternative bleaching prediction methods. Four recently proposed threshold prediction methods are compared at different spatial (1° x 1°, 0.5° x 0.5°, 4km) and temporal resolutions (monthly and biweekly) and calibrated against the global bleaching observational dataset from ReefBase between 1985 and 2005. We identified one method ("MMMmax") that had the highest predictive power across all spatial and temporal resolutions examined. An improved bleaching threshold will refine future bleaching predictions and provide more reliable real-time bleaching alerts to international coral reef managers. This work has been submitted as a manuscript and is currently in review at the *Proceedings of the 12th International Coral Reef Symposium*.

The methods developed using historical bleaching records can now be applied to SST output from the GFDL Earth System Model to make predictions about coral bleaching frequency through 2100. We will use the best bleaching prediction methods from the historical comparison as well as some additional methods that incorporate corals' potential ability to acclimatize or adapt to make projections under each of the Representative Concentration Pathways scenarios developed for the 5th IPCC Assessment. The results will be presented at the 12th International Coral Reef Symposium Proceedings in Cairns, Australia this July. A manuscript for this work will be submitted in July 2012 in time for consideration in the IPCC report. Potential journals we are targeting include: Global Change Biology or Nature Climate Change.

Publications:

Logan C.A., Dunne J., Eakin C.M., Donner S.D. In Review. A framework for comparing coral

bleaching thresholds. Proceedings of the 12th International Coral Reef Symposium, Cairns, Australia.

Logan C.A., Dunne J., Donner S.D., Eakin C.M. "Recommendation for a revised coral bleaching threshold". Ocean Sciences, Salt Lake City, Utah. Oral Presentation (February 2012).

Logan C.A., Donner S.D., Dunne J., Eakin C.M. "Modeling the effects of rising sea surface temperature on global coral reefs using empirical downscaling". International Marine Conservation Congress, Victoria, Canada. Oral Presentation (May 2011).

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 Model Applications

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

Objectives: Explain what climate drivers (spring temperature, winter temperature, day length, etc.) affect the seasonal expression of foliage in temperate deciduous forests; explain how climate-driven changes in the seasonal expression of foliage affect terrestrial ecosystem carbon budgets

Methods and Results/Accomplishments:

Terrestrial ecosystems are tightly coupled to the atmosphere through exchanges of energy, water, and carbon dioxide (Bonan 2008; Friedlingstein et al. 2006). In temperate deciduous forests, these exchanges are strongly impacted by the springtime emergence of leaves. Recent work has shown that this seasonal change in vegetation is poorly understood, leading to large biases in predictions of short-term land-atmosphere exchanges as well as long-term ecosystem carbon budgets (Schwalm et al. 2010; Richardson et al. 2012; Jeong et al. 2012). One school of thought states that budburst date depends purely on the accumulation of warm temperature; a competing hypothesis states that exposure to cold temperatures is also important for budburst (Chiang and Brown 2007; Richardson and O'Keefe 2009). In Jeong et al. (2012), we evaluated the variability budburst is using 15 years of budburst data for 17 tree species at Harvard Forest (Fig. 1a). We compared the two budburst hypotheses through reversible jump Markov chain Monte Carlo. We then investigated how uncertainties in budburst date mapped onto uncertainties in ecosystem carbon using the Geophysical Fluid Dynamics Laboratory's LM3 land model. For 15 of 17 species, we found that models with chilling periods are favored over models without chilling periods. LM3 simulations showed that the choice of budburst model induces differences in the timing of carbon uptake commencement of ~11 days, in the magnitude of April–May carbon uptake of 1.03 g C m^{-2} day^{-1}, and in total ecosystem carbon stocks of ~2 kg C m^{-2}. While the choice of whether to include a chilling period in the budburst model strongly contributes to this variability, another important factor is how the species-dependent field data gets mapped onto LM3's single deciduous plant functional type (PFT). We concluded that budburst timing has a strong impact on simulated CO_2 fluxes, and that uncertainty in carbon fluxes can be substantially reduced by improving model representation of plant diversity.

In work about to be submitted, Jeong et al. expanded this local model into a continental scale model for variations in spring phenology (Fig. 1b). The model was evaluated using newly-released continental-scale data archived by the USA National Phenology Network. We used the new model together with climate forcing from the Coupled Model Intercomparison Project phase 5 (CMIP5) to predict changes in spring phenology for the continental U.S. for the 21st century. We found that the initiation of leaf emergence in the spring ("budburst") will be advanced by up to 17 days, which represents a dramatic lengthening of the growing season (Fig. 2). The earlier budburst was mainly

attributed to warmer spring temperatures rather than to changes in winter temperature, insolation, or other factors. Furthermore, current inter-species differences in budburst date were predicted to become smaller over the course of the 21st century. These results have implications for the ability of terrestrial ecosystems to take up carbon as well as for ecosystem species composition.

References:

Bonan, G.B. (2008), Forest and climate change: Forcings, feedbacks, and the climate benefits of forests, Science, 320, 1444–1449.

Chiang, J.M., Brown, K.J., 2007. Improving the budburst phenology subroutine in the forest carbon model PnET. Ecological Modelling 205 (3–4), 515–526.Friedlingstein, P., P. M. Cox, R. Betts, et al. (2006), Climate-carbon cycle feedback analysis, results from the C4MIP model intercomparison, Journal of Climate, 19, 3337–3353.

Richardson, A. D., and J. O'Keefe (2009), Phenological differences between understory and overstory: A case study using the long-term Harvard Forest records, in Phenology of Ecosystem Processes, edited by A. Noormets, pp. 87–117, Springer, New York, doi:10.1007/978-1-4419-0026-5_4.

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Schwalm CR, Williams CA, Schaefer K et al. (2010) A model-data intercomparison of CO2 exchange across North America: results from the North American Carbon Program Site Synthesis. Journal of Geophysical Research-Biogeosciences, 115, G00H05.

Jeong, S.-J., D. Medvigy, E. Shevliakova, and S. Malyshev (2012), Uncertainties in terrestrial carbon budgets related to spring phenology, J. Geophys. Res., 117, G01030, doi:10.1029/2011JG001868.

Publications:

Jeong, S.-J., D. Medvigy, E. Shevliakova, and S. Malyshev (2012), Uncertainties in terrestrial carbon budgets related to spring phenology, J. Geophys. Res., 117, G01030, doi:10.1029/2011JG001868.

Jeong, S.-J., D. Medvigy, E. Shevliakova, and S. Malyshev (2011), Uncertainties in terrestrial carbon budgets related to spring phenology. Presented at AGU Fall 2011 Meeting.

Jeong, S.-J., D. Medvigy, E. Shevliakova, and S. Malyshev (In Prep), Climate-driven changes in temperate forest seasonality. (To be submitted to Proc. Natl. Acad. Sci. *USA*, spring 2012)

Figures:

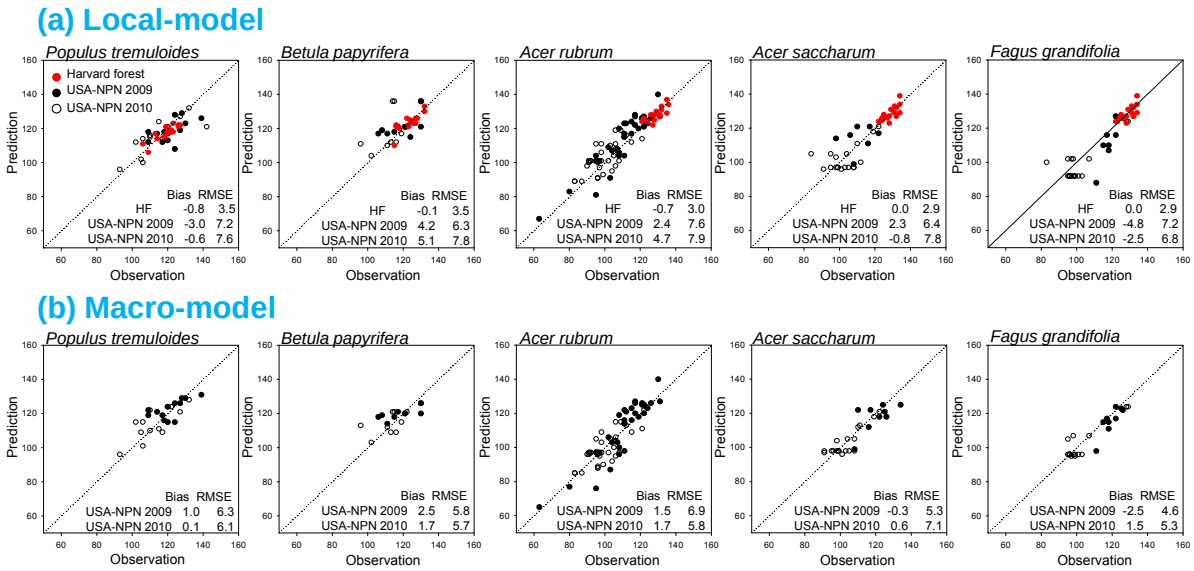

Fig 1. Predicted budburst date of five deciduous trees (*Populus tremuloides*, *Betula papyrifera*, *Acer rubrum*, *Acer saccharum*, and *Fagus grandifolia*,) by (a) local- and (b) macro-scale model over USA-NPN sites in 2009 (closed circle) and 2010 (open circle), respectively.

