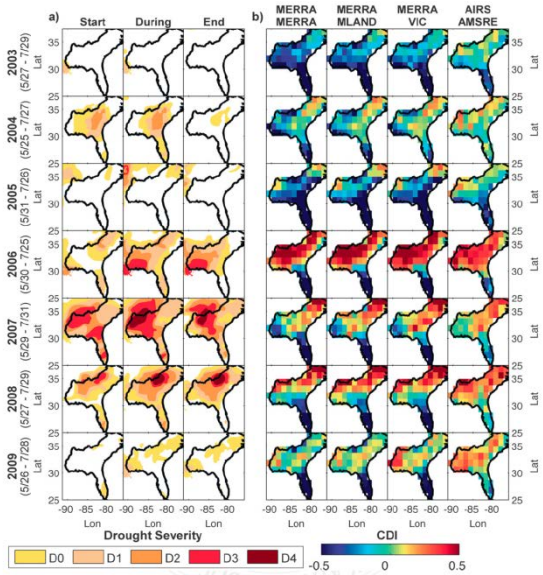
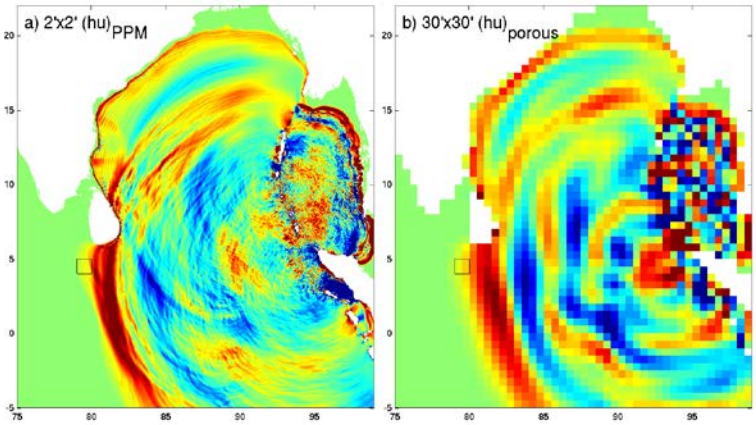


Annual Progress Report
April 1, 2012 – March 31, 2013

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



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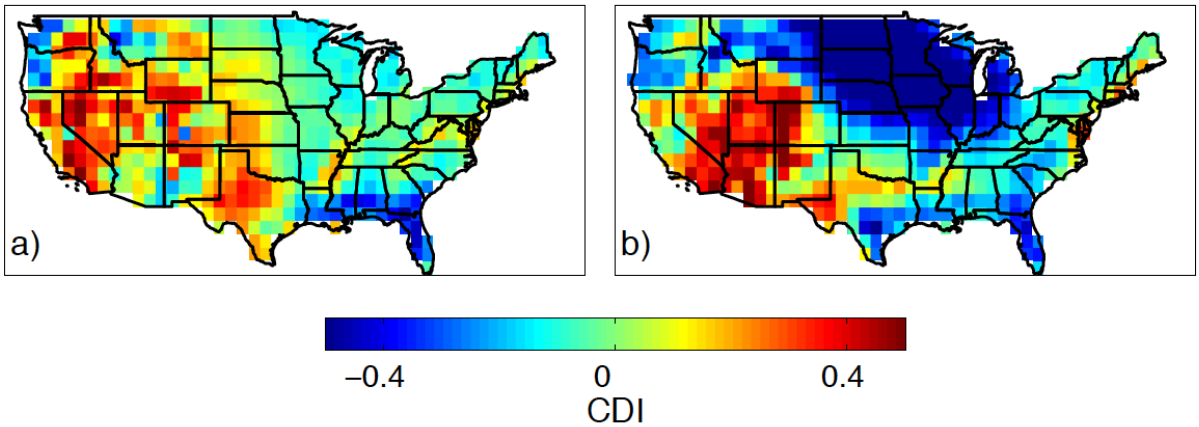

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Cooperative Institute for Climate Science
Princeton University

Annual Progress Report under cooperative agreement NA08OAR4320752
including Shadow Award NA08OAR4320915

For the period April 1, 2012 – March 31, 2013

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

Summer Institute in Weather and Climate

Once again this year, CICS continued its collaboration with a Princeton University professional development institute for New Jersey teachers. This well-established summer program, QUEST, is led by Princeton University's Teacher Preparation Program. A one-week Weather and Climate unit for teachers of students in third through eighth grades, held this summer, offered a wide range of

inquiry-based experiences through which the teachers explored the fundamentals of weather, the Earth's climate, and the interaction of land, ocean, and atmosphere. Inquiry-based investigations included air pressure, temperature, seasons, the greenhouse effect, humidity, clouds, wind, the Coriolis effect, storms, and colors in the sky. In addition to exploring the greenhouse effect and human impacts on climate and global warming, participating teachers participated in discussions that focused on understanding climate change and the need to plan remediation in respect to the public's understanding. Additionally, models were introduced to aid in the teachers' understanding of weather conditions and weather prediction. The unit was developed and taught by Dr. Steven Carson, formerly a scientist and Outreach Coordinator at GFDL, and currently a middle school science teacher in Princeton. The instructional team also included Greg Peters, a middle school teacher in Ewing, New Jersey, an "urban rim" district, who works with students from under-represented groups. Twelve teachers participated in the Weather and Climate unit, representing seven different school districts. In addition, two pre-service teachers from Princeton University participated in the institute to further their understanding of content and instruction.

Geostrophic Turbulence and Active Tracer Transport in 2 Dimensions Workshop

In collaboration with Princeton University's Program in Applied and Computational Mathematics, CICS co-hosted a workshop from March 13-15, 2013 through the Princeton Center for Theoretical Science on "Geostrophic Turbulence and Active Tracer Transport in 2 Dimensions." The workshop brought together mathematicians and atmosphere/ocean scientists from around the globe to familiarize them with ongoing research outside of their fields, and possibly fertilize new work within both groups. Many idealized models of atmospheric and oceanic flows reduce to the two-dimensional (2D) advection of a tracer that in turn determines the flow field. The classic example is non-divergent 2D flow on a plane (or a sphere), where the tracer is the vertical (or radial) component of the vorticity. Of special interest is the "geostrophic turbulence" generated in systems with two interacting active tracers, representing flow at the tropopause and the earth's surface in the simplest atmospheric case. Another example of special interest is surface quasi-geostrophic (SQG) flow, in which the state of the system is completely determined by the temperature at the surface. SQG flows bear some formal resemblance to 3D incompressible flows – for example, dimensional arguments suggest a -5/3 kinetic energy spectrum for the direct turbulent cascade to small scales, just as in 3D. SQG has developed into a model problem for those interested in singularity formation in 3D Euler or Navier-Stokes. The possible formation of singularities in SQG remains unsolved. There is also interest in possible blow-up of active scalar equations with more singular constitutive laws and in questions relating to long time behavior in the limit of small dissipative mechanisms.

The workshop provided the opportunity for mathematicians and AOS scientists to discover some common ground, and exposed participants to new methods and models that will possibly fertilize new work within both groups in the future. Approximately one dozen graduate students and post-docs attended from several U.S. universities, and 5 graduate students presented posters.

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:

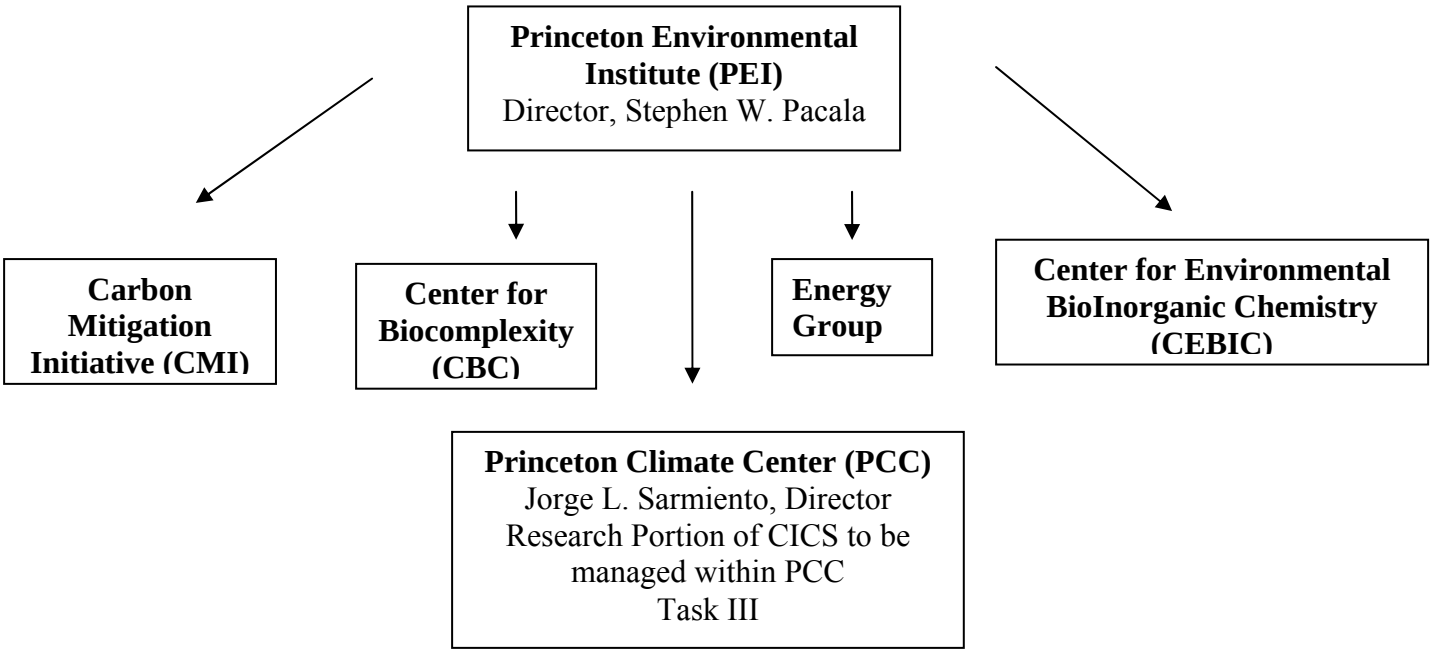
I. Administrative Activities including outreach efforts are carried out jointly by the AOS Program and Princeton Environmental Institute (PEI).

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.

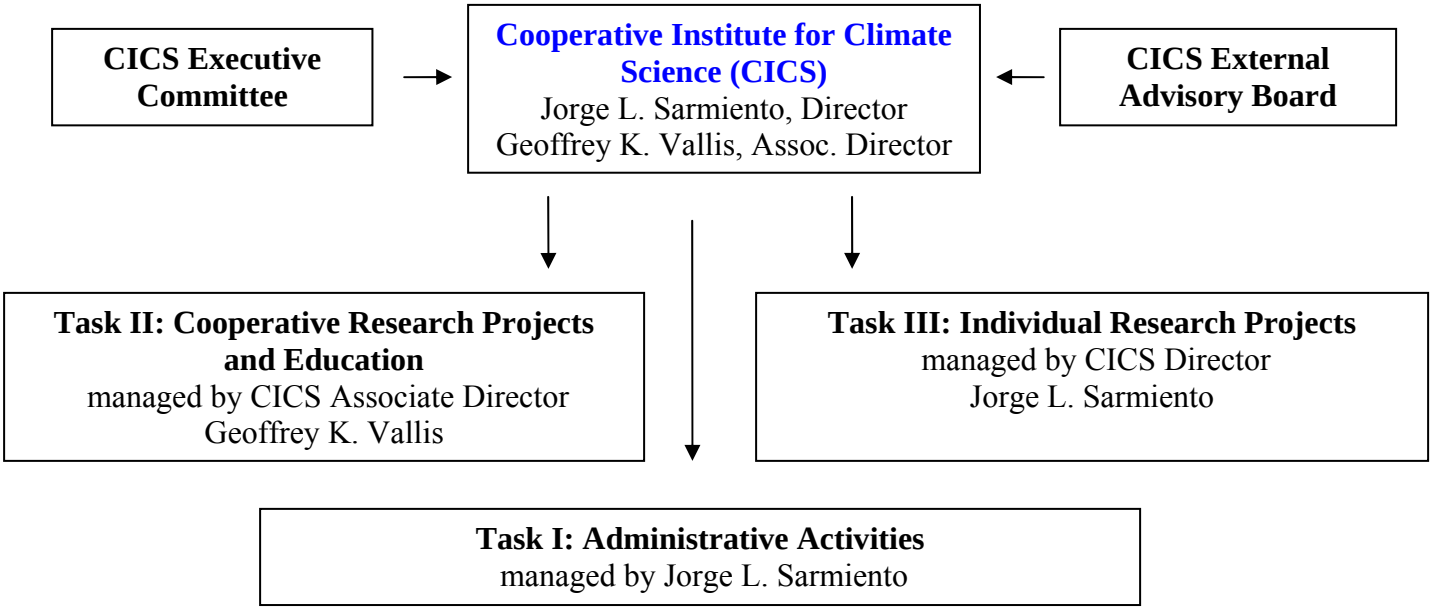
III. Principal Investigator led research projects supported by grants from NOAA that comply with the themes of CICS. These all occur within AOS and the Princeton Environmental Institute (PEI), and may also include subcontracts to research groups at other institutions on an as needed basis.

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

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

EARTH SYSTEM MODELING: DEVELOPMENT and ANALYSIS

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

Ocean Model Development

The ocean circulation depends rather sensitively on bottom topography, and it is particularly important to have a good representation of topography in ocean models. A significant development in this area is described in the report by Adcroft. A new porous barrier representation of subgridscale topography in ocean models was evaluated in a model of the 2004 Indian Ocean Tsunami. It was demonstrated that solutions obtained with this approach are significantly less sensitive to horizontal grid resolution than traditional models and methods. In particular, objectively generated topography was able to perfectly retain the actual sill-depths in straits and overflows and avoids the need for subjective correction of the topography

Ice Sheet Model Development

The behavior of ice sheets on long timescales is one of the major unknowns in climate dynamics. If one of the major ice sheets (Greenland or Antarctica) were to melt the results would be catastrophic.
CICS researcher Olga Sergienko is working to develop an ice-sheet model that can be integrated into the GFDL coupled climate model to potentially reduce the uncertainties in ice-sheet forecasting, and to do this it is essential to properly understand the major physical processes. To this end, she investigated the dynamics and thermodynamics of ice shelves floating in two distinct oceanic environments, one dominated by warm Circumpolar Deep Water (CDW) and the other one dominated by colder (~ 3°C) High Salinity Shelf Water (HSSW) using a fully coupled ice-shelf/plume model. Simulations of the coupled model revealed distinct steady states of ice shelves that are determined by the oceanic environments. Ice shelves afloat in CDW waters are significantly colder those floating in HSSW waters (Figure 1) and the ice-shelf mass balance is determined by different processes: in the HSSW case, it is between ice advection and deformation, in the CDW case it is between ice advection and melting. Ice shelves floating in CDW are more sensitive to shallowing of the thermocline depth, and ice shelves floating in HSSW are more sensitive to warming the bottom water. These results will be key to properly including ice sheet processes in coupled climate models.