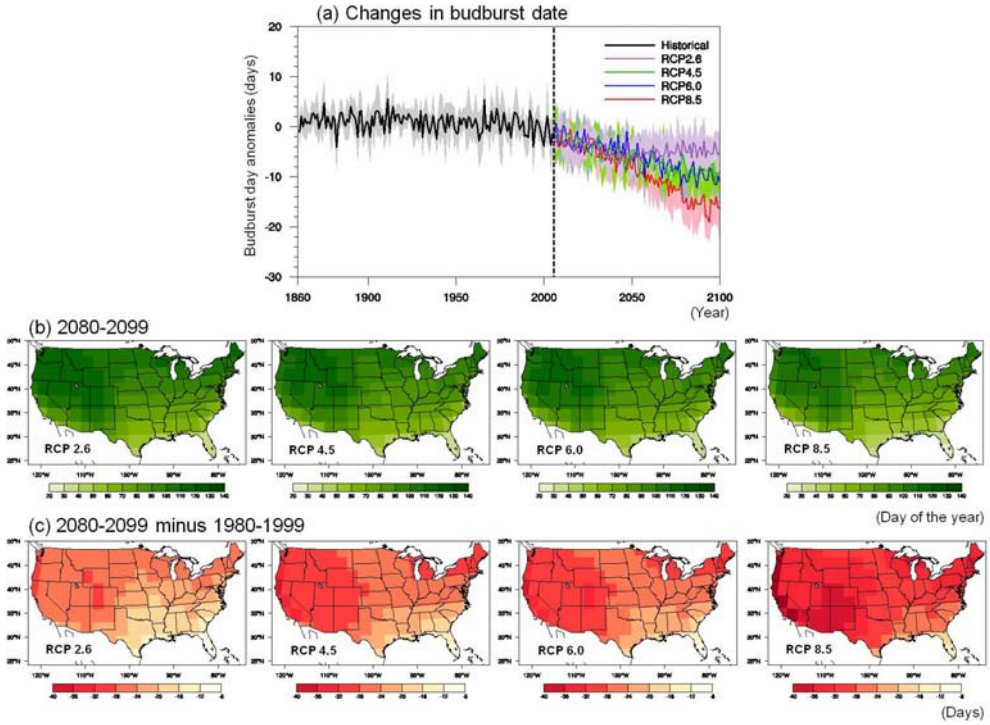

Fig 2. Changes in budburst date anomalies of *A. rubrum* from 1860 to 2100. (a) The anomalies are obtained from current climate normal (1980-1999). The solid line in the figure indicates ensemble mean of 6 kinds of CMIP5 models. Spread in the figure also means uncertainties in each scenario, which is obtained from standard deviations among 6 kinds of CMIP5 models. Spatial patterns of budburst date in the last-coming century (2080-2099) (b) and differences between last-coming century and current climate normal (1980-1999) (c).

Progress Report Title: **Design and Development of GFDL Data Portal Infrastructure and Publishing IPCC AR5 Simulation Data on GFDL Data Portal**

Principal Investigator: Sergey Nikonov (Princeton Professional Technical Specialist)

CICS/GFDL Collaborator: V.Balaji (Princeton), Aparna Radhakrishnan (DRC/GFDL), Kyle Olivo (DRC/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: Development of FMS Runtime Environment (FRE) in support of Earth system modeling activities for IPCC AR5 and other projects in part of its interaction with the GFDL Curator system. The key element is implementation of the GFDL Curator system, which maintains a database of model results delivered to the public from GFDL models. The important part of the task included support of the scientific community in the discovery, access, and delivery of data through the GFDL Data Portal developed infrastructure.

Methods and Results/Accomplishments:

GFDL Curator infrastructure as a part of FMS Runtime Environment system was implemented and used for IPCC AR5. It showed robustness and good performance in publishing and delivering IPCC data to the scientific community.

The amount of prepared IPCC AR5 data exceeds 200 TB and ~150 TB of 6 GFDL models data output was published and made available through GFDL Data Portal.

The GFDL Data Portal team is participating in ESGF (Earth System Grid Federation). ESGF Data Node was installed on GFDL Data Portal and is being maintained. About 100 TB of IPCC AR5 GFDL runs through ESGF were published.

Web services for analysis and display of model output were designed and developed. This includes statistical downscaling and bias correction of climate model output based on the work of K. Hayhoe's and collaborators' standard analysis figures for conducting experiments.

Publications:

NOAA/GFDL Model Development Database Interface (for AR5 Quality Control Process Tracking). A. Radhakrishnan, V.Balaji, K.Olivo, S.Nikonov. May 2011 GO-ESSP Workshop. Ashville, NC.

FREMetar: Efficient and Flexible Metadata Rewriting. A. Radhakrishnan, V.Balaji, K.Olivo, S.Nikonov. May 2011 GO-ESSP Workshop. Ashville, NC.

Progress Report Title: **Offsetting and Complementary Characteristics of Sulfate and Soot Direct Radiative Forcings and Climate Responses**

Principal Investigator: Ilissa Ocko (Princeton Graduate Student)

CICS/GFDL Collaborator: V. Ramaswamy (GFDL)

Other Participating Researchers: Paul Ginoux, Larry Horowitz, Yi Ming (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 how physical climate factors control the magnitudes of direct aerosol forcings, and to investigate how these forcings have contributed to climate change over the 20th C

Methods and Results/Accomplishments:

We employ the GFDL CM2.1 global climate model to investigate how important physical climate characteristics contribute to the emergence of an offset in the direct radiative forcing (DRF) between anthropogenic sulfate and black carbon (BC). BC and sulfate aerosols constitute two important perturbations to the climate system, and provide a striking contrast between a primarily scattering (sulfate) and primarily absorbing (BC) species. We find that sulfate and BC all-sky top-of-atmosphere (TOA) global-mean DRFs in CM2.1, which assumes externally mixed aerosols, exhibit a near-complete offset. There is thus a delicate balance amongst the main scattering and absorbing aerosol species in their contribution to the anthropogenic forcing. The degree of this offset varies regionally, and is subject to uncertainties in the state of mixing by aerosol species. The quantitative roles of important physical climate factors in establishing this offset are examined: cloud coverage, surface albedo and relative humidity. Clouds reduce the global-mean sulfate TOA DRF by half, and double that by BC. Sulfate forcing is increased by 60% as a result of their hygroscopic growth, while high-albedo surfaces are found to have only a minor (~10%) impact on global-mean forcings. This study highlights the crucial role of the fundamental physical climate characteristics in governing the aerosol climate forcing offset.

Aerosols, as a whole, are considered to offset the radiative and climatic effects of greenhouse gases. However, robust differences exist among the main anthropogenic aerosol species—black carbon and sulfate—resulting in an offset within aerosols. In the solar wavelengths, the relatively strong absorption capability of black carbon induces a positive direct radiative forcing (DRF) that offsets the negative DRF of purely scattering sulfate. Furthermore, although the global-mean net DRF is nearly zero, the degree of offset is regionally and seasonally dependent. To evaluate how these contrasting forcings have affected 20th century climate change, we employ the GFDL CM2.1 coupled global climate model to assess changes in key climate variables from pre-industrial to present-day. We run isolated forcing scenarios for 140 years with 3 ensemble members each. Specifically, we examine changes in air temperature, precipitation, soil moisture, and ice volume that are attributed to the presence of sulfate and black carbon. We find that black carbon and sulfate have opposing global-mean effects on all variables except precipitation. Whereas effects on global temperature are balancing (black carbon: +0.23 K; sulfate: -0.31 K), both aerosols reduce global-mean rainfall rates (black carbon: -0.015 mm/day; sulfate: -0.02 mm/day). On the zonal scale, however, black carbon and sulfate generate inverted responses from all four

climate variables. Overall, sulfate's effect on each climate variable dominates that of black carbon, and therefore the balance is tilted towards slightly offsetting the response of the climate to greenhouse gases.

Accomplishments include presenting this work at the WCRP Open Science Conference in Denver CO, where I won an Outstanding Poster Presentation Award. I have submitted a paper to JGR that has been undergoing extensive review over the past several months, and will hopefully be published in the near future.

Progress Report Title: **Tropical Modes of Dry Dynamical Cores**

Principal Investigator: Samuel Potter (Princeton Graduate Student)

CICS/GFDL Collaborator: Geoff Vallis (Princeton)

Other Participating Researchers: Isaac Held, Steve Garner (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 low frequency large-scale tropical variability in atmospheric models with no moisture. To use this understanding to better our knowledge of the Madden-Julian Oscillation in full-physics general circulation models and in the real world.

Methods and Results/Accomplishments:
I have been studying the tropical mode that leads to superrotation in the small planet and slowly rotating regimes of the GFDL dry dynamical core. I have shown that this mode bears some striking resemblance to the Madden-Julian Oscillation, which is always thought of as being an inherently moist phenomenon.

References:
Caballero and Huber, 2010: Spontaneous transition to superrotation in warm climates simulated by CAM3. GRL, 37.
Mitchell and Vallis, 2010: The Transition to Superrotation in Terrestrial Atmospheres. JGR, 115.

Progress Report Title: **Seasonality in CO_2 Fluxes in an Earth System Model**

Principal Investigator: Keith B. Rodgers (Princeton Research Scholar)

CICS/GFDL Collaborator: John Dunne (GFDL)

Other Participating Researchers: M. Ishii (MRI, Japan), Y. Plancherel (U. Oxford, England), O. Aumont (IRD, France), A. Gnanadesikan (Johns Hopkins), T. Gorgues (IRD, France), D. Iudicone (Stazione Zoologica Anton Dohrn, Italy), M. Jochum (NCAR), M. Kawamiya (JAMSTEC), K. Lindsay (NCAR), H. Nakano (MRI, Japan), H. Okajima (JAMSTEC, Japan), S. Peacock (NCAR), J. Segschneider (MPI, Hamburg), J.F. Tjiputra (U. Bergen, Norway), and R. Wanninkhof (NOAA-AOML)

Task III: Individual Projects

NOAA Sponsor: David Legler and 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: Earth System models predict that seasonality in the Earth's carbon cycle will change over the 21st century. With a focus on subtropical mode water formation, this work seeks to identify the mechanisms controlling this change in seasonality.

Methods and Results/Accomplishments:

Work has continued on an intercomparison project that evaluates the behavior of IPCC AR5 coupled carbon-climate earth system model to evaluate how the ocean carbon cycle will change over the 21st century. I am currently evaluating set of eight state-of-the-art earth system models to evaluate both the mechanisms driving future changes to the ocean carbon cycle and the implications for 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 out 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 extra-tropics 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 extra-tropics 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.

The principal implication for the climate observing system is that it will be necessary to resolve the seasonal cycle in surface pCO2 measurements, notably in subtropical mode water formation regions. Trends inferred from summer-only measurements will certainly lead to underestimates of the annual mean rate of uptake by the ocean, unless the effect of increased DIC concentrations on solubility is taken into account.

Publications:

Rodgers, K.B., M. Ishii, Y. Plancherel, O. Aumont, L. Bopp, J. Christian, J. Dunne, T. Froelicher, A. Gnanadesikan, T. Gorgues, D. Iudicone, M. Jochum, M. Kawamiya, K. Lindsay, H. Nakano, H. Okajima, S. Peacock, J. Segschneider, T.F. Tijputra, and R. Wanninkhof (2012), Large changes in seasonality of the ocean carbon cycle under anthropogenic climate changes, in preparation for Nature Geoscience.

Progress Report Title: **Bottom-up Forcing, Climate Variability, and Climate Change Impacts on Leatherback Turtles**

Principal Investigator: Vincent Saba (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Charles Stock, John Dunne (GFDL)

Other Participating Researchers: James Spotila, Maria Santidrián-Tomillo (Drexel University), Frank Paladino (Indiana-Purdue University at Fort Wayne)

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 (50%)
Climate Goal: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond

Objective(s): The main objectives of this research was to 1) reconcile the impacts of climate change in the terrestrial (nesting beach) versus the oceanic habitats of endangered eastern Pacific leatherback turtles (*Dermochelys coriacea*) and 2) understand the role of phytoplankton size-class and climate in the food web complexity and trophic transfer efficiency in leatherback foraging areas worldwide.

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 climate-forced population model (CLIMPOP) 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 (Santidrian-Tomillo et al., in review; Sieg et al., 2011). 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). The long-lived nature of leatherbacks may prevent this species from adapting via evolutionary means to rapid climate change, though plastic responses may be able to compensate[32] (i.e. active change of nesting beach or nesting season). We examined the implications of plastic responses based on contemporary relationships between climate, nesting site location, and nesting phenology.

Major leatherback nesting beaches (> 40 nesting females per year) in the eastern Pacific are relatively scarce (Figure 2) suggesting that these beaches, local ecosystems, and near-shore waters have particularly rare features that led to the establishment of a viable nesting population through natural selection. The nesting sites are bound between 10°N and 20°N. They all fall within the northeast corner of the Intertropical Convergence Zone (ITCZ) and thus share similarly warm temperatures, moderate annual rainfall, and seasonal dynamics (Figure 2). Adding the projected ensemble mean temperature and precipitation differences to these contemporary values suggests that all nesting beaches are subject to the same regional-scale projected warming and drying trends (Figure 2). Maintaining present temperature conditions by moving north of 20° N would thus require nesting in starkly drier subtropical regions with markedly different seasonal dynamics. The difference in precipitation between these two regions (2-4 mm day^{-1}) is far greater than the relatively small 0.5 mm day^{-1} decrease projected by the ensemble mean simulation at Playa Grande. Likewise, maintaining beach temperature conditions by moving south of 10 ^{o} N toward the center of the ITCZ would lead to starkly higher and more seasonally persistent precipitation. While our modeling framework cannot extrapolate over such large climate differences, the extent of these changes in combination with the diversity of additional beach suitability conditions (i.e. sand type, currents, tides, predation, etc.) make the viability of compensation for climate-driven temperature changes via simple latitudinal movement highly uncertain.

Leatherback populations in a changing climate may be more sensitive to nesting beach conditions than to oceanic conditions. 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.

The book chapter that is currently in review examines the relationship between large phytoplankton productivity and leatherback phenotype/fecundity. Table 1 shows the main results from this project.

References:

Saba, V.S., Santidrián-Tomillo, P., Reina, R.D., Spotila, J.R., Musick, J.A., Evans, D.A., Paladino, F.V. 2007. The effect of the El Niño Southern Oscillation on the reproductive frequency of eastern Pacific leatherback turtles. Journal of Applied Ecology 44 (2), 395-404.

Santidrián-Tomillo, P., Saba, V.S., Blanco, G.S., Stock, C.A., Paladino, F.V., Spotila, J.R. Climate driven egg and hatchling mortality threaten survival of eastern Pacific leatherback turtles. PLoS One, in review.

Sieg, A.E., Santidrián-Tomillo, P., Binckley, C., Wallace, B.P., Reina, R., Spotila, J.R., Paladino, F.V. 2011. Sex ratios of leatherback turtles: hatchery translocation decreases metabolic heating and female bias. Endangered Species Research, 15: 195-204.

Publications:

Saba, V.S., Stock, C.A., Spotila, J.R., Paladino, F.V., Santidrián-Tomillo, P. Projected response of an endangered marine turtle to climate change. Nature Climate Change, in review.

Saba, V.S., Stock, C.A., Dunne, J.P. Marine primary connections to leatherback biology and behavior. In: The Leatherback Turtle: Biology and Conservation (eds. J.R. Spotila and P. Santidrián-Tomillo), in review.

Santidrián-Tomillo, P., Saba, V.S., Blanco, G.S., Stock, C.A., Paladino, F.V., Spotila, J.R. Climate driven egg and hatchling mortality threaten survival of eastern Pacific leatherback turtles. PLoS One, in review.

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.

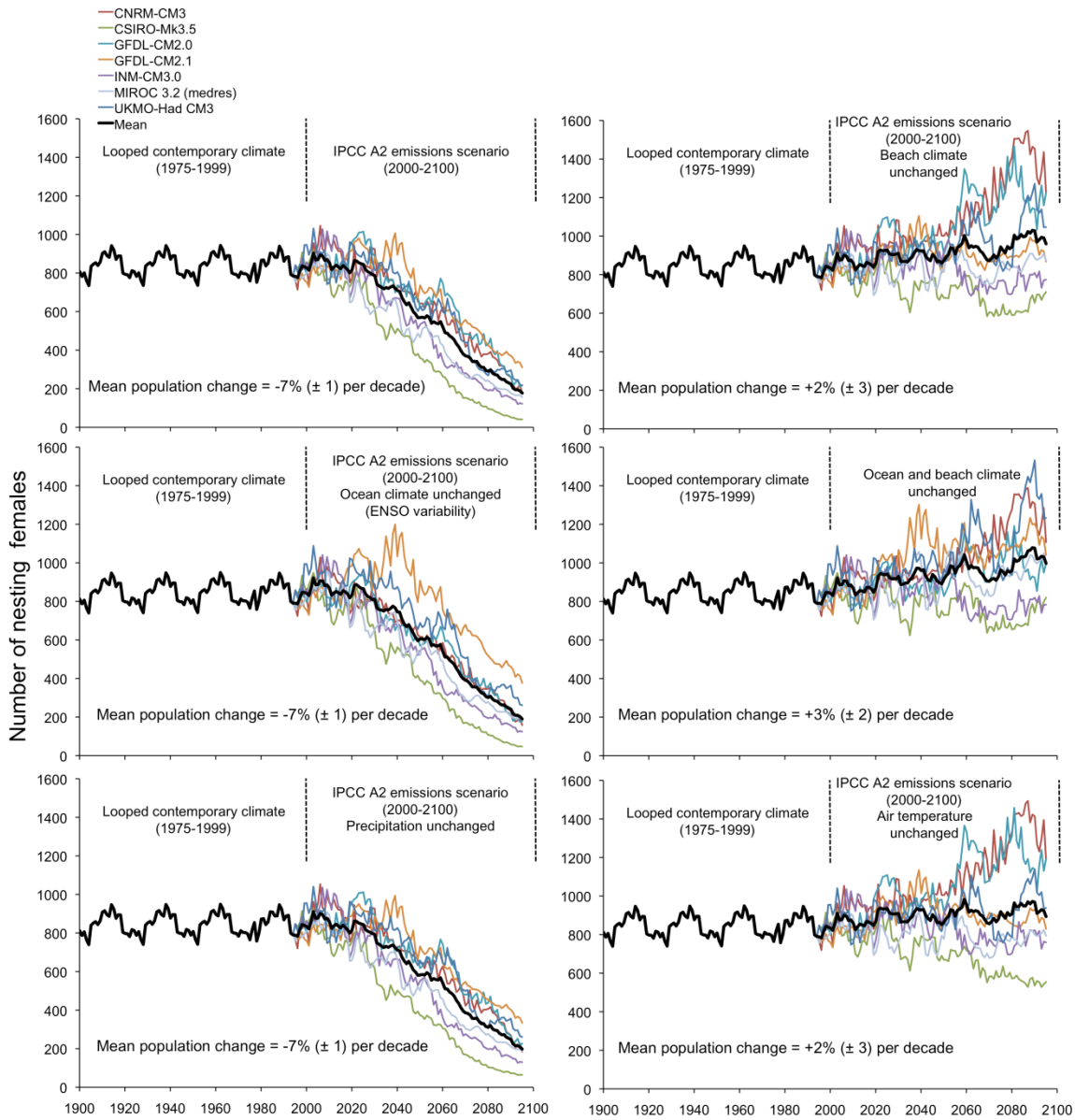

Figure 2. Surface air temperature and precipitation projections under the IPCC-SRES A2 in the area encompassing the four major leatherback nesting sites in the eastern Pacific. **(a)** Mean surface air temperature from 1975 to 1999 from the NCEP/NCAR reanalysis 1 (uses assimilated observed data). **(b)** Mean surface air temperature change between the NCEP/NCAR data from 1975 to 1999 (in panel **a**) and the seven climate model projections from 2075 to 2100 under IPCC-SRES A2. **(c)** Mean precipitation from 1975 to 1999 from the Global Precipitation Climatology Project (GPCP) version 2.2 (combines observations and satellite data). **(d)** Mean precipitation change between the GPCP data from 1975 to 1999 (in panel **c**) and the seven climate model projections from 2075 to 2100 under IPCC-SRES A2. Projections of air temperature and precipitation are based on the seven climate models used to force CLIMPOP. The four nesting sites are indicated with black diamonds.