Forest Phenology over North America

This project is examining the impact of climate warming on the seasonal expression of foliage referred to as phenology. Using data-based models and the climate simulations of the Coupled Model Intercomparison Project phase 5, it is projected that spring budburst will occur up to 17 days earlier over the next century. These changes are expected to have large effects on the US carbon budget. A new study of observations of fall phenology is underway which shows the importance of interannual climate variability as well as atmospheric CO_2 concentrations in explaining the observed variability.

EARTH SYSTEM MODELING: APPLICATIONS

Tropical Cyclone Prediction

In a study that has potentially large ramifications, CICS researcher Jan-Huey Chen found that the storm counts of both tropical storm (TS) and hurricane categories are highly predictable in the North Atlantic basin during the period from 1990-2010, especially in the second decade. The research also showed that intensity distribution of tropical cyclones 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. This demonstrated the feasibility of using a high-resolution general circulation model, designed initially for long-term climate simulations, to study the impacts of climate-change on the intensity distribution of tropical cyclones.

Assessing Hydroclimates in High Resolution Models

As climate warms, one of the most important affects on society will be the changes in the hydrology cycle. CICS researcher Sarah Kapnick has performed some very interesting studies looking at how the hydroclimate and the effects of model resolution. She found that, in comparison to its coarser predecessor, CM2.5 better captures mean annual climatologies of snow variables and the seasonal cycle of snow covered area. Kapnick also looked at the climate change aspects of snow variables in a 2xCO2 environment and found global reductions in snowfall, but regions where snowfall uniquely increases due to increased precipitation. As well as appearing in the peer-reviewed literature, this work was also picked up by various media outlets, including the Associated Press (and their partner organizations), World News with Diane Sawyer, CNN.com, and others.

Quantifying the Source of Ozone Pollution

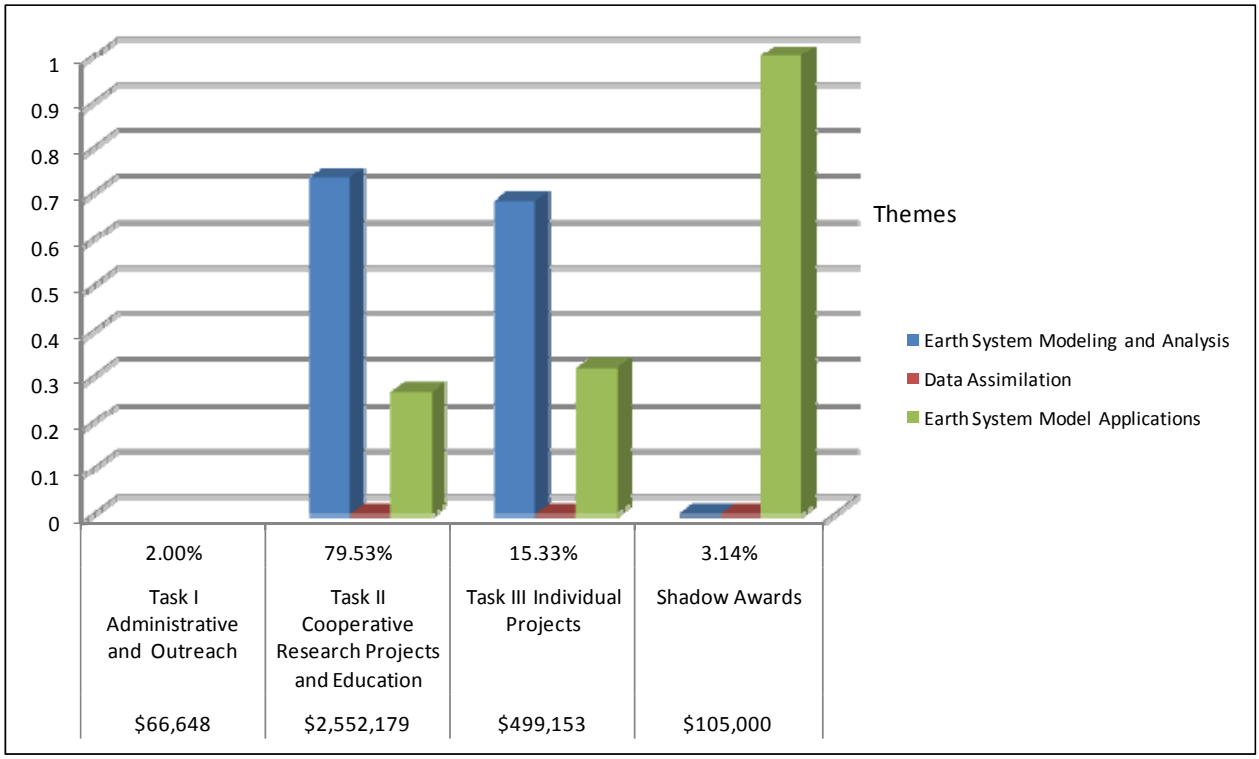
Some notable advances were made by CICS researchers in quantifying the sources of ozone pollution, as described in more detail in the report by Meiyun Lin. Such pollution significantly affects the quality of life in the US and elsewhere. Lin analyzed balloon soundings, aircraft, lidar, surface and satellite measurements from May through June 2010 using GFDL's new global high-resolution chemistry-climate model. She found that Asian pollution contributes as much as 20 percent of total ozone during springtime pollution episodes in western U.S. surface air. The current U.S. air-quality standard for ozone is 75 parts per billion. Lin and her coauthors found that about half

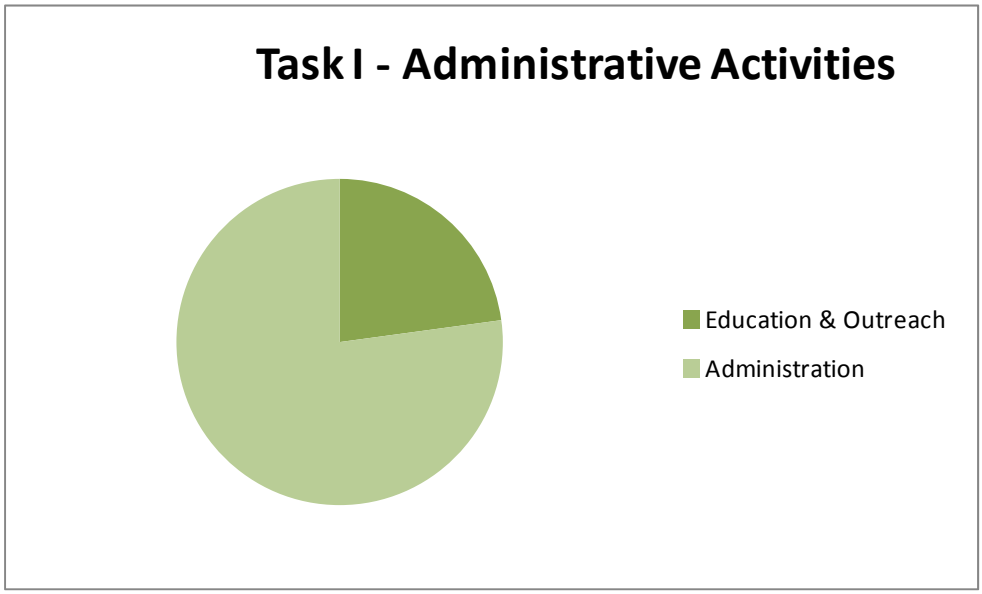
of the times where that limit was exceeded would not have occurred without the contribution from Asian air pollution. Lin also found that stratospheric ozone intrusions can contribute as much as 50 percent to ground-level ozone in parts of the western United States and directly lead to episodes of high-ozone in excess of the health-based limit. Evidence is found for 13 of such events from April to June 2010, in notable contrast to prior work concluding that stratospheric influence in surface air is rare.

Impact of Climate Warming on Coral Reefs

A revised physiologically based coral bleaching algorithm has been developed based on the global Reefbase database of bleaching observations. This work showed that the historical maximum monthly mean temperature served as the most robust proxy for coral sensitivity to bleaching. These algorithms have been used together with bias corrected climate simulations of future sea surface temperatures to refine future coral bleaching projections. The results provide a range of future bleaching frequencies, some of which dramatically improve the future outlook for reef-building corals.

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 a MPOWIR supported graduate student. Princeton University matching funds also co-supported the Summer Institute in Weather and Climate and the Geostrophic Turbulence and Active Tracer Transport in 2 Dimensions Workshop.

Project Titles

Cooperative Institute for Climate Science (CICS)
NOAA Cooperative Award NA08OAR4320752

Task I Projects

- CICS Professional Development Summer Institute in Weather and Climate (Anne Catena)
- Geostrophic Turbulence and Active Tracer Transport in 2 Dimensions Workshop (Isaac Held)

Task II Projects

- Aerosol Radiative Effects through the Lens of East Asian Solar Dimming (Geeta Persad)
- Assessing the Hydroclimate in a High-Resolution Global Coupled Model Framework (Sarah Kapnick)
- Climate Response to Saharan Dust Perturbations (Jeffrey Strong)
- Climatic Impacts of Internal-Wave Driven Mixing in the Ocean (Angelique Melet)
- Cloud and Radiation Variability Associated with El Nino (Claire Radley)
- Contrasting Features of Scattering and Absorbing Aerosol Direct Radiative Forcings and Climate Responses (Ilissa Ocko)
- Controlling Factors in Atmospheric Oxidation Capacity (Jingqiu Mao)
- Development and Implementation of the Multi-canopy Land Surface Physics (Sergey Malyshev)
- Development of an Ice-Sheet Model (Olga Sergienko)
- Flexible Modeling System (FMS) (V. Balaji)
- GFDL Data Portal Post IPCC Adaptation (Serguei Nikonov)
- Hybrid Ocean Model Development (Alistair Adcroft)
- Investigations into the Predictability of Arctic Sea Ice on Seasonal to Interannual Time Scales (Sarah Keeley)
- Land Carbon Dynamics and Climate Change (Elena Shevliakova)
- Modeling the Effects of Climate Change and Ocean Acidification on Global Coral Reefs (Cheryl Logan)
- NOAA/GFDL Earth System Model Downscaling in the California Current Large Marine Ecosystem (Ryan Rykaczewski)
- Ocean, Atmosphere and Climate Dynamics (Geoffrey Vallis)
- Ocean Heat and Carbon Uptake under Global Warming (Yu Zhang)
- Ocean Heat Transport and Atmospheric Feedbacks on Global Climate (David Brayshaw)
- Ocean Mixing Processes and Parameterization (Sonya Legg)
- Ocean Surface Gravity Waves and Climate Modeling (Yalin Fan)
- Processes that Control Climate Change over the Southern Hemisphere (Isidoro Orlanski)
- Regularity of Baroclinic Waves in the Martian and Terrestrial Atmospheres (Todd Mooring)
- Seasonal Prediction of Tropical Cyclones Using the 25-km Resolution GFDL High-Resolution Atmospheric Model (HiRAM) (Jan-Huey Chen)
- Spontaneous Superrotation in Idealized Atmospheric Models (Samuel Potter)
- The Asymmetry of the Duration and Sequencing of ENSO (Kityan Choi)

Task II Projects continued

- The Dependency of Tropical Cyclone Scale on Domain Size and Larger Scale Environment (Wenyu Zhou)
- The Importance of Supercriticality on the Horizontal Scale and Vertical Structure of Baroclinic Eddies in a Dry GCM (Junyi Chai)
- The Nordic Seas Overflows and their Influences on Climate (He Wang)
- Sources of Springtime Ozone Pollution Events in the Western United States (Meiyun Lin)
- Towards Accurate Predictions of Regional Precipitation Change Due to Anthropogenic Aerosol and Greenhouse Gas Emissions (Spencer Hill)
- Understanding Aerosol-Induced Regional Circulation and Hydroclimate Changes with Climate Model Simulations and Observations (Massimo Bollasina)

Task III Projects

- Cross-shelf Exchange Processes in the Bering Sea: Downscaling Climate Models and Ecosystems Implications (Enrique Curchitser – Rutgers)
- Detection and Attribution of Abrupt and Gradual Changes in the Carbon System (Claudie Beaulieu)
- Large-scale Variations in Forest Phenology and their Impacts on Surface Water, Energy, and Carbon Fluxes over North America (David Medvigy)
- Predicting the Impacts of Climate Change on Mesopelagic Ecosystems: Particle Remineralization in the Mesopelagic Zone (K. Allison Smith)
- Predicting the Impacts of Climate Change on Mesopelagic Ecosystems: Respiratory Niches in the Pelagic Ocean (K. Allison Smith)
- Regional Climate Studies Using the Weather Research and Forecasting Model (James Smith)
- Signal Tracking of Antarctic Open-Ocean Polynyas (Hannah Zanowski)
- Top-down Controls on Marine Microbial Diversity and its Effects on Primary Productivity in the Oceans (Simon Levin)
- Will Non-Linearities in the Buffering Capacity of Seawater Dominate the Ocean Carbon-Climate Feedback over the 21st Century? (Keith Rodgers)

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)

Progress Reports:

Earth System Modeling and Analysis

Progress Report Title: **Hybrid Ocean Model Development**

Principal Investigator: Alistair Adcroft (Princeton Research Oceanographer)

CICS/GFDL Collaborator: Sonya Legg (Princeton), Robert Hallberg (GFDL), Stephen Griffies (GFDL), John Dunne (GFDL)

Other Participating Researchers: Mehmet Ilicak (Univ. Bergen)

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-based Management (20%)
Climate Goal: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond (80%)

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

Methods and Results/Accomplishments:

I developed a porous barrier representation of subgrid –scale topography in ocean models which I evaluated in a model of the 2004 Indian Ocean Tsunami. There, I demonstrated that solutions obtained with this approach are significantly less sensitive to horizontal grid resolution than traditional models and methods. I also show that objectively generated topography is able to perfectly retain the actual sill-depths in straits and overflows and avoids the need for subjective correction of the topography. This method has yet to be implemented and evaluated in a three-dimensional GCM. I expect that once available, the additional topographic information will open up new opportunities for parameterization of processes involving topographic interactions (speculative).

The GOLD model was released and frozen in the summer. MOM5 was released and frozen in the fall. Work on MOM6 began in the winter and will unify the two former models. There will be only one model from here on.

Publications:

Representation of topography by porous barriers and objective interpolation of topographic data. A. Adcroft, 2012: Ocean Modelling, doi:10.1016/j.ocemod.2013.03.002, in press.

Atlantic Watermass and Circulation Response to Persistent Freshwater Forcing in Two Coupled General Circulation Models. M. Harrison, A. Adcroft and R. Hallberg, 2012: submitted to Climate Dynamics.

Sensitivity of 21st Century global-mean steric sea level rise to ocean model formulation. R. Hallberg, Adcroft, A., Dunne, J., Krasting, J. and Stouffer, R., 2012: J. Climate, doi:10.1175/JCLI-D-12-00506.1, in press.

An Order-invariant Real-to-Integer Conversion Sum. R. Hallberg and A. Adcroft, 2012: submitted to Parallel Computing.

Routes to Energy Dissipation for Geostrophic Flows in the Southern Ocean. Nikurashin, M., G. Vallis and A. Adcroft, 2013: Nature - Geosciences, 6, 48-51. doi:10.1038/ngeo1657.

GFDL's ESM2 global coupled climate-carbon Earth System Models Part II: Carbon system formulation and baseline simulation characteristics. Dunne, J. P., John, J.G. , Shevliakova, E.N., Stouffer, R.J., Krasting, J.P., Malyshev, S.L., Milly, P.C.D., Sentman, L.A., Adcroft, A., Cooke, W., Dunne, K.A., Griffies, S.M., Hallberg, R.W., Harrison, M.J., Levy, H., Wittenberg, A.T., Phillipps, P.J., Zadeh, N., April 2013: J. Climate, 26(7), doi:10.1175/JCLI-D-12-00150.1.

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, 26, 231-245. doi:10.1175/JCLI-D-12-00121.1.

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, 25, 6646-6665. doi:10.1175/JCLI-D-11-00560.1.

Investigation of the Surface and Circulation Impacts of Cloud Whitening Geoengineering. E. Baughman, E., Gnanadesikan, A., DeGaetano, A., and Adcroft, A., 2012: J. Climate, 25, doi:10.1175/JCLI-D-11-00282.1.

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., 2012: J. Climate, 25, 2755-2781. doi:10.1175/JCLI-D-11-00316.1.

Spurious dianeutral mixing and the role of momentum closure. Ilicak, M., Adcroft, A., Hallberg. R. and Griffies S., 2012: Ocean Modelling, 45-46, 37-58. doi:10.1016/j.ocemod.2011.10.003.

Figures:

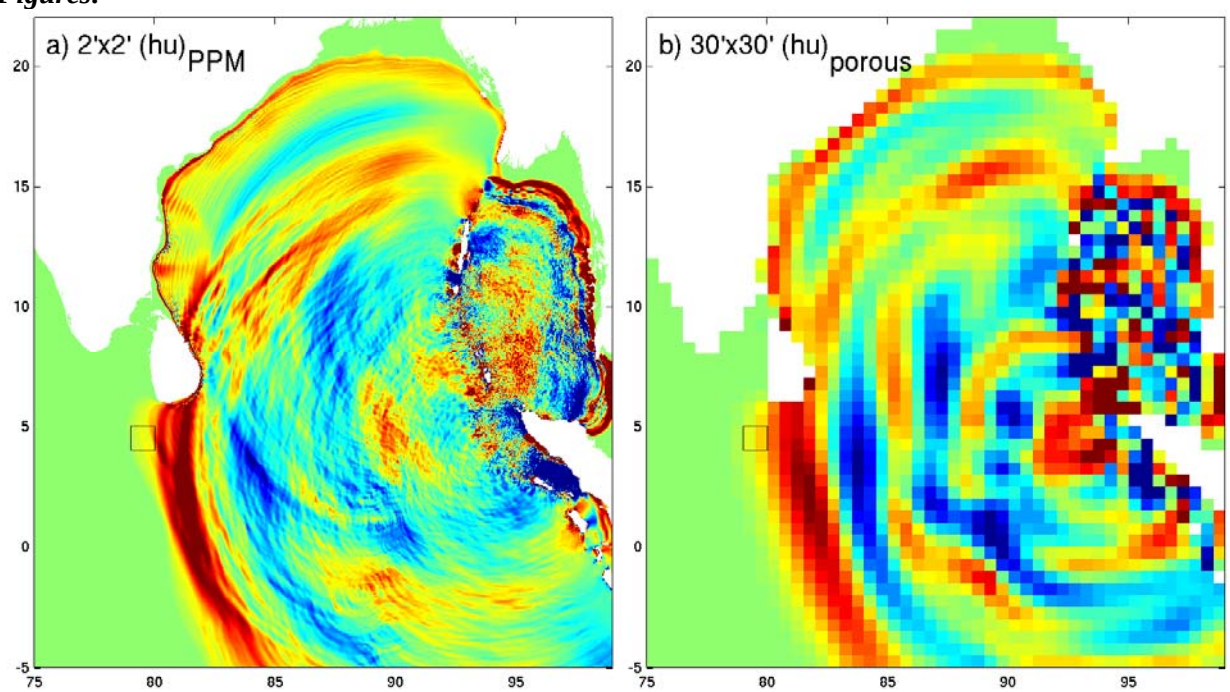


Fig. 1: The surface displacement simulated at a) fine-resolution with a traditional discretization (2 arc-minute) and b) coarse-resolution with the porous barrier method (1/2 degree). The arrival time of the coarse-resolution model is normal inaccurate when using a traditional discretization but here, the coarse-resolution arrival time is consistent with the fine-resolution result.

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); finalized and delivered National Academies Panel on 'A National Strategy for Climate Modeling' <http://www8.nationalacademies.org/cp/projectview.aspx?key=49288>; served on Science Advisory Board, Oak Ridge Climate Change Science Institute; and served on 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 Fueglistaler); G8 international grant award from NSF ($300k 2011-2013); organized Summer School on Atmospheric Modeling (SSAM-2012) at Princeton NJ, July 2012, with 30 national and international students; grant award from International Centre for Theoretical Physics (ICTP), Trieste, for International Summer School on Ocean Modeling, Hyderabad, India, July 2013; and
keynote address at Parallel Computing Technologies (ParCompTech) Conference, Bangalore, India, February 2013.

References:

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

Publications:

Balaji, V., 2013a: ESM I/O Layers. Earth System Modelling - Volume 4, Springer Berlin Heidelberg, SpringerBriefs in Earth System Sciences, 13–20, DOI: 10.1007/978-3-642-36464-8_3.

Balaji, V., 2013b: Future Perspectives. Earth System Modelling - Volume 4, Springer Berlin Heidelberg, SpringerBriefs in Earth System Sciences, 49–51, DOI: 10.1007/978-3-642-36464-8_7.

Balaji, V., 2013c: Input/Output and Postprocessing. Earth System Modelling - Volume 4, Springer Berlin Heidelberg, SpringerBriefs in Earth System Sciences, 1–2, DOI: 10.1007/978-3-642-36464-8_1.

Balaji, V., 2013d: Scientific computing in the age of complexity. XRDS, 19 (3), 12–17, DOI: 10.1145/2425676.2425684.

Valcke, S., Balaji, V., Craig, A., DeLuca, C., Dunlap, R., Ford, R. W., Jacob, R., Larson, J., O'Kuinghttons, R., Riley, G. D., and Vertenstein, M., 2012: Coupling technologies for Earth System Modelling, Geosci. Model Dev., 5, 1589-1596.

Lawrence, B. N., et al., 2012: Describing Earth System Simulations with the Metafor CIM. Geoscientific Model Development Discussions, 5(2), 1669--1689.

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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.

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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.

Progress Report Title: **The Importance of Supercriticality on the Horizontal Scale and Vertical Structure of Baroclinic Eddies in a Dry GCM**

Principal Investigator: Junyi Chai (Princeton Graduate Student)

CICS/GFDL Collaborator: Geoffrey Vallis (Princeton), Isaac Held (GFDL), Steve Garner (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

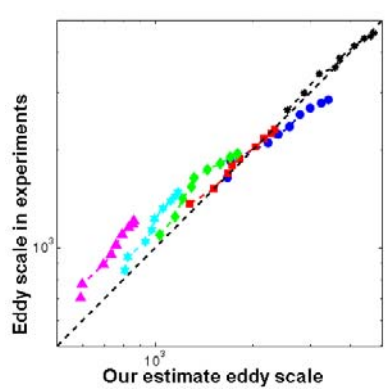
Objectives: This is a theoretical work combined with experiment validations which provides an understanding on the eddy scale in a regime relevant for our real atmosphere.

Methods and Results/Accomplishments:

In a primitive equation dry GCM, the supercriticality is generally not sensitive to meridional temperature gradient, rotation rate, and planet radius, etc. Here we change the supercriticality by changing the diabatic heating rate on the mean flow. We show that the eddy's horizontal scale *Le* increases although the Rossby deformation radius decreases, when we increase the diabatic heating rate. Using the same experimental setting for a GCM without eddy-eddy interactions, we prove that inverse cascade is not responsible for the increase in eddy scale. Furthermore, we show that the vertical structure of the eddies changes with its horizontal scale. We explain this from the Charney model, in which the baroclinic wave's horizontal scale and vertical extend increases with supercriticality in the low supercriticality regime. We propose that an estimate for the horizontal scale of the eddy is

$$L_e \sim C \frac{\xi}{1+\xi} L_R,$$

in which ξ is supercriticality and LR is the deformation radius. The constant C is about 10, a large factor but consistent with both linear instability calculation and modelling results. This estimate is suitable for the regime ξ ~ O(1), in which the eddy scale is similar to the energy generation scale and inverse cascade is not important. When ξ ~ 1, we argue that this estimate gives the energy generation scale, and it is not sensitive to criticality. The agreement of our scaling and numerical experiment results is shown below.



References:

Schneider, T., and C. C. Walker, 2006: Self-organization of atmospheric macroturbulence into critical states of weak nonlinear eddy-eddy interactions. Journal of the Atmospheric Sciences, 63, 1569-1586.

Pablo Zurita-Gotor. 2008: The sensitivity of the isentropic slope in a primitive-equation dry model. Journal of the Atmospheric Sciences: Vol 65, No 1, pp 43-65

Publications:

The importance of supercriticality on the horizontal scale and vertical structure of baroclinic eddies in a dry GCM (in preparation).

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 Modeling and Analysis
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: To understand 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

Methods and Results/Accomplishments:

We utilized nested bio-physical ocean models for both hindcast and projections in both the Bering Sea and the California Current. The nested ocean was based on the widely used ROMS circulation model coupled to two different biological models: NEMURO in the Bering Sea and CoSINE in the California Current. The hindcast simulation (1958-2008) was forced by CORE II atmospheric forcing and SODA ocean boundary conditions for physics and WOA for the biological fields. The projections, which were supported by funds from the California Current Integrated Ecosystem Assessment program, were carried out by downscaling the GFDL CM2.1mESM to the ROMS model for the period of 1970 to 2050. Future states were using the RCP8.5 scenario. It is worth noting that the downscaled projection included the linking of two distinct ecosystem models (COBALT globally and CoSINE regionally).

To date the following have been accomplished in this project:

Bering Sea: 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. 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 which 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 includes the completion of two manuscripts describing the physics of the model and 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 are currently working on a third manuscript describing the nutrient fluxes on the Bering shelf and relating the interannual and decadal variability to North Pacific climate indices.

California Current: 1) The coupling and testing of an enhanced version of the CoSINE model with ROMS. The version we have now coupled and is running in the CCS has carbon and oxygen chemistry along the NPZD with the aim of investigating their evolution under climate change. 2) Design of a downscaling strategy for the biological component of the coupled model: The biogeochemical models used in global climate models are different than the ones we are using for the regional projections (CoSINE or NEMURO). Though some of the fields have direct matches (e.g., NO3), others (phyto- and zoo-plankton) do not. For the projection of future states we need to incorporate the trends predicted by the global models and cannot rely on climatological boundary conditions more appropriate for hindcasts. 3) Downscaled bio-physical projection of California Current climate for the period of 1970-2050 using the 20th century climate transitioning to RCP8.5. This simulation is now complete and we are in the process of analyzing the output for both physics and biogeochemistry.

Publications:

Danielson, S., K. Hedstrom, K, Aagard, T. Weingartner and E.N. Curchitser, 2012. Wind-induced reorganization of the Bering shelf circulation. Geo. Res. Lett. doi:10.1029/2012GL051231.

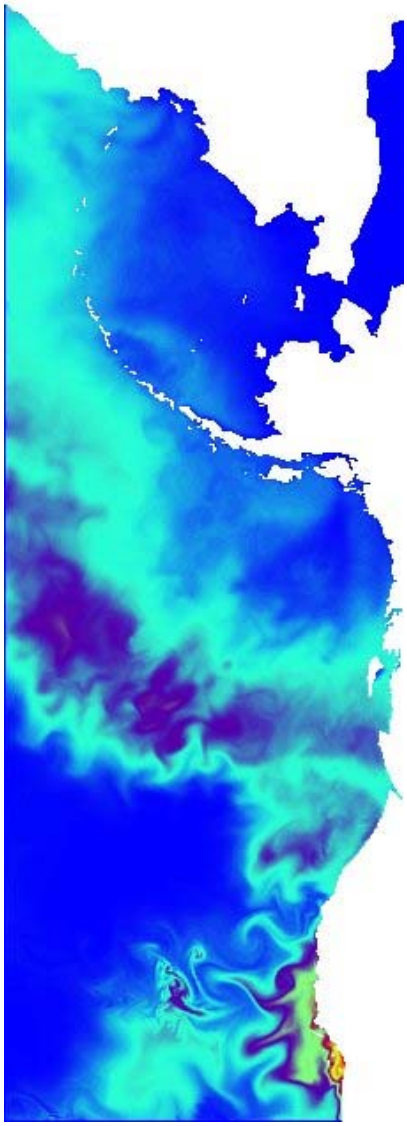


Figure 1: Primary productivity from the coupled ROMS-CoSINE model being used for projections in the northeast Pacific.

Progress Report Title: **Ocean Surface Gravity Waves and Climate Modeling**

Principal Investigator: Yalin Fan (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Stephen Griffies, Shian-Jiann Lin, and Isaac Held (GFDL)

Other Participating Researchers: Hendrik Tolman (NCEP/EMC)

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: Evaluate global wave climatology from wave coupled high-resolution atmospheric model (HiRAM); Generate wave projections for the end of the 21st century; Investigate Langmuir turbulence effect on climate simulations.

Methods and Results/Accomplishments:

During the past year, simulated global wave climatology for a 29-year period using wave coupled HiRAM was extensively evaluated against buoy observations, satellite measurements and ERA40 reanalysis and showed very good agreements 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. This work is published on the Journal of Climate.

Surface wind and significant wave height response to global warming are investigated using the wave coupled HiRAM by perturbing the sea surface temperatures with anomalies generated by WGCM CMIP-3 coupled models that use the IPCC/AR4/A1B scenario late in the 21st century. This work is accepted for publication on the Journal of Climate. This study is also published on Nature Climate Change as part of the first community-derived multi-model ensemble of wave-climate projections.