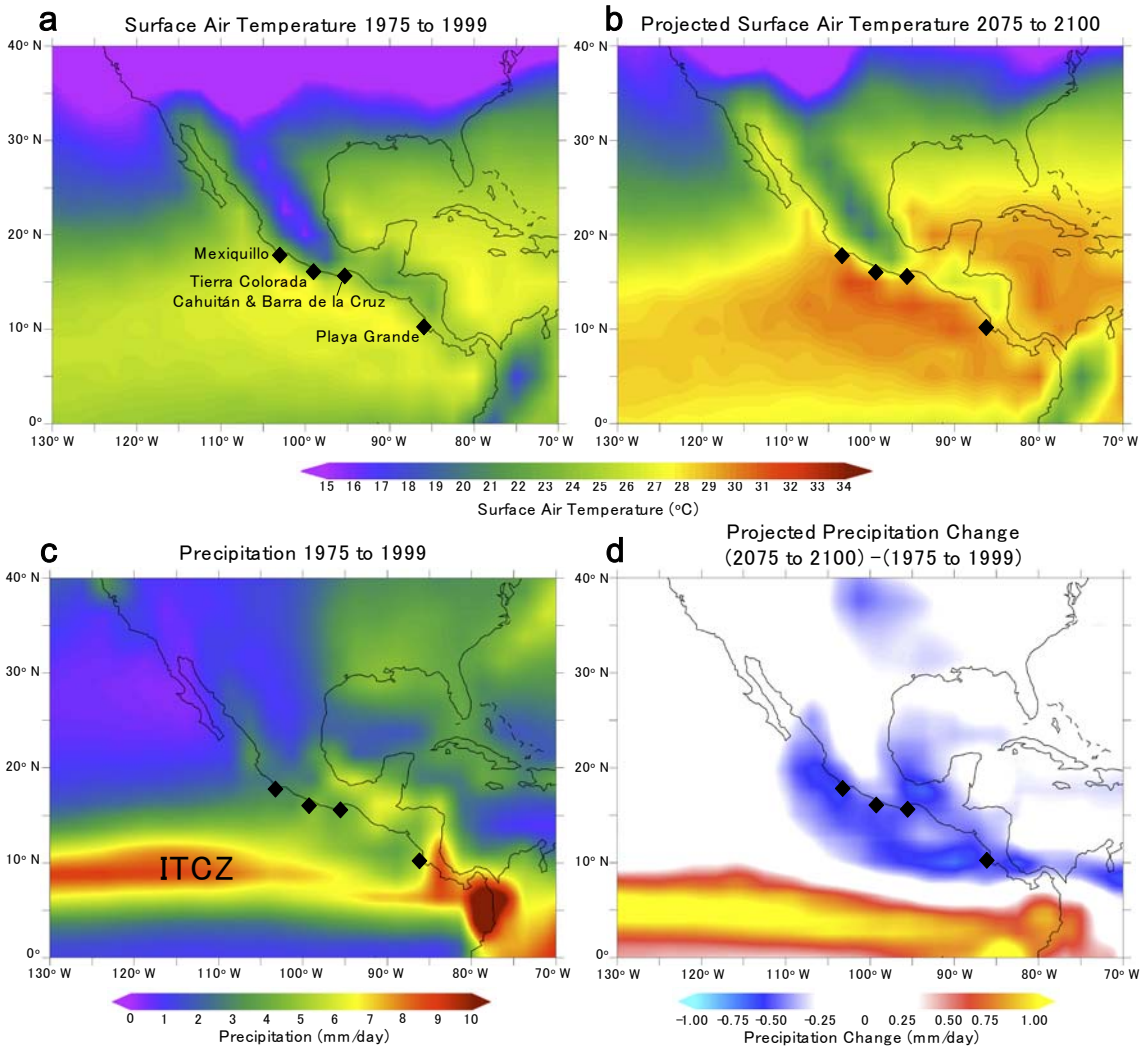

Table 1. Magnitude and temporal variability of large phytoplankton NPP estimated by the Tracers of Phytoplankton with Allometric Zooplankton (TOPAZ) biogeochemical model among leatherback migration areas worldwide.

Nesting Population	Migration Area(s)	Large Phytoplankton Maximum Bloom Period[a]	Mean Proportion of Large Phytoplankton Integrated Productivity at Max Bloom[a]	Mean Integrated Productivity of Large Phytoplankton at Max Bloom (10^{12} g C day^{-1})[a]	Resource Availability Ratio (RAR)[c]	Large Phytoplankton Bloom Cycle[d]
Western Atlantic	North Atlantic (NA)	Apr-May	36% (± 2%)	6.2 (± 0.8)	0.40	Seasonal (96%)
	Western Tropical Atlantic (WTA)	Apr-May	9% (± 0%)	1.0 (± 0.1)	0.05	Seasonal (99%)
	Eastern Tropical Atlantic (ETA)	Apr-May	13% (± 1%)	1.9 (± 0.3)	0.22	Seasonal (81%)
	Mediterranean (MED)	May-Jun	9% (± 0%)	0.9 (± 0.1)	0.28	Seasonal (98%)
Eastern Atlantic	Eastern South Atlantic (ESA)	Sep-Oct	18% (± 2%)	2.2 (± 0.4)	0.11	Seasonal (76%)
	Western South Atlantic (WSA)	Sep-Oct	17% (± 3%)	1.8 (± 0.5)	0.12	Seasonal (91%)
Western Indian	Agulhas Current System (ACS)	Oct-Nov	20% (± 2%)	3.1 (± 0.3)	0.51	Seasonal (71%)
	Eastern South Atlantic (ESA)	Sep-Oct	18% (± 2%)	2.2 (± 0.4)	0.11	Seasonal (76%)
Eastern Pacific	Eastern Subtropical Pacific (ESTP)	Dec-Jan[b]	13% (± 2%)	0.6 (± 0.2)	0.10	Interannual (33%)
	Eastern Tropical Pacific (ETP)	Aug-Sep[b]	24% (± 3%)	4.7 (± 0.6)	0.31[e]	Interannual (19%)
	Southeastern Pacific (SEP)	Sep-Oct	9% (± 0%)	0.8 (± 0.1)	0.03	Seasonal (68%)
Western Pacific	Central/Western North Pacific (CWNP)	Apr-May	24% (± 2%)	2.5 (± 0.3)	0.05	Seasonal (99%)
	Northeastern Pacific (NEP)	Apr-May	15% (± 2%)	1.2 (± 0.2)	0.15	Seasonal (70%)
	Western Tropical Pacific (WTP)	Sep-Oct	11% (± 2%)	1.5 (± 0.4)	0.06	Interannual (7%)
	Southwestern Pacific (SWP)	Oct-Nov	14% (± 0%)	1.6 (± 0.2)	0.05	Seasonal (83%)

[a] TOPAZ model estimate.
[b] Maximum bloom is not always during this period due to interannual variability.
[c] Ratio of large phytoplankton productivity at maximum bloom to migration area size.
[d] Based on Fourier regression of the large phytoplankton NPP time-series. Percent represents the proportion of seasonal variability.
[e] Resource availability ratio in the ETP during the 1997-98 El Nino = 0.18

Progress Report Title: **Data Processing for Atmospheric Observations, Land Model Parameterizations, and Data-Model Comparisons**

Principal Investigator: Jorge L. Sarmiento (Princeton)

Other Participating Researchers: Ni-Zhang Golaz (Princeton)

CICS/GFDL Collaborator: Geoffrey K. Vallis (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: As described in previous reports, the goal of this work was to study the adaptation and acclimation within ecosystems, which may affect the future of carbon sources and sinks in response to climate change. Using a stand alone land model - the Dynamic Vegetation Model LM3V, jointly developed at GFDL and Princeton University (Shevliakova et. al. 2009), we first 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, we further developed an automated system to fit parameters in the model to forest inventory (FIA) data using formal, quantitative methods, which increased the efficiency of the parameter optimization process. 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. Another system was developed to utilize the north American carbon program (NACP) site level interim synthesis datasets, which automatically converts all site's meteorological input and CO_2 data with different observation periods, different time frequencies, different variable names to be LM3V ready, so LM3V can directly read-in at each location and be run at all sites simultaneously. The development of these systems paved the way for the optimization efforts in ecosystem modeling.

Methods and Results/Accomplishments:

The main outcome of these studies is that they have built a framework for combining a multitude of constraints for the dynamic land model with observed data sets, and paved a foundation for future carbon data assimilation projects. During the period between April – June 2011, the main focus was on data processing (similar to submitting IPCC data except at a mini scale). The land model in the parameter optimization process was forced by the historical weather-reanalysis product (Sheffield 2006) extracted for each site that mirrors the selected FIA plots. To evaluate any errors that may cause bias from a global dataset, Sheffield's data were extracted again to match all NACP sites, and NACP site data were also processed to match the time resolution of Sheffield's data and the comparison datasets were made available. Model outputs from LM3V of 32 selected sites were processed to meet all the requirements set by the NACP site level interim synthesis and the datasets are available for submission. All datasets are available on GFDL's archive. (Please also see last year's report for more details.)

References:

Sheffield, J., G. Goteti, and E. F. Wood, 2006: Development of a 50-year high-resolution global dataset of meteorological forcings for land surface modeling. Journal of Climate, 19, 3088-3111.