A fully coupled global atmosphere-wave-ocean simulation system was developed by incorporate WAVEWATCH III into the GFDL coupled model CM2.1 (Figure 1). A sea state dependent momentum flux parameterization developed in Fan et al (2012) has been implemented together with two Langmuir turbulence parameterizations in the ocean model. This newly coupled system is evaluated using the 1990 control run following Delworth et al (2006). Preliminary results have suggested that parameterization using turbulent Langmuir number alone as suggested by McWilliams & Sullivan (2000) is not suitable for global ocean circulation models, while the parameterization includes the ocean stratification by Smyth et al (2002) has shown promising results. Our results also show that Langmuir turbulence not only can deepen mixed layer depth as recognized by previous studies, it can also help to maintain the stratification in ice-covered regions.

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McWilliams JC, Sullivan PP. 2000. Vertical mixing by Langmuir circulations. Spill Sci. Technol. Bull. 6:225–37.

Smyth, W. D., E. D. Skyllingstad, G. B. Grawford, and H. Wijesekera, 2002: Nonlocal fluxes and Stokes drift effects in the K-profile parameterization. Ocean Dyn. 52, 104-115, DOI 10.1007/s10236-002-0012-9.

Publications:

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Fan, Yalin, Isaac M Held, Shian-Jiann Lin, and X L Wang, in press*:* Ocean Warming effect on Surface Gravity Wave Climate Change for the end of the 21st Century**.** Journal of Climate**.** doi:10.1175/JCLI-D-12-00410.1.

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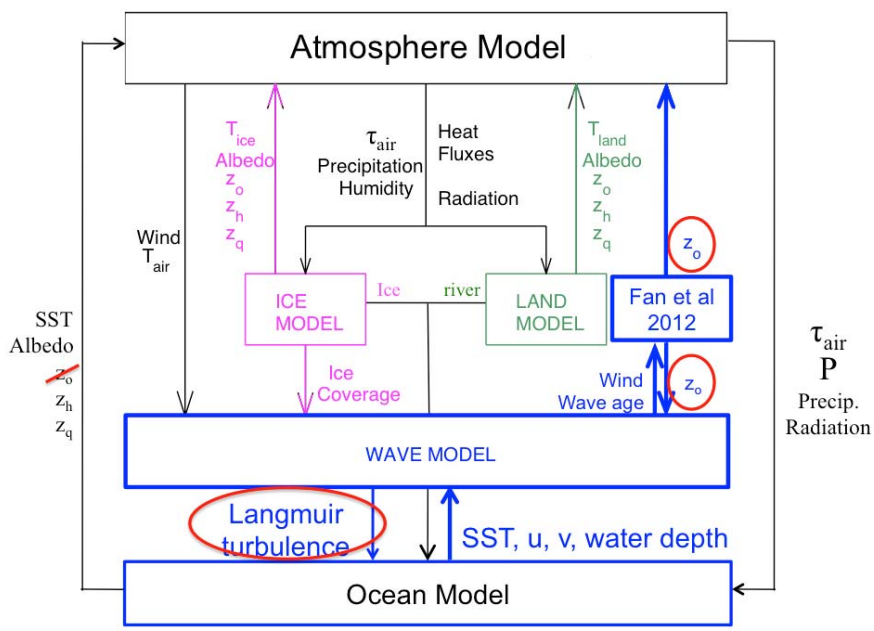

Figure 1. A schematic diagram of the atmosphere-land-ice-ocean-wave coupled model. The arrows indicate the prognostic variables that are passed between the model components. In the diagram, z_o, z_q, and z_h, are momentum, latent heat, and sensible heat roughness lengths. T_{air}, T_{ice}, and T_{land}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

Progress Report Title: **Investigations into the Predictability of Arctic Sea Ice on Seasonal to Interannual Time Scales**

Principal Investigator: Sarah Keeley (Princeton Visiting Research Fellow/European Centre for Medium-Range Weather Forecasts)

CICS/GFDL Collaborator: Rym M'sadek (GFDL), Bill Hurlin (GFDL), Mike Winton (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: 1) To run GFDL model contribution to the APPOSITE (UK funded) research project which is a multi-perfect-model study to investigate the predictability of Arctic sea ice on seasonal to interannual timescales 2) Compare the seasonal forecast systems of GFDL and ECMWF in terms of Arctic sea ice prediction

Methods and Results/Accomplishments:

Perfect Predictability Experiments: We ran a control integration of CM3.0 on Gaea so that we could extract start files from which we could then carry out perfect predictability experiments and have a bitwise reproducible control run. In the experimental framework we wished to identify states within the control run where different states of the climate system may limit the potential predictability. We analyzed the state of the MOC, Heat transport in the Arctic and the sea ice extent and volume. We identified different starting points in the control run based on different properties of the system.

With invaluable support from Bill Hurlin we carried out ensemble predictions (16 members, 3year predictions, January and July start dates.) The results have been submitted to the APPOSITE database and further analysis of the data will take place in the coming months.

Comparison of the Seasonal prediction of Arctic sea-ice using GFDL and ECMWF models: The operational ECMWF seasonal forecasting system does not include a sea ice model which allows the dynamic evolution of sea ice. Since returning from Princeton ongoing model development work has allowed a research version of a seasonal forecasting system that can be compared to that used for seasonal prediction at GFDL.

The ECMWF system has different schemes to produce the ice initial conditions using ocean-ice model: 1. A free running system forced with atmospheric fluxes from ERA-Interim. (grey dashed in figure 1) 2. Atmospheric fluxes from ERA-Interim + a linear (spatially uniform) nudging scheme that relaxes ice to the observed concentration with a 1day time scale. (blue line in figure 1) 3. Atmospheric fluxes from ERA-Interim + a spatially and time varying nudging scheme which relaxes to the observed ice concentration with a weight that is dependent on model and observational differences – this is similar method to the PIOMAS (Lindsay & Zhang, 2006) implementation. (red line in figure 1)

We note that constraining the ice edge may not improve the initial stat. Figure 2 shows the initial sate volume in comparison with the PIOMAS data and highlights the differences in volume from the two different nudging schemes.

We then run 11 ensemble hindcasts from 1983- 2012 for a selection of forecast start months and consider the prediction of the September sea ice extent (as an initial test of the systems performance).

We have assessed the initial conditions in a similar way to that of GFDL see figures 1-3 and at the time of writing are processing the data to make a comparison with the GFDL system (shown in figure 4).

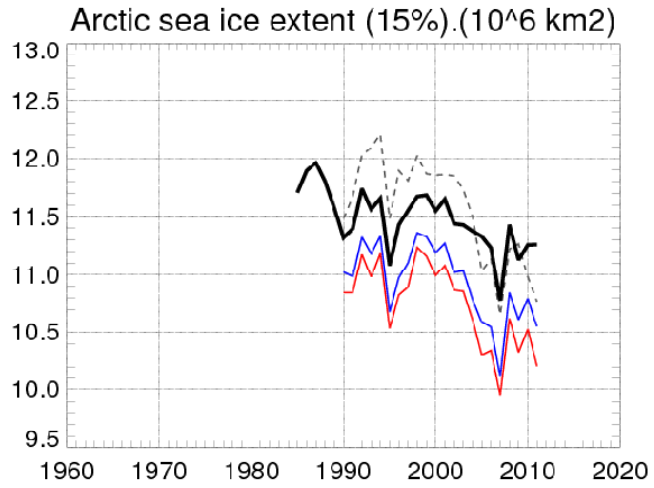

Figure 1: Arctic sea ice extent for: Observations from OIv2 (black), free running system (grey dashed line), linear nudging (blue) and nonlinear nudging (red).

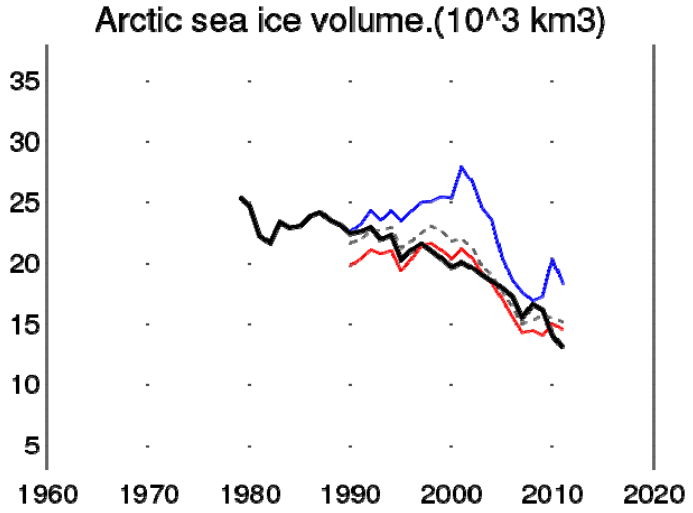

Figure 2: Arctic sea ice volume for: "Observed" Estimates from PIOMAS (black), free running system (grey dashed line), linear nudging (blue) and nonlinear nudging (red).

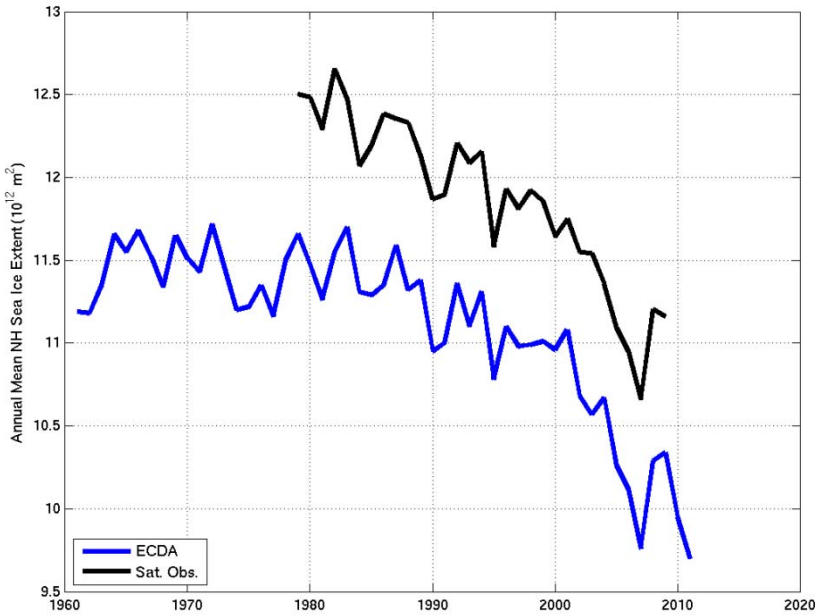

Figure 3: GFDL initial conditions from ECDA system

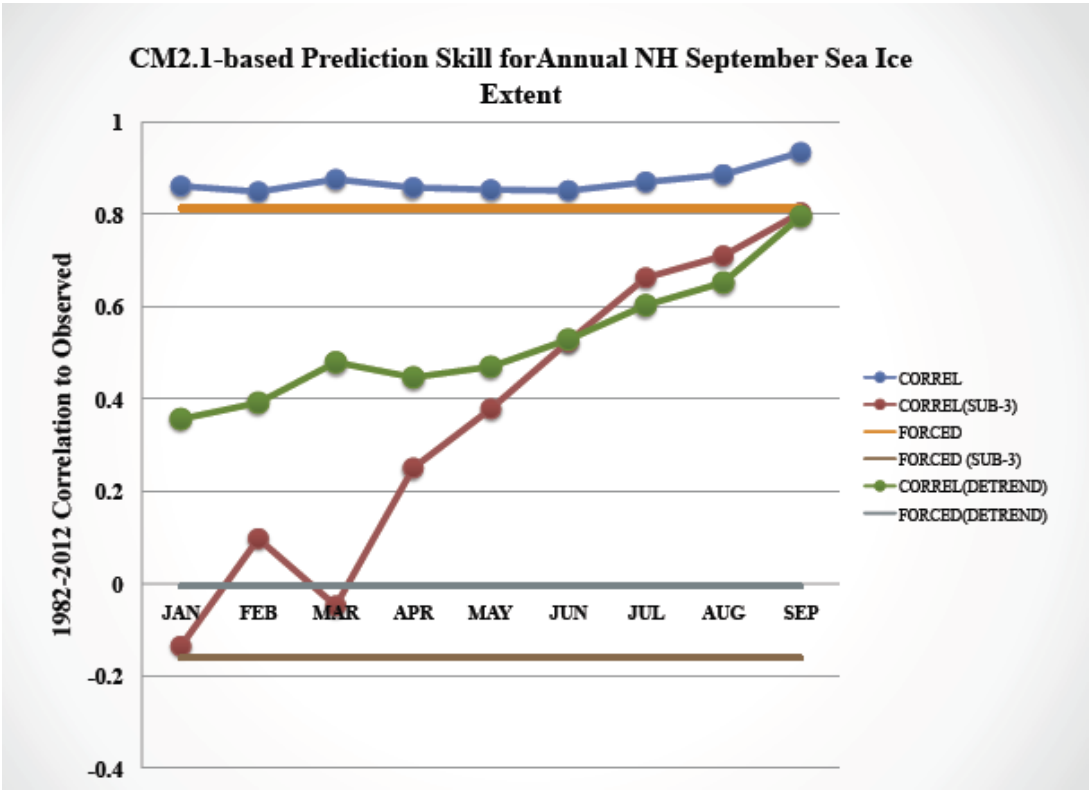

Figure 4: correlation skill for annual mean September sea ice extent for different initialization months

References:

Lindsay, R. W., Zhang, J., 2006. Assimilation of ice concentration in an ice-ocean model. J. Atmos. Ocean. Tech. 23, 742-749.

Publications:

Work will be presented at the Seasonal to Decadal meeting in Toulouse. We anticipate submission of the work in the peer reviewed literature in coming months.

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

Principal Investigator: Sonya Legg (Princeton Research Oceanographer)

CICS/GFDL Collaborator: Robert Hallberg and Steve Griffies (GFDL), Alistair Adcroft, Mehmet Ilicak, Maxim Nikurashin, Maarten Buijsman, He Wang, Angelique Melet, and Robert Nazarian (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. Work in collaboration with Jody Klymak at University of Victoria has resulted in a parameterization of tidal mixing at tall steep topography, which is now being implemented into GFDL models as part of the Internal Wave Driven Mixing Climate Process Team. A paper describing the nonlinear breaking waves at tall steep topography recently appeared in Oceanography (Klymak et al, 2012). A second aspect of tidal mixing, 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: one manuscript describing this phenomena in the South China Sea was published in the past year (Buijsman et al, 2012), another is in press (Klymak et al, 2013) and a third describing the influence of 3-dimensional flow and complex topography is under review (Buijsman et al, 2013).

A major focus of the past year has been the fate of large-scale internal waves upon reflection from sloping topography. A manuscript describing a parameter space survey and the dependence of wave breaking and mixing on the topographic height, slope and incoming low mode wave amplitude is currently under review (Legg 2013). Simulations are continuing exploring the extensions of these ideas to 3-dimensional topography and variable stratification. 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 new, more physically based parameterizations of tidal mixing, such as developed by Kurt Polzin at WHOI, into the GOLD ocean climate model. A manuscript currently in press (Melet et al 2013a) evaluates the sensitivity of the large-scale stratification to the change in mixing distribution introduced by this new parameterization. A second manuscript (Melet et al, 2013b) in preparation describes the impact of a parameterization of lee-wave driven mixing on the large-scale circulation. All of these studies form part of the subject area of the Internal Wave Driven Mixing Climate Process Team, headed by Jennifer MacKinnon, and involving researchers from different US institutions, including GFDL, which has recently been renewed for a further 2 years.

With regard to overflows, 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, and sensitivity to model formulation, topography and mixing. A manuscript describing this study is now in preparation.

Publications:

Buijsman, M., S. Legg, and J. Klymak, 2012: Double Ridge Internal Tide Interference and its Effect on Dissipation in Luzon Strait. J. Phys. Oceanogr., 42, p1337-1356, doi:10.1175/JPO-D-11-0210.1.

Klymak, J.M., S. Legg, M.H. Alford, M. Buijsman, R. Pinkel, and J.D. Nash, 2012: The direct breaking of internal waves at steep topography. Oceanography, 25, 150-159.

Melet, A., R. Hallberg, S. Legg and K. Polzin, 2013a: Sensitivity of the Pacific Ocean state to the vertical distribution of internal-tide driven mixing. J. Phys. Oceanogr., 43(3)**,** doi:10.1175/JPO-D-12-055.1.

Klymak, J., M. Buijsman, S. Legg and R. Pinkel, 2013: Parameterizing baroclinic internal tide scattering and breaking on supercritical topography: the one- and two-ridge cases. J. Phys. Oceanogr., in press.

Legg, S., 2013: Scattering of low-mode internal waves at finite isolated topography. J. Phys. Oceanogr., submitted.

Buijsman, M.C., J. Klymak, and S. Legg, 2013: Three-dimensional double ridge internal tide resonance, J. Phys. Oceanogr., submitted.

Melet, A.; Hallberg, R.; Legg, S. and M. Nikurashin, 2013b: Sensitivity of the Ocean state to lee wave driven mixing. Submitted to the Journal of Physical Oceanography.

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.

Melet, A.; Hallberg, R.; Legg, S. and M. Nikurashin. Sensitivity of the Ocean State to Internal Lee Wave Driven Mixing. Poster at the AGU fall meeting, San Francisco, Dec. 2012.

Legg, S., J. M. Klymak, M. Nikurashin, M. C. Buijsman, A. V. Melet, R. Hallberg. Development of Parameterizations of Tidal Mixing Using Numerical Process Studies. Poster at the AGU fall meeting, San Francisco, Dec 2012.

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 (Princeton Professor)

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

Other Participating Researchers: Juan A. Bonachela (EEB, Princeton) Steve D. Allison and Adam C. Martiny (University of California, Irvine)

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-based 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:

During the last year, we have extended the one-nutrient uptake model for phytoplankton we developed in 2011 to include explicitly the uptake of nitrogen and phosphorus, two of the most important nutrients for phytoplankton. This new model accounts for the ratio of carbon, nitrogen and phosphorus, and how phytoplankton cells regulate their stoichiometry to acclimate to different environment. Our model focuses on protein regulation as main mechanism driving phytoplankton stoichiometry. The internal content on each nutrient influences the up-regulation or down-regulation of the synthesis of photosynthetic and nutrient uptake proteins. Protein regulation sets indirectly cell-level interaction between the nutrients, overlooked in other models or imposed through phenomenological expressions. This regulation establishes, in turn, the resource allocation strategies of the cells. Thus, we obtain a mechanistic model in which cell stoichiometry changes in reaction to changes in environmental conditions. As a result, our model shows uptake, growth and carbon:nitrogen:phosphorus ratios that behave into the expectations given by experimental work. Furthermore, our model offers insight on unclear aspects of phytoplankton stoichiometry. For instance, our model shows a wide range of opportunities for co-limitation by phosphorus and nitrogen, while in other approaches co-limitation only occurs under very specific environmental conditions. When organisms can potentially be limited by two nutrients, co-limitation has competitive advantages over single-limitation. Thus, our new approach links, as our 2011 model, protein regulation ability with competitive advantages. On the other hand, and again differently from other models, cells described by our approach cannot mimic the input ratio of nutrient fluxes in an unlimited way. The physiological ranges of the cell set the limits to that "homeostatic" strategy (i.e. growth rate close to the maximum, or internal content of the nutrient close to the maximum or minimum storage limits). This limitation can be important when describing, e.g. bloom events.

Concerning the second objective, our efforts have focused on providing a coherent ecological and evolutionary description of the phytoplankton-virus interactions. We first verified that the use of a simple, constant pool of viruses may produce biased results, as viral dynamics depend non-trivially on host quantity and quality (physiological state of the host). Furthermore, important aspects of the infection

cycle, such as infection probability, duration of the infection and offspring number, depend on environmental conditions, and need to be taken into account as well. Thus, we used simple phytoplankton growth models to assess the impact of including these ingredients into standard formulations of phytoplankton-virus interactions, at both ecological and evolutionary levels. We found that not only do these factors introduce a quantitative difference in the ecological time, but including or not these factors has important consequences on the evolutionary strategies of the virus.

Because these two studies offer a more realistic description of phytoplankton stoichiometry and virus top-down regulation, respectively, under different environmental conditions, they may improve significantly the biomass and community composition estimates of earth systems models (see Future Plans).

References:

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, 20633 (2011).

C. A. Klausmeier, E. Litchman, and S. A. Levin, Phytoplankton growth and stoichiometry under multiple nutrient limitation, Limnol. Oceanogr. 49, 1463–1470 (2004).

G. Bougaran, O. Bernard, and A. Sciandra, Modeling continuous cultures of microalgae colimited by nitrogen and phosphorus, J. Theor. Biol. 265, 443–454 (2010).

I. R. Elrifi and D. H. Turpin, Steady state luxury consumption and the concept of optimum nutrient ratios: a study with phosphate and nitrate limited Selenastrum minutum (Chlorophyta), J. Phycol. 21, 592–602 (1985).

Publications:

Bonachela, J. A., Allison, S. D., Martiny, A. C., and Levin, S. A.: A~model for variable phytoplankton stoichiometry based on cell protein regulation, Biogeosciences Discuss., 10, 3241-3279, doi:10.5194/bgd-10-3241-2013, 2013.

J. A. Bonachela and SA Levin, Equivalence of Models for Viral Infection in the Evolutionary Context, in preparation (2013).

Progress Report Title: **Sources of Springtime Ozone Pollution Events in the Western United States**

Principal Investigator: Meiyun Lin (Princeton Associate Research Scholar)

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

Other Participating Researchers: Arlene Fiore (Columbia University/Lamont), Owen Cooper (NOAA ESRL), Samuel Oltmans (University of Colorado/CIRES), Andy Landford (NOAA ESRL)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

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

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

Objectives: Estimating the contributions of Asian pollution and stratospheric intrusions to surface ozone over the western United States to support National Ambient Air Quality Standard setting, implementation, and attainment planning

Methods and Results/Accomplishments:

When setting the U.S. National Ambient Air Quality Standard (NAAQS) for ground-level ozone, background ozone estimates are needed to ensure that the standard is attainable with domestic emission controls. The Clean Air Act requires EPA to periodically review the scientific basis for these standards by preparing an Integrated Science Assessment (ISA). As the U.S. EPA is conducting the ozone ISA in preparation for the 2013 review, the two papers led by Dr. Meiyun Lin made significant discoveries that further our abilities to understand Asian and stratospheric influences on Western U.S. ozone air quality. Her findings, published in Journal of Geophysical Research this year, indicate that episodic contributions from Asian pollution and stratospheric intrusions may compromise the ability of the western United States to attain an ever-tightening national air quality standard for ground-level ozone.

To determine the extent to which Asian pollution and stratospheric ozone intrusions are affecting ozone air quality in the western U.S., Lin analyzed balloon soundings, aircraft, lidar, surface and satellite measurements from May through June 2010 using GFDL's new global high-resolution chemistry-climate model. *Lin et al. (2012a)* found that Asian pollution contributes as much as 20 percent of total ozone during springtime pollution episodes in western U.S. surface air. The current U.S. air-quality standard for ozone is 75 parts per billion. Lin and her coauthors found that about half of the times where that limit was exceeded would not have occurred without the contribution from Asian air pollution. Lin et al. (2012a) was included in Top Research Accomplishments of 2012 for NOAA OAR and featured in Science Now by Richard A. Kerr, a senior science writer, Nature News, AGU Research Spotlights, and NYT Green Blog. Dr. Lin was interviewed and quoted in major media reports.

In a second paper published this year, Lin found that stratospheric ozone intrusions can contribute as much as 50 percent to ground-level ozone in parts of the western United States and directly lead to episodes of high-ozone in excess of the health-based limit. Evidence is found for 13 of such events from April to June 2010, in notable contrast to prior work concluding that stratospheric influence in surface air is rare. Stratosphere-to-troposphere transport of ozone is a common occurrence at mid- and high latitudes, but its influence on tropospheric ozone levels remains a long-standing question despite decades of research. *Lin et al (2012b)* shows that the high-resolution GFDL AM3 model with fully coupled

stratospheric and tropospheric chemistry captures the observed layered features and sharp ozone gradients of deep stratospheric intrusions. This represents a major improvement over previous chemical transport models. *Lin et al. (2012b)* ranks second in JGR's Most Viewed Articles in October 2012, with nearly 300 downloads in two weeks. "The work of *Lin et al. [2012b]* is a major advance within the modeling framework in the ability to quantify the contributions to background ozone", said Dr. Samuel Oltmans, former chief of the Ozone and Water Vapor Group of the Global Monitoring Division at NOAA ESRL, in a public comment to EPA Clean Air Scientific Advisory Committee (CASAC) Ozone Review Panel.

Both papers Lin published in 2012 are cited in the third review draft of the ozone ISA. This ozone ISA presents a concise synthesis and evaluation of the most policy-relevant science and will ultimately provide the scientific bases for EPA's decision regarding the adequacy of the current national ambient air quality standards for ozone to protect human health, public welfare, and the environment.

In recognition of the major significance of Lin's work to the field, Lin was invited to speak at NOAA Senior Research Council, NOAA/ESRL Chemical Science Division Seminar, NASA Aura and Sounder Science Team Meetings, NOAA GFDL Science Symposium, Western Air Resources Council Western Ozone Transport Workshop, and California Air Quality Management District Seminar. She also delivered effective talks at national and international conferences, including Tropospheric Ozone Changes Workshop held in France, United Nations Task Force on Hemispheric Transport of Air Pollution Workshop, and AGU Fall Meetings.

Publications:

Fang, Y., A. M. Fiore, J.-F. Lamarque, L. W. Horowitz, and M. Lin (2013), Using synthetic tracers as a proxy for summertime PM2.5 air quality over the Northeastern United States in physical climate models, Geophys. Res. Lett., 40, doi:10.1002/grl.50162.

Naik, V., Voulgarakis, A., Fiore, A. M., Horowitz, L. W., Lamarque, J.-F., Lin, M., Prather, M. J., Young, P. J., Bergmann, D., Cameron-Smith, P. J., Cionni, I., Collins, W. J., Dalsøren, S. B., Doherty, R., Eyring, V., Faluvegi, G., Folberth, G. A., Josse, B., Lee, Y. H., MacKenzie, I. A., Nagashima, T., van Noije, T. P. C., Plummer, D. A., Righi, M., Rumbold, S. T., Skeie, R., Shindell, D. T., Stevenson, D. S., Strode, S., Sudo, K., Szopa, S., and Zeng, G.: Preindustrial to present day changes in tropospheric hydroxyl radical and methane lifetime from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP), Atmos. Chem. Phys. Discuss., 12, 30755-30804, doi:10.5194/acpd-12-30755-2012, 2012.

Lin M., A. M. Fiore , O. R. Cooper , L. W. Horowitz , A. O. Langford , Hiram Levy II , B. J. Johnson , V. Naik , S. J. Oltmans , C. Senff (2012): Springtime high surface ozone events over the western United States: Quantifying the role of stratospheric intrusions, J. of Geophys. Res., 117, D00V22, doi:10.1029/2012JD018151. (JGR Most Viewed Articles in October 2012)

Lin, M., A. M. Fiore, L. W. Horowitz, O. R. R. Cooper, V. Naik, J. S. Holloway, B. J. J. Johnson, A. M. Middlebrook, S. J. J. Oltmans, I. B. Pollack, T. B. Ryerson, J. Warner, C. Wiedinmyer, J. Wilson, and B. Wyman (2012), Transport of Asian ozone pollution into surface air over the western United States in spring, J. Geophys. Res., doi:10.1029/2011JD016961. (AGU Editors' Highlight, Featured in Science Now, Nature News, Top Research Accomplishments of 2012 for NOAA, NYT Green Blog and other public media).

Invited Talks and Presentations:

AGU Fall Meeting 2012, San Francisco, CA (Dec 2012) Developing space-based indicators of stratospheric influence on Western U.S. high surface ozone events.

NASA Sounder Science Team Meeting, Maryland (November, 2012) Improving predictability of surface high-O3 episodes from intercontinental transport and stratospheric intrusions: Exploration of AIRS Data (Invited).

Western States Air Resources Council: Western Ozone Transport, Nevada (October, 2012) Daily to decadal variability in sources of springtime surface ozone events over the western United States: stratospheric intrusions, Asian pollution, and fires (Invited).

NASA Aura Science Team Meeting, Pasadena (October, 2012) Identifying and forecasting deep stratospheric ozone intrusions over the western United States from space (Invited).

NASA Air Quality Applied Sciences Team (AQAST) Meeting 3, Univ. of Wisconsin (June 2012) Strong stratospheric influence on springtime surface high-O_3 events over the western United States in spring: Not-so-rare events?

California's South Coast Air Quality Management District Seminar, Ontario, CA (May 2012) Global sources of local ozone pollution in Southern California (Invited).

NOAA ESRL Chemical Science Division Seminar, Boulder, CO (May 2012) Background ozone over the United States in 1980-2010: origin, extremes, and long-term changes (Invited).

UN Task Force on Hemispheric Transport of Air Pollution: 2011-2015 Work Plan Meeting, Pasadena, CA (Feb. 2012) Transport of Asian ozone pollution into surface air over the western United States in spring.

Progress Report Title: **Development and Implementation of the Multi-canopy Land Surface Physics**

Principal Investigator: Sergey Malyshev (Princeton Professional Specialist)

CICS/GFDL Collaborator: Elena Shevliakova (Princeton)

Other Participating Researchers: Ensheng Weng (Princeton), Stephen W. Pacala (Princeton), Jeremy W. Lichstein (U. of Florida)

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 represent physical properties and interactions within complicated land surface, with multiple different kinds of vegetation co-existing in one place

Methods and Results/Accomplishments:

Current land surface schemes use simplified representation of the vegetation canopies, typically scaling leaf/canopy physiological processes up to ecosystem levels and reducing terrestrial ecosystems into few plant functional types based on the concept that global terrestrial vegetation cover is composed of discrete and distinct vegetation types and climate change will induce shifts of pre-defined vegetation types. To represent realistic evolution of ecosystems and carbon storage, one would need to account for processes within an ecosystem, such as competition between different species for available resources, such as light and water.