Shevliakova, E., S. W. Pacala, S. Malyshev, G. C. Hurtt, P. C. D. Milly, J. P. Caspersen, L. T. Sentman, J. P. Fisk, C. Wirth, and C. Crevoisier, 2009: Carbon cycling under 300 years of land use change: importance of the secondary vegetation sink, Global Biogeochem. Cycles, 23, GB2022, doi: 10.1029/2007GB003176.

Progress Report Title: **Effects of Historic Land Use and Vegetation Regrowth on 20th Century Climate Change and Terrestrial Carbon Sinks**

Principal Investigator: Elena Shevliakova (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Ronald Stouffer (GFDL), Steve Pacala (EEB)

Other Participating Researchers: Sergey Malyshev (Princeton), John Krasting (GFDL), George Hurtt (UMD)

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 explore the role of terrestrial biosphere and land-use processes in the climate system from the preindustrial 1850s to present with the GFDL Earth System Models (ESMs)

Methods and Results/Accomplishments:

During 2011, I have analyzed the new CMIP5 ESM experiments, particularly the effects of historic land use (LU) on the carbon cycle and climate. GFDL 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 the significant role of the terrestrial biosphere and land-use processes in the climate system from the preindustrial 1850s to present and into the future.

Results of my analysis suggest that historic LU CO2 fluxes contributed approximately 30-40 ppm to the current atmospheric CO2 concentration and are responsible for approximately 0.2-0.3 °C warming of the global surface air temperature (i.e. ~1/3 of total observed warming), indicating that biogeochemical effect outweighs biophysical effect. According to ESM2G simulations, the present day atmospheric CO2 concentration would be significantly higher and the global average temperature would be warmer if not for the CO2 fertilization sink on managed and unmanaged lands. The ongoing sink on managed lands is due to re-growth of the secondary forests (1.5 Gt/yr) in both the tropics and temperate regions. The ongoing sink on unmanaged lands is substantially smaller in our simulations (1.6 Gt/yr) than estimated in other studies. Our projections indicate that the sink could continue into the future only if the land ecosystems continue to benefit from the CO_2 fertilization effect.

Publications:

Shevliakova, E., R.J. Stouffer, S. Malyshev, J.P. Krasting, S.W. Pacala, et al. (in prep). Historic Land Use and the 20th Century Climate Change.

Shevliakova, E., S.W. Pacala, R.J. Stouffer, S. Malyshev, J.P. Krasting, G.C. Hurtt et al. (in prep). Ongoing Carbon Sink on Managed and Unmanaged Lands.

Donner, L., et al., July 2011: The dynamical core, physical parameterizations, and basic simulation characteristics of the atmospheric component AM3 of the GFDL Global Coupled Model CM3. Journal of Climate, 24(13), DOI:10.1175/2011JCLI3955.1.

Sentman, Lori T., Elena Shevliakova, Ronald J Stouffer, and Sergey Malyshev, October 2011: Time scales of terrestrial carbon response related to land-use application: Implications for initializing an earth system model. Earth Interactions, 15(30), DOI:10.1175/2011EI401.1.

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 Vecchi (GFDL), Tom Knutson (GFDL), Ming Zhao (GFDL), Paul Ginoux (GFDL)

Other Participating Researchers: June Yeung, Dan Wright, 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 & 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 tropical cyclones have continued in collaboration with the Hurricane Research Group at GFDL. During the preceding year, we have examined landfalling tropical cyclone frquency (Villarini et al. 2012) using tools developed in previous studies and examined rainfall distribution over land from tropical cyclones (Villarini et al. 2011). When modeling U.S. landfalling and North Atlantic hurricane counts with the undercount correction by Vecchi and Knutson, tropical Atlantic and tropical mean SSTs are the key predictors. We used a binomial regression model to describe the fraction of North Atlantic tropical storms making landfall in the United States in terms of climate indexes. We found that the observations are influenced by both local and remote effects. In particular, the local effects are related to NAO, while remote effects are associated with tropical mean SST and/or SOI.

Urbanization and heavy rainfall have been examined for the New York - New Jersey metropolitan area building on previous studies of Yeung et al. 2011. In the past year, we have examined rainfall distribution for the 50 "largest" convective storms in the New York metropolitan area. Storms were selected based on cloud-to-ground (CG) lightning observations from the National Lightning Detection Network (NLDN) during the period 1996 - 2010 (the period of radar observations from the KDIX WSR-88D radar covering New York City and New Jersey. Storm tracking analyses were carried out using the TITAN storm tracking algorithms and the climatology of severe thunderstorms was developed (Yeung et al. 2012). In contrast to preceding studies, we found little evidence for storm splitting around New York City. WRF simulations have been carried out for a population of the most severe storms. These analyses are targeted at characterizing systematic biases in WRF simulations of extreme rainfall.

We have carried out climatological analyses of urban modification of rainfall in Baltimore (Smith et al. 2012) and Atlanta (Wright et al. 2012) based on long (10 year) high-resolution radar rainfall data sets developed from volume scan reflectivity observations using the Hydro-NEXRAD system. Analyses

in Baltimore and Atlanta highlight pronounced spatial heterogeneities in warm season rainfall over the urban areas and suggest possible physical mechanisms at play. Future research will combine regional climate model simulations with analyses of "long" records of high-resolution radar rainfall fields. During the previous year, we have initiated urban studies for Charlotte, North Carolina and Milwaukee, Wisconsin. Radar rainfall data sets for the two settings have been assembled and initial analyses have been completed. We have also begun simulation studies for these two regions.

We have examined the hydrology, hydrometeorology and hydroclimatology of extreme floods in the central US through analyses motivated by the catastrophic June 2008 flooding in Iowa (Smith et al. 2012b). Hydroclimatological analyses show that clustering of heavy rainfall events is an important element of regional flood hazards. Regional climate model simulations are carried out to examine the role of "coupling" between the land surface and atmosphere for extreme rainfall events. These analyses are based on numerical experiments in which roughness lengths of heat and momentum are modified based on recent studies by Lemone and colleagues. Results suggest that land-atmosphere coupling can alter the spatial distribution of heavy rainfall somewhat, but has small impact on the occurrence of heavy rain over the region.

We have continued analyses of long-term trends in heavy rainfall and flooding (Smith et al. 2012; and new studies in Wisconsin, Texas and North Carolina), following studies reported in previous years. Analyses in the US center on long stream gaging records from the US Geological Survey examine both abrupt changes and slowly varying trends. Change points and trends in Iowa floods are linked to changing agricultural practices).

Publications:

Smith, J. A., M. L. Baeck, G. Villarini, D. B. Wright, and W. F. Krajewski, Extreme flood response: the June 2008 flooding in Iowa, Water Resources Research, in review, 2012b.

Smith, J. A., M. L.Baeck, G. Villarini, C. Welty, A. J. Miller, W. F. Krajewski, Analyses of a long-term high-resolution radar rainfall data set for the Baltimore metropolitan region, Water Resources Research, 48, W04504, doi:10.1029/2011WR010641, 2012.

Smith, J.A., M.L. Baeck, A.A. Ntelekos, G. Villarini, and M. Steiner, Extreme rainfall and flooding from orographic thunderstorms in the Central Appalachians, Water Resources Research, 47, W04514, doi:10.1029/2010WR010190, 2011.

Smith, J. A., G. Villarini and M. L. Baeck, Mixture distributions and the climatology of extreme rainfall and flooding in the eastern US, Journal of Hydrometeorology, 12(2), 294 - 309, 2011.

Villarini, G., G.A. Vecchi, and J.A. Smith, U.S. landfalling and North Atlantic hurricanes: Statistical modeling of their frequencies and ratios, Monthly Weather Review, 140(1), 44 – 65, doi:10.1175/MWR-D-11-00063.1, 2012.

Villarini, G., J.A. Smith, R. Vitolo, and D.B. Stephenson, On the temporal clustering of US floods and its relationship to climate teleconnection patterns, International Journal of Climatology, in press, 2012.

Villarini, G., J.A. Smith, F. Serinaldi, A.A. Ntelekos, and U. Schwarz, Analyses of extreme flooding in Austria over the period 1951 - 2006, Int. J. of Climatology, in press, 2012.

Villarini, G., J. A. Smith, M. L. Baeck, T. Marchok and G. A. Vecchi, Characterization of Rainfall Distribution and Flooding Associated with U.S. Landfalling Tropical Cyclones: Analyses of Hurricanes Frances, Ivan, and Jeanne (2004), J. of Geophysical Research (Atmospheres), 116, D23116, doi:10.1029/2011JD016175, 2011.

Villarini, G., J.A. Smith, F. Serinaldi, and A.A. Ntelekos, Analyses of seasonal and annual maximum daily discharge records for central Europe, Journal of Hydrology, 339, pp. 299 – 312, 2011.

Villarini, G., J. A. Smith, M. L. Baeck, R. Vitolo, D. B. Stephenson and W.F. Krajewski, On the frequency of heavy rainfall for the upper Midwest of the United States, Journal of Hydrology, 400, pp 103 - 120, 2011.

Villarini, G. G. A. Vecchi, T. R. Knutson, M. Zhao and J. A. Smith, Reconciling Differing Model Projections of Changes in the Frequency of Tropical Storms in the North Atlantic Basin in a Warmer

Climate, Journal of Climate, 24(13), 3224-3238, 2011.

Villarini, G. G. A. Vecchi, T. R. Knutson and J. A. Smith, Is the Recorded Increase in Short Duration North Atlantic Tropical Storms Spurious?, J. Geophys. Res., 116, D10114, doi:10.1029/2010JD015493, 2011.

Villarini, G., J. A. Smith, M. L. Baeck, and W.F. Krajewski, Examining regional flood frequency in the Midwest US, Journal of the American Water Resources Association, Journal of the American Water Resources Association, 47(3), 447-463, 2011.

Yeung, J., J. A. Smith, M. L. Baeck and G. Villarini, Climatological analyses of severe thunderstorms over the New York City metropolitan region, in preparation for submission.

Yeung, J. K, J. A. Smith, G. Villarini, A. A. Ntelekos, M. L. Baeck, and W. F. Krajewski, Regional precipitation climatology of the NewYork – New Jersey Metropolitan Region, Advances in Water Resources, 34(2), 184-204, 2011.

Wright, D. B., J. A. Smith, M. L. Baeck and G. Villarini, The hydroclimatology of extreme rainfall and flooding in the Atlanta metropolitan region, Water Resources Research, in press.

Progress Report Title: **Biophysical Models and the Spatial Ecology of Temperature and Oxygen in the Mesopelagic Zone of the Global Ocean**

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

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

Other Participating Researchers: Daniele Bianchi (McGill University)

Task III: Individual Projects

NOAA Sponsor: Brian Gross (GFDL)

Themes: Earth System Model Applications

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

Objectives: My overall objective is to develop and implement biophysical models of physiological processes to predict the impacts of climate change on ocean ecosystems. Present projects focus on particle remineralization, fish respiration, and zooplankton diel vertical migration.

Methods and Results/Accomplishments:

Particle Remineralization: Particle remineralization is a key process that is already incorporated in Earth System Models. However, present approaches for predicting remineralization rates have very limited mechanistic resolution of the links between heterotrophic bacterial activity and particle attenuation. In order to explore the links between bacteria and particles, I have developed a six compartment 1-dimensional depth resolved model (150 to 2000 m) that traces carbon, C. The six compartments are dissolved organic matter, free-living bacteria, particulate organic matter, particle-attached bacteria, extracellular enzyme, and hydrolysate. To determine the effect of temperature increases due to climate change on particle remineralization, physical and biological rates in the model are temperature dependent. Mass transfer rates account for the effect of temperature on kinematic viscosity and the enzyme and uptake rates account for the effect of temperature using process-specific Q10s, which is the measured change in a rate for a 10°C change in temperature (Schmidt-Nielsen 1980, Jumars et al. 1993). The model successfully predicts particle flux at the Bermuda Atlantic Time Series Station which is located in an oligotrophic gyre (Figure 1). We are currently using the model to explore the effect of temperature on remineralization

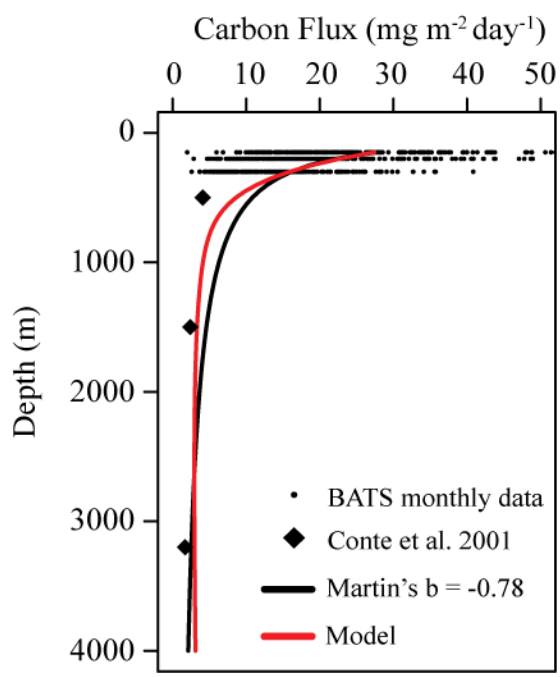

Figure 1. Carbon flux at the Bermuda Atlantic Times Series (BATS) Station. Conte et al. (2001) refers to the mean organic carbon flux collected in deep sediment traps. "Martin's b" is the empirical curve used to describe particle attenuation at BATS in Steinberg et al. (2000). The model was forced using the mean particle flux at 150 m and the mean temperature profile from BATS CTD measurements.

rates which is an ongoing area of research. The long-term goal is to incorporate this model into an Earth System Model.

Fish Respiration: I developed a mechanistic model of a fish gill in order to more fully explore the impacts of ocean acidification and deoxygenation on fish physiology and ecology. Fish are aerobic organisms that uptake oxygen and release carbon dioxide in their gills using diffusion gradients. Gas exchange in the gill requires seawater oxygen to be higher than blood oxygen and seawater carbon dioxide to be lower than blood carbon dioxide. Therefore, rising levels of carbon in the seawater environment may have consequences for gas exchange. Oxygen availability is also a concern because oxygen minimum zones appear to be increasing worldwide. The increase in carbon dioxide and decrease in oxygen in the ocean environment may result in a reduction in habitat, and the effect it will have on pelagic fisheries and ecosystems is an increasing concern. Predicting habitat reduction is difficult because the physiological responses to hypoxic and suboxic levels of oxygen are highly variable among species. The fish gill model incorporates physics, blood physiology, and gill morphology and can be adapted for different fish species. It is forced with temperature, oxygen, and carbon dioxide and preliminary results indicate that temperature and carbon dioxide are important factors controlling oxygen uptake. In addition, I am working on quantifying oxygen uptake and predicting habitat thickness for a range of physiological and morphological traits in the global ocean for the present and exploring the potential impacts of climate change over the next century.

Zooplankton Diel Vertical Migration: Daniele Bianchi and I have been collaborating to produce a comprehensive database of global observations of diel vertical migration that will aid verification and development of a 3D zooplankton diel vertical migration model. Last summer, we mentored an undergraduate intern from Princeton University, Devika Balachandran, who analysed data from plankton tows using the NOAA Copepod database. The focus of her research was to determine the percentage of the zooplankton biomass that vertically migrates by comparing night tows and day tows. We are also using acoustic data from shipboard Acoustic Doppler Current Profilers to determine the depth of migration globally.

References:

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Schmidt-Nielsen, K. 1980. Animal physiology: Adaptation and environment. Cambridge University Press, New York.

Steinberg, D.K., C.A. Carlson, N.R. Bates, S.A. Goldthwait, L.P. Madin, and A.F. Michaels. 2000. Zooplankton vertical migration and the active transport of dissolved organic and inorganic carbon in the Sargasso Sea. Deep-Sea Research I 47:137-158.

Publications:

Smith, K.A., C.A. Stock, J.P. Dunne, and J.L. Sarmiento. Quantifying the role of bacterial extracellular enzymes in marine remineralization processes. Advances in Marine Ecosystem Modelling Research Symposium. Plymouth, United Kingdom. June, 2011. (Oral)

Smith, K.A., J.P. Dunne, and J.L. Sarmiento. Predicting future habitat changes above oxygen minimum zones using a gill model. EUR-OCEANS Conference - Ocean deoxygenation and implications for biogeochemical cycles and ecosystems. Toulouse, France. October, 2011. (Poster)

Smith, K.A., C.A. Stock, J.P. Dunne, and J.L. Sarmiento. Modeling the microbial processes controlling particle remineralization. 3rd GEOTRACES Data-Model Synergy Workshop - Ocean particles, their role in the biogeochemical cycle of trace elements & isotopes. Barcelona, Spain. November, 2012. (Poster)

Smith, K.A., C.A. Stock, J.P. Dunne, and J.L. Sarmiento. Attached bacteria flux as a mechanistic control on mesopelagic particle remineralization. Ocean Sciences Conference. Salt Lake City, UT. February, 2012. (Poster)

Smith, K.A., J.P. Dunne, and J.L. Sarmiento. Predicting the impact of climate change on habitat size in the mesopelagic zone. Ocean Sciences Conference. Salt Lake City, UT. February, 2012. (Poster)

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

Principal Investigator: Geoffrey Vallis (Princeton Faculty)

Other Participating Researchers: Joe Kidston (UNSW), Pablo Zurita-Gotor (Madrid), Peng Xie (Princeton), Max Nikurashin (Princeton), Antoine Venaille (Lyons)

Theme: Earth System Model Applications

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

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 two research topics, one of which is central to our goals to understand how the atmosphere responds to global warming, and the other which addresses a fundamental problem in atmospheric dynamics. In particular we have investigated the mechanisms of a poleward shift in the midlatitude baroclinic zone and associated jets, and we have investigated the factors determining the height of the tropopause.

Methods and Results/Accomplishments:

Regarding the first topic, we have investigated the mechanisms that might lead to a poleward shift of the jet stream under global warming. Such a shift is observed to occur in many General Circulation Models, and could lead to important changes in regional climate. We argue that part of the reason for a polewards shift is a combination of the effects of changes in poleward wave propagation, along with an increase in barotropic instability.

Regarding the tropopause height, we have shown that its height is determined by a combination of dynamical and thermodynamical constraints. If the thermodynamical constraint is a strong one, then the tropopause height may be sufficiently constrained so that the flow becomes supercritical. This result has important implications for how the tropopause height might change in a warming world.

In addition to these topics, the PI has developed a new quantitative theory for the strength and structure of the meridional overturning circulation, including interhemispheric effects. Preliminary tests with a GCM show encouraging agreement. The theory is described elsewhere in this report. The PI has also shown that the heat uptake in the ocean under global warming can lead to sufficiently large changes in the circulation that the uptake cannot be considered a passive process. Finally, a book by the PI entitled *Climate and the Oceans* was published by Princeton University Press.

Publications:

Vallis, G. K. 2011. Climate and the Oceans, Princeton Univ. Press, 242 pp.

Venaille, A., Vallis, G.K. and Griffies, S.M., 2011. The catalytic effect of beta in the barotropization of inviscid fluids. J. Fluid Mech. Submitted.

Kidston, J. and Vallis, G.K., 2012. The relationship between the speed and latitude of the eddy-driven jet in a stirred barotropic model. J. Atmos. Sci. In press.

Ilicak, M. and Vallis, G.K., 2011. Simulations and phenomenology of horizontal convection. Tellus. In press.

Nikurashin, M. and Vallis, G.K., 2011a. A theory of deep stratification and interhemispheric overturning circulation and associated stratification. J. Phys. Oceanogr. Submitted.