In present work, we are aiming to describe the establishment and evolution of unmanaged (e.g. natural) forests. To achieve that goal, it is necessary to represent the physical processes within a complicated vegetation structure, including size, age, and species distribution.

In our model, the vegetation is represented by a number of "cohorts." Each cohort is a set of individuals of certain species and age, of roughly the same size. The cohorts evolve in time as vegetation growth, or environmental conditions change. Cohorts arrange themselves in a set of layers, with tallest cohorts filling up the canopy space to get the preferential access to light, according to Perfect Plasticity Approximation (PPA) (Strigul et al, 2008). The short-wave radiation propagation through the canopy is calculated using two-stream approximation (Pinty et al., 2008), in the assumption of random overlap of cohorts in neighboring layers. The radiation scheme handles arbitrary number of layers with arbitrary number of cohorts distributed among them. It also allows for the gaps in the non-filled canopy layers, to properly describe self-shading of sparse vegetation in inhospitable regions or in the understories. The long-wave radiation is done similarly to short-wave, with additional consideration of each cohort's canopy as a thermal radiation source.

Each cohort's canopy has its own temperature, and amounts of intercepted water and snow. All cohorts exchange water, energy, and carbon dioxide with the common canopy air space. Each cohort interacts with soil moisture separately, where it competes for the available water with all other cohorts, depending on vertical distribution of roots and soil moisture.

This sophisticated physics treatment, as well as a preliminary version of the biological parameterizations, has been implemented in the framework of GFDL's Flexible Modeling System (FMS), as well as standalone code, suitable for use on workstations. My personal contribution was design,

development, and implementation of the model physics, including competition for light and water among plants. This is a long-term project that is expected to continue for several years. We are currently working on the publication of first results, focusing on establishing of an ecosystem in a certain location (Weng et al., in preparation). Some preliminary results are shown in the figures below.

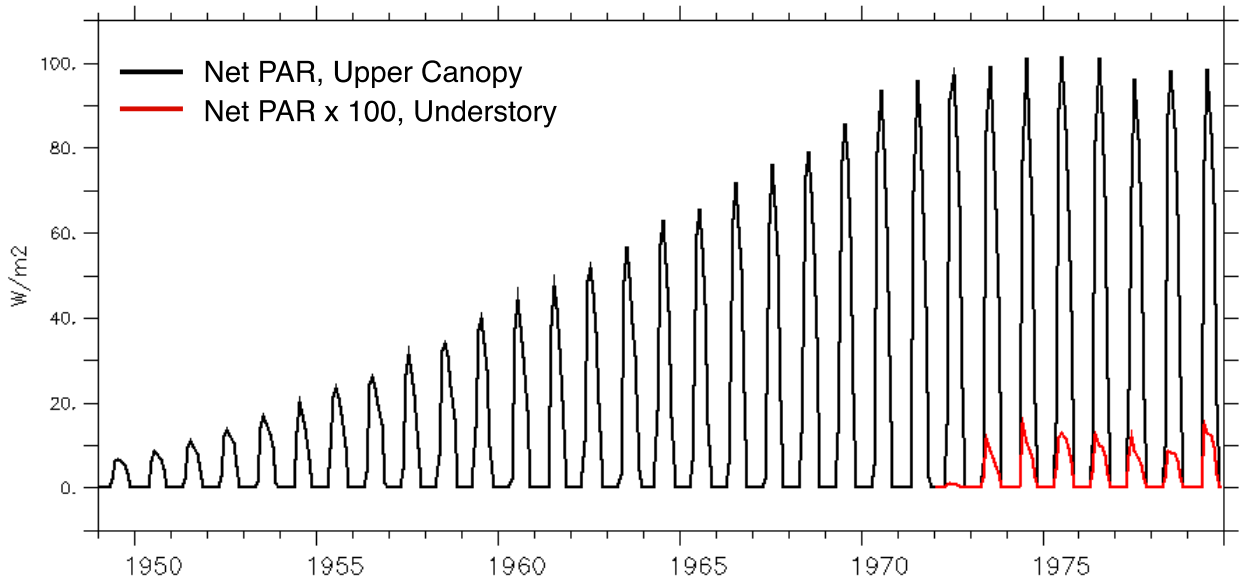

Figure 1. Net Photosynthetically-Active Radiation (PAR) in the upper canopy and the understory for the Willow Creek site (90.1W,45.8N), during the vegetation establishment period. Note that the understory values were multiplied by 100. The appearance of the red line marks the moment when the upper canopy closes; before that all the trees exist in the upper canopy and have roughly equal access to light; after that moment the shorter trees are at severe disadvantage in competition for light.

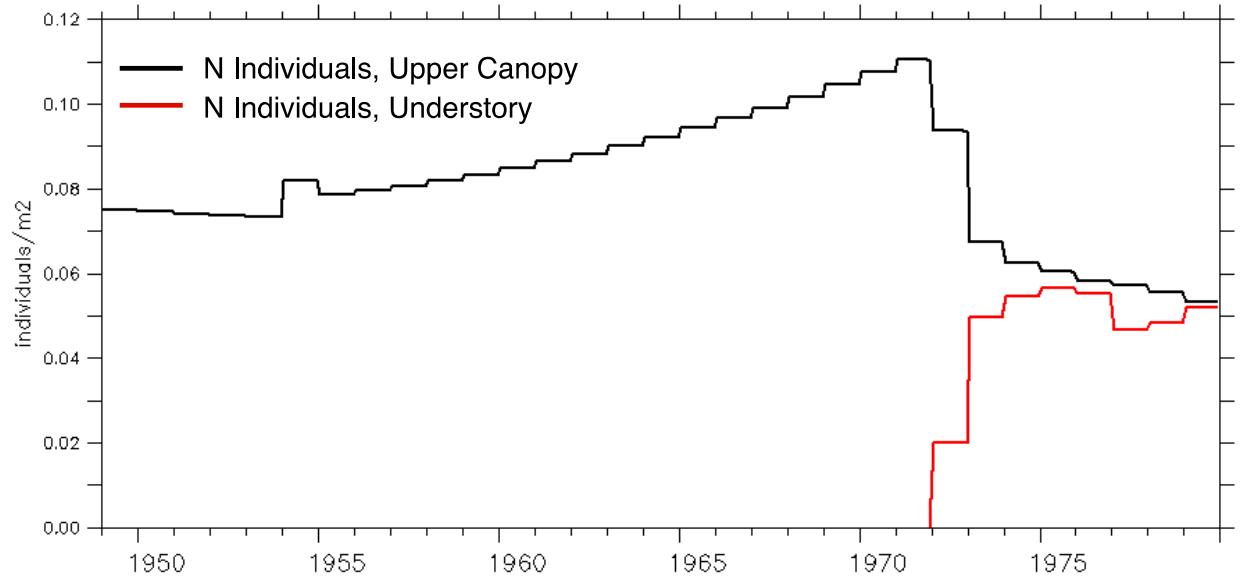

Figure 2. Same as in Figure 1, except shows the spatial density of plants (individuals/m2) in the upper canopy layer and in the understory. The local maximum in 1954 corresponds to the time when the initial plants become mature enough to procreate. The decline of upper canopy plant density in 1972 and after is due to transition of some canopy trees to the understory because of the taller trees overshadowing them as they increase their canopy area.

References:

Strigul, N., Pristinski, D., Dushoff, J., and Pacala, S. W. (2008): Scaling from trees to forests: Tractable macroscopic equations for forest dynamics. Ecological Monographs, 78, No.4, 523–545, doi:10.1890/08-0082.1.

Pinty, B., T. Lavergne, R. E. Dickinson, J.-L. Widlowski, N. Gobron, and M. M. Verstraete (2006): Simplifying the interaction of land surfaces with radiation for relating remote sensing products to climate models. Journal of Geophysical Research, 111, D02 116, doi:10.1029/2005JD005952.

Publications:

Ensheng Weng, Jeremy W. Lichstein, Sergey Malyshev, Elena Shevliakova, Stephen W. Pacala How forest community processes affect ecosystem C dynamics: A modeling analysis. In preparation.

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 proposed a new catalytic mechanism (Cu-Fe-HOx cycling) for heterogeneous chemistry. I have implemented a complete set of heterogeneous process into GFDL AM3 model. I also developed a state-of-the-art isoprene oxidation mechanism, which solves a long-standing ozone problem over eastern US. Our next step is to implement this isoprene oxidation mechanism into AM3, and use SENEX field campaign to validate this mechanism and better understand SOA formation.

Accomplishments: (1) We discovered a major and previously unrecognized role of aerosol in atmospheric oxidant chemistry, with the paper published on ACP. This mechanism has solved several long-standing problems in the global chemistry modeling community. It also shows great importance in radiative forcing, ocean iron fertilization and adverse human health effects. (2) Using AM3 model with this new heterogeneous chemistry, we published a paper in GRL on understanding the radiative forcing from biomass burning emissions. This paper reveals the warming effect from aerosols in contrast to the traditional cooling effects. (3) Published a paper on OH measurements over California forests. This paper largely reconciles the discrepancies between observed and modeled OH over forests, which has been under debate for five years. This paper becomes the most cited paper on ACP in 2012 (1 out of 738 papers). (4) Writing a paper on a new isoprene oxidation chemistry that solved the high ozone bias over eastern US, which is a long-standing problem in global chemistry modeling community. This chemistry is now implemented in AM3 for the upcoming field campaign (SENEX). (5) Submitted two proposals on organic nitrates (to NOAA) and aerosols (to EPA).

Publications:

J. Mao, et al. : Ozone and organic nitrates over the eastern United States: sensitivity to isoprene chemistry, 2013, to be submitted.

Ren, X, and Jingqiu Mao, et al., in press: Atmospheric Oxidation Chemistry and Ozone Production: Results from SHARP 2009 in Houston, Texas. Journal of Geophysical Research. doi:10.1002/jgrd.50342.

J. Mao, Horowitz, L., Naik V., Fan, S., Liu, J., and Fiore, A.: Sensitivity of tropospheric oxidants to biomass burning emissions: implications for radiative forcing, Geophys. Res. Lett, doi:10.1002/grl.50210, 2013.

J. Mao, Fan, S., Jacob, D. J., and Travis, K. R.: Radical loss in the atmosphere from Cu-Fe redox coupling in aerosols, Atmos. Chem. Phys., 13, 509-519, doi:10.5194/acp-13-509-2013, 2013.

J. Mao, Ren, X., Zhang, L., Van Duin, D. M., Cohen, R. C., Park, J.-H., Goldstein, A. H., Paulot, F., Beaver, M. R., Crounse, J. D., Wennberg, P. O., DiGangi, J. P., Henry, S. B., Keutsch, F. N., Park, C., Schade, G. W., Wolfe, G. M., Thornton, J. A., and Brune, W. H.: Insights into hydroxyl measurements and atmospheric oxidation in a California forest, Atmos. Chem. Phys., 12, 8009-8020, doi:10.5194/acp-12-8009-2012, 2012 (Most cited of ACP papers in 2012, of 738 papers).

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Olson, J. R., Crawford, J. H., Brune, W., Mao, J., Ren, X., Fried, A., Anderson, B., Apel, E., Beaver, M., Blake, D., Chen, G., Crounse, J., Dibb, J., Diskin, G., Hall, S. R., Huey, L. G., Knapp, D., Richter, D., Riemer, D., Clair, J. St., Ullmann, K., Walega, J., Weibring, P., Weinheimer, A., Wennberg, P., and Wisthaler, A.: An analysis of fast photochemistry over high northern latitudes during spring and summer using in-situ observations from ARCTAS and TOPSE, Atmos. Chem. Phys., 12, 6799-6825, doi:10.5194/acp-12-6799-2012, 2012.

Ren, X., Mao, J., Brune, W. H., Cantrell, C. A., Mauldin III, R. L., Hornbrook, R. S., Kosciuch, E., Olson, J. R., Crawford, J. H., Chen, G., and Singh, H. B.: Airborne intercomparison of HOx measurements using laser-induced fluorescence and chemical ionization mass spectrometry during ARCTAS, Atmos. Meas. Tech., 5, 2025-2037, doi:10.5194/amt-5-2025-2012, 2012 (link).

Marais, E. A., Jacob, D. J., Kurosu, T. P., Chance, K., Murphy, J. G., Reeves, C., Mills, G., Casadio, S., Millet, D. B., Barkley, M. P., Paulot, F., and Mao, J.: Isoprene emissions in Africa inferred from OMI observations of formaldehyde columns, Atmos. Chem. Phys., 12, 6219-6235, doi:10.5194/acp-12-6219-2012, 2012.

Fischer, E. V., D. J. Jacob, D. B. Millet, R. M. Yantosca, and J. Mao , The role of the ocean in the global atmospheric budget of acetone, Geophys. Res. Lett., 39, L01807, doi:10.1029/2011GL050086, 2012.

Presentations:

Measurement and modeling of aerosol Fe speciation, ACS meeting, Philadelphia, PA, 2012.

Radical loss in the atmosphere from Cu-Fe redox coupling in aerosols (Invited), AGU meeting, San Francisco, CA, 2012.

Radical loss in the atmosphere from Cu-Fe redox coupling in aerosols, IGAC meeting, Beijing, 2012.

GEOS-Chem biennial meeting, Cambridge, MA, 2011.

Progress Report Title: **Large-scale Variations in Forest Phenology and their Impacts on Surface Water, Energy, and Carbon Fluxes over North America**

Principal Investigator: David Medvigy (Princeton Assistant Professor)

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

Task III: Individual Projects

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: (1) Understand what climate drivers (temperature, day length, etc.) affect the seasonal expression of foliage ("phenology") in temperate deciduous forests (2) Develop models for spring and fall phenology in temperate deciduous forests (3) Understand phenology variations between species, and incorporate this into our model

Methods and Results/Accomplishments:

We have completed our analysis of spring phenology in temperate deciduous forests. We developed a new framework for understanding the macro-scale variations in spring phenology by using new data from the USA National Phenology Network. Changes in spring budburst for the U.S. were predicted by using Coupled Model Intercomparison Project phase 5 outputs. We found that macro-scale budburst simulations for the coming century indicate that projected warming leads to earlier budburst by up to 17 days. The latitudinal gradient of budburst becomes less pronounced due to spatially-varying sensitivity of budburst to climate change, even in the most conservative emissions scenarios. Currently existing inter-species differences in budburst date are predicted to become smaller, indicating the potential for secondary impacts at the ecosystem level. We expect that these climate-driven changes in phenology will have large effects on the carbon budget of U.S. This work was published in *Geophysical Research Letters*, and was highlighted in *Eos*, featured on New York Public Radio and Princeton Journal Watch, and recommended by Faculty of 1000.