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Nikurashin, M. and Vallis, G.K., 2011. A theory of deep stratification and overturning circulation in the ocean. J. Phys. Oceanogr., 41, 485–502. doi:10.1175/2010JPO4529.1.

Padilla, L., Vallis, G.K. and Rowley, C., 2011. Probabilistic estimates of transient climate sensitivity subject to uncertainty in forcing and natural variability. J. Climate, 24, 5521– 5537. doi: 10.1175/2011JCLI3989.1

Venaille, A., Vallis, G.K. and Smith, K.S., 2011. Baroclinic turbulence in the ocean: analysis with primitive equation and quasi-geostrophic simulations. J. Phys. Oceanogr, 41, 1605-1623.

Xie, P. and Vallis, G.K., 2011. The passive and active nature of ocean heat uptake in heat in idealized climate change experiments. Climate Dynamics, pp. 1–18. doi:10.1007/s00382- 011-1063-8.

Zurita-Gotor, P. and Vallis, G.K., 2011. Dynamics of mid-latitude tropopause height in an idealized dynamical model. J. Atmos. Sci. 68, 823–838. doi: http://dx.doi.org/10.1175/2010JAS3631.1

Progress Reports:

Education/Outreach

Progress Report Title: **Advancing Land-use Modeling and Analysis for Carbon Cycling Studies Workshop, Princeton, NJ, May 16-19 2011**

Principal Investigator: Elena Shevliakova (Princeton Associate Research Scholar)

Other Participating Researchers: S. Sitch (University of Exeter), J. House (QUEST, UK), K. K. Goldewijk (RIVM, Netherland), D. Morton (NASA), G. Hurtt (U. Maryland), R Houghton (WHRC), F. Hoffman (ORNL), J. Atul (UIUC), C. Le Quéré (U East Anglia), P. Cias (IPSL), C. Jones (MOHC), J. Pongratz (MPI, Germany), Shilong Piao (China), Louise Chini (U. Maryland), P. Lawrence (NCAR), R. Birdsey (USFS), S. Frolking (UNH), Y. Pan (USFS), B. Poulter (LSCE, France)

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: To bring together experts in land-use/management data, modeling and analysis in order to develop a strategy for understanding and reducing uncertainty in the characterization of the past effects of land-use changes, including secondary forests, and for improving projections of land C fluxes and their implications for climate change

Methods and Results/Accomplishments:

In collaboration with GFDL and Princeton University's Environmental Institute (PEI), CICS co-hosted a workshop May 17-18, 2011, focused on land use changes -- past and future. Experts from all the major climate modeling and observational groups, worldwide, participated in the workshop.

Climate models used for making future projections of climate changes over this century and beyond have become progressively more sophisticated over the years. In response to the need to understand future changes in the carbon cycle, models have begun to incorporate components to simulate the carbon changes due to direct human activities (e.g., land use changes) and those that result from climate changes.

The goal of the workshop was to organize the land use analysis activity (model and observations) in support of the fifth IPCC assessment. The analysis activity has three components. One is to compare the model results to observations over the historical period. This activity will lead to an understanding of what the models can, and cannot, simulate and what new observations are needed to help in this evaluation.

A second component involves the comparison of the models to each other, to understand why they are producing different results. This activity will help quantify the uncertainty associated with the projection of future changes. The third component is the comparison of these model results to simpler models used to make the future emission projections. Errors in the simple models can lead to very important implications for establishing any future emission targets or goals, for example, limiting the future warming below some threshold.

Workshop Participants May 2011

Publications:

Shevliakova, E., R.J. Stouffer, S. Malyshev, C.D. Jones, P. Thornton, J. Pongratz, and G.C. Hurtt. Analysis of Land-Use changes and Carbon Cycling Dynamics in CMIP5 ESM experiments, the CMIP5 workshop, 5-9 March 2012, Honolulu, Hawaii.

Shadow Award Progress Reports:

Earth System Modeling and Analysis

Progress Report Title: **Improving Climate Predictions by Reducing Uncertainties about CO_2 Fertilization in the Terrestrial Biosphere**

Principal Investigator: Lars O. Hedin (Princeton Professor)

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

Other Participating Researchers: Stefan Gerber (Princeton), Stephen W. Pacala (Princeton), S. Joseph Wright (Smithsonian Tropical Research Institute)

NOAA Sponsor: Ken Mooney (Ocean Climate Observation Program)

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 land carbon (C) sink represents the perhaps greatest uncertainty in the earth carbon cycle. Saturation of this sink would dramatically magnify the carbon mitigation problem, but we currently do not know how to mechanistically represent this sink and its temporal dynamics in the next generation of earth system models. Our work centers on developing such knowledge and representation in models.

Methods and Results/Accomplishments:

Using the Princeton-GFDL global land model developed by our group (LM3V-N; Gerber, Hedin et al. 2010) we have over the past year examined how land-use history, atmospheric nitrogen (N) deposition, and climatic conditions interact to govern land ecosystem response to atmospheric CO_2. First, we applied the model to the longest and most complete record (50 years) of forest growth and watershed nutrient dynamics available worldwide, and could successfully resolve the influence of climate change and land disturbance on the N cycle (Bernal, Hedin et al. *PNAS,* 2012). Second, we applied the model to the global land C sink (Gerber, Hedin et al. *Nature*, in review). The model successfully recreated the observed historical trend of intensifying land C uptake since the industrial revolution, but only when specific N feedbacks were included. Moreover, by analyzing the interaction of land-use changes and C and N cycles we identified and quantified three previously unexamined sources of non-linearity in the land C cycle: (i) a C sink foregone that would have occurred if agricultural lands had been left in their original state; (ii) an accelerated response of secondary vegetation to CO_2 and N, and (iii) a compounded clearance loss of C from deforestation. We calculated (Gerber, Hedin et al. *Nature*, in review) that these effects combine to reduce the present net C sink by ~40% (0.4 Pg yr-1) and that each effect is becoming increasingly important in determining the trajectory of CO2 uptake of the land biosphere. Third, we have examined how tropical forests differ from temperate forests in the N cycle and in nutrient limitation on plant growth (Brookshire, Hedin et al. 2011 and 2012; Wright, Hedin et al. 2011). Fourth, we have continued to develop LM3V-N to incorporate seasonal growth responses of trees to soil nutrients and climate. Specifically, we are comparing model predictions against large-scale free-air CO_2 enrichment (FACE) experiments from different forests worldwide. Our model appears able to resolve why experimental responses differ across experimental locations, with some forests displaying sustained high responsiveness to CO_2 (Wisconsin), some displaying transient down-regulation of growth (Duke-FACE and Oak Ridge-FACE), and others displaying no significant response (Switzerland). Our findings 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 CO_2.

Publications:

Bernal, S., L.O. Hedin, G.E. Likens, S. Gerber, and D.C. Buso. 2012. Complex response of the forest nitrogen cycle to climate change. Proceedings of the National Academy of Sciences, DOI: 10.1073/pnas.1121448109.

Brookshire, E.N.J., L.O. Hedin, J.D. Newbold, D.M. Sigman, and J.K Jackson. 2012. Sustained losses of bioavailable nitrogen from montane tropical forests. Nature Geoscience, DOI: 10.1038/NGEO1372.

Brookshire, E.N.J., S. Gerber, D.N.L. Menge, and L.O. Hedin. 2011. Large losses of inorganic nitrogen from tropical rainforests suggest a lack of nitrogen limitation. Ecology Letters, DOI: 10.1111/j.1461-0248.2011.01701.

Gerber, S., Hedin, L.O., Oppenheimer, M., Pacala, S.W., and Shevliakova, E. 2010. Nitrogen cycling and feedbacks in a global dynamic land model. Global Biogeochemical Cycles 24, GB1001, doi 10.1029/2008GB003336.

Gerber, S., Hedin, L.O., Keel, S.G., Pacala, S.W., and Shevliakova, E. 2012. Land use and nitrogen feedbacks constrain the trajectory of the land carbon sink. Nature (in review).

Wright, S.J., J.B. Yavitt., N. Wurzburger, B.L. Turner, E.V.J. Tanner, E.J. Sayer, L.S. Santiago, M. Kaspari, L.O. Hedin, K.E. Harms, M.N. Garcia, and M.D. Corre. 2011. Potassium, phosphorus or nitrogen limit root allocation, tree growth and litter production in a lowland tropical forest. Ecology 92(8): 1616–1625.

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)

NOAA Sponsor: Kendra Hammond (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 (30%)
Weather & Water Goal: Serve Society's Needs for Weather and Water Information (70%)

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; and 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. After NCEP upgraded CFS to CFSv2, we analyzed 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.

Publications:

Yuan Xing; Wood Eric F.; Luo Lifeng; Ming Pan. 2011. A first look at Climate Forecast System version 2 (CFSv2) for hydrological seasonal prediction, Geophys. Res. Letts. 38, Art. No. L13402, DOI: 10.1029/2011GL047792.

Xia, Youlong et al. 2012a Continental-Scale Water and Energy Flux Analysis and Validation 1 for the North-American Land Data Assimilation System Project Phase 2 (NLDAS-2), Part 1: Intercomparison and Application of Model Products. J Geophysical Research 117, D03109, doi:10.1029/2011JD016048.

Xia, Youlong et al. 2012b Continental-Scale Water and Energy Flux Analysis and Validation for North-American Land Data Assimilation System Project Phase 2, Part 2: Validation of Model-Simulated Streamflow J Geophysical Research, 117, D03110, doi:10.1029/2011JD016051.