We have completed an analysis of fall phenology, and have a manuscript in the final phases of preparation. We intend to submit this manuscript to *Global Change Biology* in March 2013. In this study, we used a new, ground-based, regional-scale dataset from the USA National Phenology Network to develop a predictive model for fall leaf coloring. We then used the model to perform hindcasting of leaf coloring dates in the U.S., Europe, and Asia from ca. 1940-2010. The timing of leaf coloring was explained by sums of cold temperature accumulation. Summation begins once a photoperiod threshold is passed, and leaf coloration occurs when cold temperature accumulation exceeds a given threshold. Compared to species with low shade tolerance, species with higher shade tolerance required a shorter photoperiod to initiate the cold temperature accumulation, but also required less cold temperature accumulation to trigger leaf coloring. The combined effects of photoperiod and temperature realistically explained variations of leaf coloring from local to continental scales. Hindcasting results for the U.S. and Europe showed clear multi-decadal variations in leaf coloring date that were strongly correlated with the Atlantic Multidecadal Oscillation (AMO) and atmospheric CO_2 concentrations. However, hindcasting results for East Asia showed correlations with CO_2 concentrations but not the AMO. These results highlight the importance of natural climate variability and its differential impacts on different continents

for leaf coloring dates. These results have implications for large-scale changes in terrestrial ecosystem dynamics related to climate change, including both natural variability and future global warming.

Publications:

Jeong, S.-J., D. Medvigy, E. Shevliakova, and S. Malyshev. Combined impact of natural climate variability and CO_2 concentrations on the fall leaf coloration of temperate deciduous trees. To be submitted to Global Change Biology in March 2013.

Jeong, S.-J., D. Medvigy, E. Shevliakova, and S. Malyshev, 2013. Predicting changes in temperate forest budburst using continental-scale observations and models. Geophys. Res. Lett., 40, doi:10.1029/2012GL054431.

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.

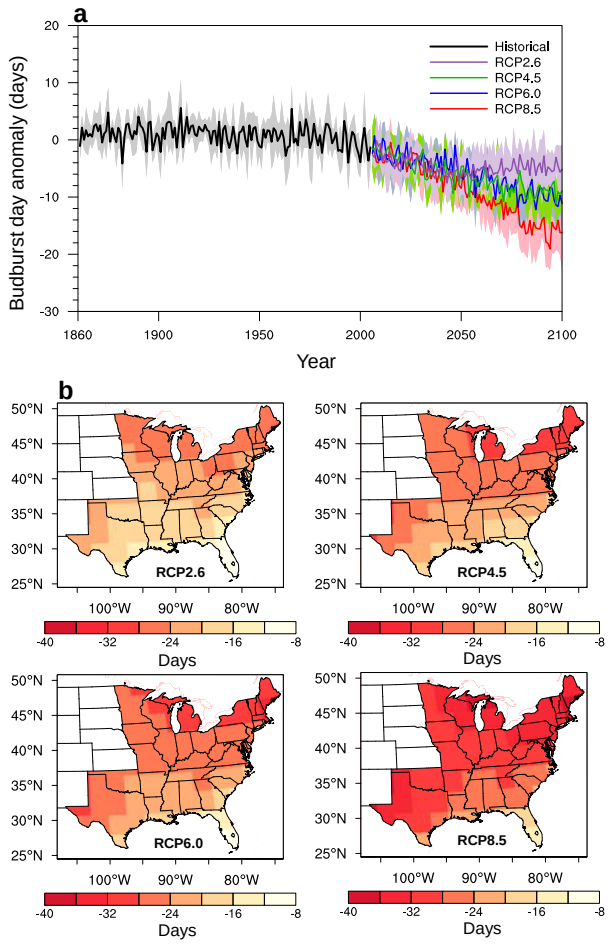

Figure: *Acer rubrum* (*Red maple*) budburst date anomalies relative to the 1980-1999 average: (a) Spatially-averaged budburst date anomaly for the eastern U.S. The solid line in the figure indicates the ensemble mean of 7 CMIP5 models, and the shading indicates the ensemble standard deviation. (b) Spatial patterns of budburst date anomaly for the 2080-2099 period. The different maps correspond to the indicated RCPs. The domain is based on the current distribution of *A. rubrum* from United States Department of Agriculture.

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), Maxim Nikurashin (UTAS)

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 only parameterize local internal-tide breaking, using the scheme of St Laurent et al. (2002).

In a first study, we examined the sensitivity of the ocean state to the vertical distribution of internal tide driven mixing. We compared two 1000-yr simulations of the CM2G model using the same formulation for internal-tide energy input at the bottom but two different vertical profiles of energy dissipation : the ad hoc vertical profile of St Laurent et al. and a new more physically-based parameterization with a state dependent profile (Polzin 2009). 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.

In a second study, we examined the impact of adding an additional source of energy into internal waves, related to lee wave generation by geostrophic flows over rough topography. We performed a series of sensitivity experiments using the CM2G model, including a parameterization of lee wave driven mixing in addition to the tidal mixing parameterization. We show that although the global energy input into lee waves is small compared to that of internal tides, lee wave driven mixing makes a significant impact on the ocean state, notably on the stratification and meridional overturning circulation. The different spatial distribution of the internal-tide and lee wave energy input impacts this sensitivity. These results suggest that lee wave driven mixing should be parameterized in climate models.

References:

The Climate Process Team on internal-wave driven mixing can be found at http://www-pord.ucsd.edu/~jen/cpt/CPT/Documents_files/cpt_proposal.pdf.

Polzin, K. L., 2009: An abyssal recipe. Ocean Modelling, 30 (4), 298 – 309.

St Laurent, L. C., H. L. Simmons, and S. R. Jayne, 2002: Estimating tidally driven mixing in the deep ocean. Geophysical Research Letters, 29 (23), 2106.

Publications:

Melet, A.; Hallberg, R.; Legg, S. and K. Polzin. "Sensitivity of the Ocean state to the vertical distribution of internal-tide driven mixing". Journal of Physical Oceanography, 43(3), 602–615, 2013.

Melet, A.; Hallberg, R.; Legg, S. and M. Nikurashin. "Sensitivity of the Ocean state to lee wave driven mixing". Submitted to the Journal of Physical Oceanography in March 2013.

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.

Melet, A.; Hallberg, R.; Legg, S. and M. Nikurashin. "Sensitivity of the Ocean State to Internal Lee Wave Driven Mixing". Poster at the AGU fall meeting, San Francisco, Dec. 2012.

Progress Report Title: **Regularity of Baroclinic Waves in the Martian and Terrestrial Atmospheres**

Principal Investigator: Todd Mooring (Princeton Graduate Student)

CICS/GFDL Collaborator: R. John Wilson (GFDL), Geoffrey K. 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: Understand why the baroclinic eddy activity in the atmosphere of Mars is much more regular than that of the Earth

Methods and Results/Accomplishments:

Observations of Martian surface meteorology by the Viking landers in the 1970s revealed that Mars possesses planetary-scale eddies that are much more regular than those found on the Earth (Ryan et al. 1978, Barnes 1980). Two main hypotheses have been suggested for the cause of this difference between the two planets: the Rossby deformation radius of the atmosphere is much larger relative to the planetary radius on Mars than it is on Earth (Leovy 1979), and the relatively stronger thermal damping of the Martian atmosphere (Barnes 1986).

Major advances in Martian atmospheric data, in the form of orbiter-based measurements enabling production of a reanalysis (Lewis et al. 2007), and advances in numerical modeling capabilities make the present a good time for further study of this issue. We are exploring wave regularity on Earth and Mars using diagnosis of reanalysis datasets and experiments with an idealized general circulation model. The reanalyses are intended to define the terrestrial and Martian eddy activity regimes and real-world values of potentially relevant parameters such as the static stability, while the idealized GCM provides a simplified framework within which the causes of the wave regularity may be better isolated.

We have developed a new method for quantifying wave regularity that can leverage four-dimensional fields from GCMs or reanalysis datasets, going beyond the essentially one-dimensional time series data provided by Viking. A meteorological field such as temperature is filtered to retain only the transient eddies, and then the field is decomposed into traveling waves using a space-time Fourier analysis. Each Fourier mode may be ascribed a particular fraction of the total variance in the field, from which it is possible to calculate the fraction of the variance that can be explained as a function of the number of modes used. We argue that the smaller the number of modes required to explain a given fraction of the variance in a field, the more regular it is. Application of this diagnostic to terrestrial and Martian reanalyses indicates that Mars is more regular, as expected. Preliminary results also indicate that the terrestrial southern hemisphere is more regular than the northern hemisphere.

Several experiments have been conducted with the idealized GCM, which uses Newtonian temperature relaxation forcing in the GFDL cubed sphere dynamical core. Success has been achieved in altering the degree of wave regularity via changes to the forcing, although more detailed analyses to identify why exactly the regularity changes remain in progress. Attempts are also underway to make more Mars-like circulations in the idealized GCM while retaining a relatively simple spatial structure of forcing.

References:

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C. B. Leovy. Martian meteorology. Ann. Rev. Astron. Astr., 17:387—413, 1979.

S. R. Lewis, P. L. Read, B. J. Conrath, J. C. Pearl, and M. D. Smith. Assimilation of thermal emission spectrometer atmospheric data during the Mars Global Surveyor aerobraking period. Icarus,192:327—347, 2007.

J. A. Ryan, R. M. Henry, S. L. Hess, C. B. Leovy, J. E. Tillman, and C. Walcek. Mars meteorology: three seasons at the surface. Geophys. Res. Lett., 5(8):715—719, 1978.

Publications:

T. A. Mooring, R. J. Wilson, and G. K. Vallis. Regularity of Baroclinic Waves in the Atmosphere of Mars. AGU Fall Meeting, San Francisco, Ca. (Oral Presentation, December 2012).

T. A. Mooring, R. J. Wilson, and G. K. Vallis, Regularity of Baroclinic Waves in the Terrestrial and Martian Atmospheres. Comparative Climatology of Terrestrial Planets, Boulder, Colo. (Poster Presentation, June 2012).

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 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, tornadoes are some of these extreme mesoscale events that could be associate 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, and present models do reasonable well describing the scale of these cyclones, and their associate 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 that 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 it is shown by IPCC models results due to global warming scenarios (shown in Fig 1*) . 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. A paper summarizing these results is being submitted for publication.

* The trend in the FAI has been graphically enhanced (black shadow) to separated from the different precipitation curves.

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 has 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 clear yet the physical process that 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 whether other studies point to the decrease of the stratospheric ozone as to be the main responsible.

We initiated recently a study that focus on the seasonal variability of the climate change. In the study we try to asses which source the stratospheric ozone or the ocean warming have 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 t_polar) or b) low level equatorial zonal temperature (850hPa, hereafter T_equator) explain the observed surface wind (10m) differences of the two eighteen year periods 1982-1999 minus 1964-1981. The results seem consistent between the reanalysis and the runs that include ozone depletion (runs Bens). The sharp stratospheric temperature decrease (T_polar) in the decades 1982-1999 explains better than the (T_equator), the observed changes in the surface wind for the period Oct-Mar (ONDJFM), where as the equatorial changes (T_equator) seems to explain the changes for most of the rest of the year. These results suggest of 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 will be submitted for publication.

Publications:

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.

Orlanski, Isidoro, April 2013: The effects of Polar Stratospheric and Equatorial Surface Temperatures on the Recent Changes of the Circulation in the Southern Hemisphere (submitted to Journal of Atmospheric Sc.).

To be submitted for publication:

Solman, S A., and Isidoro Orlanski, May 2013: Poleward shift and change of frontal activity in the Southern Hemisphere over the last 40 years (Journal of Atmospheric Sc.).

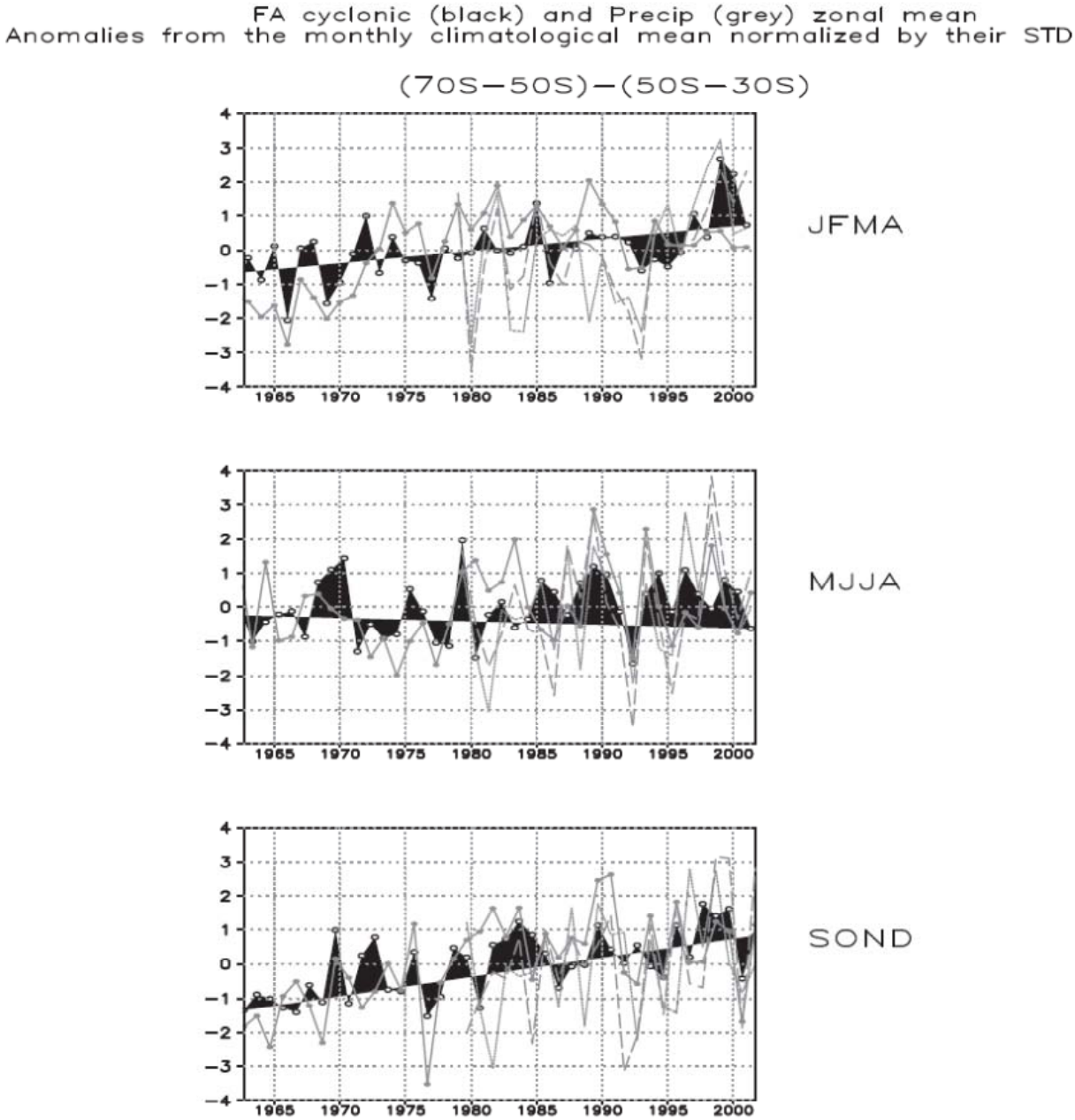

Figure 1: Time series of the difference of the zonal mean anomalies averaged over subpolar latitudes (70ºS to 50ºS) and over subtropical latitudes (50ºS to 30ºS) of Frontal Actvity (black lines) and precipitation (grey lines) normalized by their respective standard deviations. Top, middle and bottom rows correspond to seasonal means for JFMA, MJJA and SOND, respectively. Continuous, dotted and dashed lines correspond to ERA40, GPCP and ERA-Interim precipitation data, respectively.