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

Principal Investigator: Eric F Wood (Princeton Professor)

Other Participating Researchers: Kingtse Mo (NCEP/CPC)

NOAA Sponsor: Kingste Mo (NCEP/CPC)

Theme: Earth System Model Applications

NOAA Goal:
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 goal of this proposal is to use the Climate Forecast System Reanalysis and Reforecast System (CFSRR) to improve drought prediction with a focus on the selected basins over the Southeast. The specific objectives are: downscale and bias correct the CFS forecasts over the Southeast (SE) based on the Bayesian methods developed at Princeton; implement and test the system at NCEP/EMC; develop drought indices (standardized precipitation index (SPI), soil moisture percentile, and standardized runoff index (SRI)) over the SE based on the forecasts; design products to provide water supply information to SERFC and the NIDIS user community over the Southeast; and work closely with the Southeast River Forecast Center (SERFC) and OHD develop applications.

Methods and Results/Accomplishments:

We are collaborating with CPC to successfully implement at CPC the hydrological forecast system developed at Princeton and applying this to the NIDIS SE testbed. We are carrying out related work to better understand the drought mechanisms in the SE and determine if the CFS predictions are able to capture these mechanisms. One mechanism is land-atmospheric coupling and the role of coupling in initiating summertime convection. Analysis has shown that CFSv2 is biased wet when dry conditions persist. This implies that forecasting the continuation of drought is poorly captured.

Publications:

Yoon, Jin-Ho, Kingtse Mo and Eric F. Wood, 2012, Dynamic-Model-Based Seasonal Prediction of Meteorological Drought over the Contiguous United States, J. Hydrometeor, 13, 463–482.

	JI Lead Author				NOAA Lead Author				Other Lead Author			
	FY09	FY 10	FY11	FY12	FY09	FY10	FY11	FY12	FY09	FY10	FY 11	FY12
Peer-reviewed	14	31	30	30	2	3	2	5	6	21	29	31
Non Peer-reviewed	14	13	3	41*	2	4	2	2*	2	7	2	2*
Chapters in books	1	1										
Ph.D. Thesis		2	3	2								

**Including Presentations*

ADMINISTRATIVE STAFF

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Task I: Administrative Activities and Outreach Supported Personnel

Name	**Rank**
Brody, Sarah Rachel	MPOWIR Graduate Student
Sarmiento, Jorge L.	CICS Director
Vallis, Geoffrey K.	CICS Associate Director
Whalen, Caitlin B.	MPOWIR Graduate Student

Departures - Task II and Task III

Takeshi Doi – April 2012: Japan Agency for Marine-Earth Science and Technology
Daniel Goldberg – July 2011: Massachusetts Institute of Technology – Researcher
Lucas Harris – January 2012: NOAA/Geophysical Fluid Dynamics Laboratory – Physical Scientist
Mehmet Ilicak – March 2012: University of Norway - Faculty
Cheryl Logan – January 2012: California State University Monterey Bay – Faculty
Vincent Saba – September 2011: NOAA/Northeast Fisheries Science Center - Researcher

Ph.D. Defenses

Student: Ying Li
Advisor: Gabriel Lau – October 2011
Dissertation: Dynamical Mechanisms for the Teleconnection between ENSO and NAO in late Winter
Current Affiliation: Colorado State University - Postdoctoral Research Associate

Student: Ian Lloyd
Advisor: Gabriel Lau – May 2011
Dissertation: Extreme Subseasonal Tropical Air-Sea Interactions and their Relation to Ocean Thermal Stratification
Current Affiliation: Congressional Science Fellowship – Washington, DC

Task II: Cooperative Research Projects and Education Supported Personnel

Name	**Rank**	**Host**
Adcroft, Alistair	Research Oceanographer	GFDL Director
Balaji, V.	Sr. Professional Technical Specialist	GFDL Director
Bollasina, Massimo	Postdoctoral Research Associate	Ming
Ballinger, Andrew	Graduate Student	Held
Chen, Jan-Huey	Postdoctoral Research Associate	SJ Lin
Choi, Kityan	Graduate Student	Vecchi
Doi, Takeshi	Postdoctoral Research Associate	Vecchi
Fan, Yalin	Associate Research Scholar	Lin
Goldberg, Daniel	Postdoctoral Research Associate	Sergienko
Harris, Lucas	Postdoctoral Research Associate	Lin
Ilicak, Mehmet	Associate Research Scholar	Hallberg
Jucker, Martin	Visiting Postdoctoral Research Associate	Vallis
Kapnick, Sarah	Postdoctoral Research Associate	Delworth
Legg, Sonya	Research Oceanographer	GFDL Director
Li, Ying	Graduate Student	Lau
Lin, Meiyun	Associate Research Scholar	Fiore
Logan, Cheryl	Postdoctoral Research Associate	Dunne
Malyshev, Sergey	Associate Research Scholar	Pacala
Mao, Jingqiu	Associate Research Scholar	Horowitz
Melet, Angelique	Postdoctoral Research Associate	Hallberg
Muller, Caroline	Associate Research Scholar	Held
Nikonov, Sergey	Professional Technical Specialist	Balaji
Ocko, Ilissa	Graduate Student	Ramaswamy
Orlanski, Isidoro	Sr. Research Meteorologist	GFDL Director
O'Rourke, Amanda	Graduate Student	Vallis
Paynter, David	Associate Research Scholar	Ramaswamy
Potter, Sam	Graduate Student	Vallis
Radley, Claire	Graduate Student	Donner
Saba, Vincent	Associate Research Scholar	Stock
Sergienko, Olga	Associate Research Scholar	Hallberg
Shevliakova, Elena	Associate Research Scholar	Pacala
Vallis, Geoffrey	Sr. Research Geoscientist	GFDL Director
Wang, He	Graduate Student	Legg
Zhang, Sophie	Postdoctoral Research Associate	Vallis
Zhou, Wenyu	Graduate Student	Held

Task III: Individual Research Projects Supported Personnel

Name	**Rank**	**Advisor**
Beaulieu, Claudie	Postdoctoral Research Associate	Sarmiento
Bonachela Fajardo, Juan	Postdoctoral Research Associate	Levin
Golaz, Ni-Zhang	Environmental Modeler & Analyst	Sarmiento
Hervieux, Gaelle	Postdoctoral Associate	Curchitser
Jeong, Su-Jong	Postdoctoral Research Associate	Medvigy
Key, Robert M.	Research Oceanographer	PI
Lin, Xiaohua	Senior Research Specialist	Key
Majkut, Joseph	Graduate Student	Sarmiento
Rodgers, Keith	Research Scholar	Sarmiento
Smith, K. Allison	Postdoctoral Research Associate	Sarmiento
Wright, Daniel	Graduate Student	Smith
Yeung, June	Graduate Student	Smith

Shadow Awards: Individual Research Projects Supported Personnel

Name	**Rank**	**Advisor**
Hedin, Lars	Faculty	-
Keel, Sonja	Postdoctoral Research Associate	Hedin
Roundy, Joshua	Graduate Student	Wood
Yuan, Xing	Associate Research Scholar	Wood

Personnel				
Category	Number	B.S.	M.S.	Ph.D.
Faculty	1		-	1
Research Scientist	6	-	-	6
Visiting Scientist	1	-	-	1
Postdoctoral Research Associate	14	-	-	14
Professional Technical Staff	4	-	2	2
Associate Research Scholar	10	-	-	10
Administrative	0	-	-	-
Total (≥ 50% support)	**30**			**30**
Undergraduates	0	-	-	-
Graduate Students	14	4	9	1
Employees that receive < 50% NOAA funding (not including graduate students)	6	-	2	4
Located at the Lab (include name of lab)	GFDL-33	2	6	25
Obtained NOAA employment within the last year	2			2

Note: does not include shadow award personnel

CICS FY'12 List of Awards for Institutional Award NA08OAR4320752

Amount	PI	Project Title
$ 64,039[*16]	Jorge L. Sarmiento	Administration (Task I) *GFDL-Brian Gross*
$ 20,000[*16]	Jorge L. Sarmiento	Administration (Task I) MPOWIR
$ 152,000 [*14]	Robert M. Key	Global Carbon Data Management and Synthesis Project (Task III) *COD-Joel Levy*
$ 60,000 [*15]	Keith Rodgers	Using Models to improve our ability to monitor ocean uptake of anthropogenic carbon (Task III) *COD-Joel Levy*
$ 37,715 [*16]	James A. Smith	Regional Climate Studies Using the Weather Research and Forecasting Model (Task III) *GFDL-Brian Gross*
$ 49,283 [*16]	Simon Levin	Top-down controls on marine microbial diversity and its effects on primary productivity in the oceans (Task III) *GFDL-Brian Gross*
$ 86,119 [*16]	Claudie Beaulieu	Detection and Attribution of shifts in the carbon system (Task III) *GFDL-Brian Gross*
$ 59,967 [*16]	K. Allison Smith	Competitive interactions between bacteria and zooplankton along oxygen concentration gradients in global ocean models (Task III) *GFDL-Brian Gross*
$ 55,521 [*16]	David Medvigy	A mechanistic framework for predicting land-atmosphere carbon fluxes (Task III) *GFDL-Brian Gross*
$2,493,226 [*16]	Geoffery K. Vallis	Cooperative Research Projects and Education (Task II) *GFDL-Brian Gross*

Amendment No./PI	**Amount**	**Project Title**
Amendment #15: PI: Keith Rodgers	$60,000	Using Models to Improve our Ability to Monitor Ocean Uptake of Anthropogenic Carbon
Amendment #14: PI: Robert Key	$152,000	Global Carbon Data Management and Synthesis Project
Amendment #16: PI: Jorge Sarmeinto Co-PI: Geoff Vallis	$2,816,226	CICS-Princeton: Year 3 Task I: $120,000 ($35,961 rebudgeted to Task III) Task II: $2,493,226 Task III: $203,000

CICS FY'12 List of Awards for Shadow Award NA08OAR4320915

Amendment No./PI	Amount	Title
Amendment #8: PI: Eric Wood	$105,000	Development of an experimental national hydrologic prediction system *CPO-Kendra Hammond*