Progress Report Title: **Aerosol Radiative Effects through the Lens of East Asian Solar Dimming**

Principal Investigator: Geeta Persad (Princeton Graduate Student)

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: The objective of this project is to understand the contribution of different features of the GFDL AM2.1 and AM3 models' aerosol treatment on the surface solar radiation and absorption values that the models produce. We analyze the models' recreation of trends in solar dimming over Southeast China as a framework for doing so.

Methods and Results/Accomplishments:

The top of atmosphere radiative forcing of aerosols is a major source of uncertainty in climate prediction. This work focuses on understanding the aerosol direct radiative effect through the lens of East Asian solar dimming in an effort to enhance our overall understanding of aerosol/radiation interactions. We make use of the fact that the top of atmosphere radiative impact of aerosols can be decomposed into surface and atmosphere components. Therefore, by constraining the surface and atmospheric radiative impact of aerosols, we may be able to constrain the top of atmosphere radiative impact of aerosols.

We analyze clear-sky solar dimming trends over East Asia in GFDL's AM2.1 and AM3 atmospheric general circulation models (AGCMs). We use attribution runs in the two AGCMs to isolate the impact of aerosols on the solar dimming trends, and analyze shortwave radiation variables output by the models to characterize the contribution to solar dimming from atmospheric absorption. We then use each model's standalone radiation code, which allows easy manipulation of various features of the aerosol treatment, to quantify the relative contribution of various aerosol characteristics to the aerosol/shortwave radiation interactions in the model.

Key findings from the AGCMs are that the two models have similar solar dimming trends, despite significantly different aerosol treatments, and that both models are strongly driven by aerosol absorption. By isolating various aerosol characteristics in the standalone radiation code, we are able to establish that a cancellation of effects between increased absorption caused by internal mixing of aerosols in AM3 and decreased absorption caused by smaller aerosol column burdens in AM3 largely drives the similarity between the two models (see figure). We also establish that hygroscopic growth can interact with the mixing state of the aerosol, such that the hygroscopic growth of internally mixed aerosols in AM3 produces significantly more absorption than the hygroscopic growth of externally mixed aerosols in AM2.1. We also establish that other aerosol characteristics, such as the seasonal distribution of the aerosol, have little effect on the annual mean absorption and surface solar radiation values.

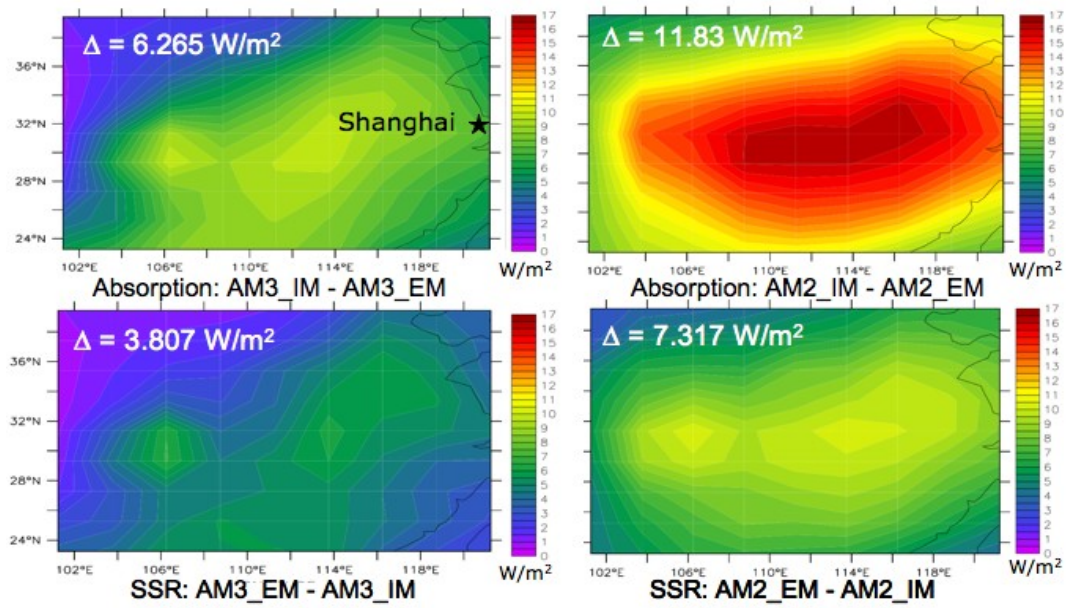

Figure: The change in absorption (top) and surface solar radiation (bottom) due to the presence of internal mixing in AM3 (left) and AM2.1 (right). Results demonstrate that stronger absorption and reduced surface solar radiation result from internal mixing, but that AM2.1's larger aerosol burden produces a stronger signal.

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Ramanathan, V., P. J. Crutzen, J. T. Kiehl, and D. Rosenfeld. Aerosols, Climate, and the Hydrological Cycle. Science 294, no. 5549 (December 7, 2001): 2119–2124. doi:10.1126/science.1064034.

Wild, Martin. Global Dimming and Brightening: A Review. Journal of Geophysical Research 114 (June 27, 2009). doi:10.1029/2008JD011470.

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Persad, Geeta, Yi Ming, and V Ramaswamy, April 2012: Tropical tropospheric-only responses to absorbing aerosols**.** Journal of Climate, 25(7)**,** doi:10.1175/JCLI-D-11-00122.1.

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Persad, G., Y. Ming, and V. Ramaswamy, 2012: Aerosol-driven Surface Solar Dimming Over Asia: Insights from a Model-Observation Intercomparison. 2013 American Geophysical Union Fall Meeting, San Francisco, CA.

Persad, G., Y. Ming, and V. Ramaswamy, 2013: Surface and atmospheric forcing by anthropogenic aerosols: Insights from a model-observation intercomparison. Fifth Symposium on Aerosol-Cloud-Climate Interactions at 93rd AMS Annual Meeting, Austin, TX.

Progress Report Title: **Cloud and Radiation Variability Associated with El Nino**

Principal Investigator: Claire Radley (Princeton Graduate Student)

CICS/GFDL Collaborator: Leo Donner (GFDL), Yi Ming (GFDL)

Other Participating Researchers: 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: Cloud feedbacks are known to be one of the largest sources of uncertainty in climate change predictions. If we are to decrease our cloud feedback uncertainty then we must obtain a greater understanding of the sensitivity of clouds to changing environmental conditions.

Methods and Results/Accomplishments:

Given that observations are not available to compare against climate change predictions, we must make use of natural, short term variability in the climate system. In this way we are able to force the atmosphere by perturbing sea surface temperatures and then evaluate how the model simulates changes in the top-of-atmosphere radiation budget, various cloud types and precipitation.

The El Niño Southern Oscillation (ENSO) is the dominant form of variability in the tropics. In this study we examine the response of the atmosphere, during El Niño events, in both observations and GFDL's atmosphere-only models: AM2, AM3 and HiRAM. Locally, both shortwave and longwave top-of-atmosphere (TOA) fluxes show strong correlation with ENSO, but in the tropical and global mean the correlation is strong only for the longwave. This implies strong cancellation of induced geographical shifts in cloud distributions. All models reasonably reproduce longwave TOA, but show large deficiencies for shortwave fluxes in the tropical/global average.

We show that there are strong biases in cloud amount in the models mean state, and that these translate linearly to biases in anomalies. The same scaling argument works for precipitation but not TOA radiation fluxes. The scaling argument also doesn't work when considering the tropical or global averages of anomalies. Surprisingly the tropical averages of cloud anomalies and cloud radiative forcing are very close to zero, which suggests that the clear sky anomaly dominates the overall TOA radiative signal.

Publications:

Cloud and Radiation Variability Associated with El Nino, presented at the Australian Meteorological and Oceanographic Society Meeting 2012, Melbourne, Australia.

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: Yonggang Liu and Christopher Little (Woodrow Wilson School, Princeton University), Daniel Goldberg (MIT)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: Improve understanding of the near future behavior of ice-sheets and their interaction with other components of the climate system. Specifically, improve understanding of ice-sheet/ocean interactions and physical processes and mechanisms controlling their variability on short (decadal to centennial) time scales.

Methods and Results/Accomplishments:

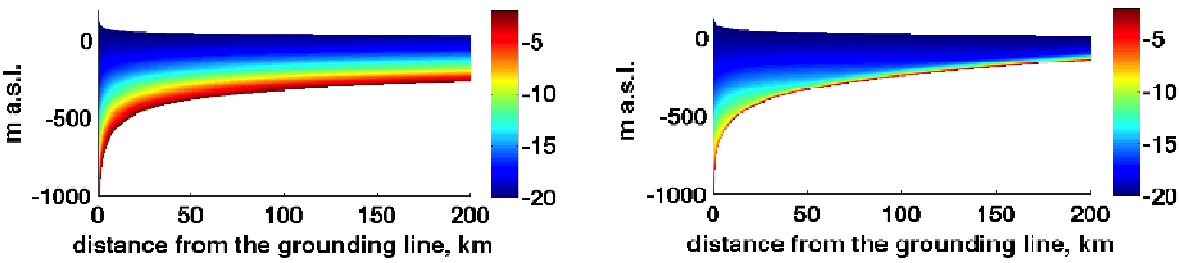
In collaboration with Christopher Little and Daniel Goldberg, the investigation of dynamics and thermodynamics of ice shelves floating in two distinct oceanic environments, one dominated by warm Circumpolar Deep Water (CDW) and the other one dominated by colder (~ 3°C) High Salinity Shelf Water (HSSW) have been carried out with a fully coupled ice-shelf/plume model. Complemented by a newly derived analytic expression for the steady-state temperature distribution in ice shelves, simulations of the coupled model revealed distinct steady states of ice shelves that are determined by the oceanic environments. Ice shelves afloat in CDW waters are significantly colder those floating in HSSW waters (Figure 1). It was found that the ice-shelf mass balance is determined by different processes: in the HSSW case, it is between ice advection and deformation, in the CDW case it is between ice advection and melting. Ice shelves floating in CDW are more sensitive to shallowing of the thermocline depth, and ice shelves floating in HSSW are more sensitive to warming the bottom water.

In addition to thermodynamic interaction, ice shelves interact with cavities underneath them mechanically. The normal modes have been computed for a coupled ice-shelf/sub-ice-shelf cavity system. These calculations show that higher normal modes of the coupled systems are less sensitive to the depth of the cavity and ocean in front of it, however, more sensitive to the ice-shelf parameters like flexural rigidity. This can explain why floating ice tongues have similar lengths despite floating into oceans with different bathymetry around Antarctica.

Spectacular disintegrations of Larsen B Ice Shelf in 2002 preceded by extensive surface melting of the ice shelf that was accompanied by formation of supraglacial lakes (ogives). Analysis of flexural stresses experienced by ice shelves after drainage of supraglacial lakes (ogives) shows that they are orders of magnitude larger than the background viscous stresses. Most likely, drainage of these lakes causes fracturing of the ice shelf at its base and development of basal crevasses that lead to ice-shelf disintegration.

Recent observations revealed presence of subglacial lakes under ice streams in Antarctica and supraglacial lakes on fast flowing parts of Greenland ice sheets. Though, these lakes seem unrelated, the analysis of ice dynamics coupled with sub- and supraglacial water flows shows that locations of these

lakes are determined by the same physical process: ice flow over bed with heterogeneous basal conditions -- either undulated bed topography or highly variable basal traction.



(a) HSSW (b) CDW

Figure 1. Ice-shelf temperature (^{o}C) of ice shelves floating in different oceanic environments: (a) High Salinity Shelf Water; (b) Circumpolar Deep Water.

Publications:

Refereed articles:

Goldberg D. N., C. M. Little, O. V. Sergienko, A. Gnanadesikan, R. Hallberg and M. Oppenheimer. 2012a. Investigation of land ice-ocean interaction with a fully coupled ice-ocean model, Part 1: Model description and behavior, J. Geophys. Res., 117, F02037, doi:10.1029/2011JF002246.

Goldberg C. M. Little, O. V. Sergienko, A. Gnanadesikan, R. Hallberg and M. Oppenheimer. 2012b. Investigation of land ice-ocean interaction with a fully coupled ice-ocean model, Sensitivity to external forcings, J. Geophys. Res., 117, F02038, doi:10.1029/2011JF002247.

MacAyeal D. R. and O. V. Sergienko 2013. The flexural dynamics of melting ice shelves. Annals of Glaciology. 54(63) p. 1-10 doi: 10.3189/2013AoG63A256.

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Sergienko O. V. 2013a. Glaciological twins: basally controlled subglacial and supraglacial lakes. Journal of Glaciology, Vol. 59, No. 213, p. 3-8 doi: 10.3189/2013JoG12J040.

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MacAyeal D. R. and O. V. Sergienko, 2012. Impacts of surface-water lakes and dolines on ice-shelf stability Abstract C42B-06 presented at 2012 Fall Meeting, AGU, San Francisco, Calif., 3-7 Dec. 2012.

Sergienko O. V. 2012. Ice shelves in cold and warm oceanic environments. Abstract presented at 2012 WAIS meeting Pack Forest Conference Center, Eatonville, WA, 19-22 Sept, 2012.

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Progress Report Title: **Land Carbon Dynamics and Climate Change**

Principal Investigator: Elena Shevliakova (Princeton Senior Climate Modeler)

CICS/GFDL Collaborator: Ronald Stouffer (GFDL), Sergey Malyshev (Princeton)

Other Participating Researchers: Steve Pacala (Princeton)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: To understand past and future role of land in the global carbon cycle and climate system

Methods and Results/Accomplishments:

During 2012, I participated in the development, evaluation, and analysis of the GFDL comprehensive Earth System Models ESM2M and ESM2G (Dunne et al 2012 a, b). Both ESMs use the same atmospheric component as the GFDL physical climate model CM2.1 with revised land, sea ice and iceberg components as well as terrestrial ecology and ocean biogeochemistry. For the ocean component, ESM2G uses Generalized Ocean Layer Dynamics (GOLD). The Land model version 3 (LM3) is used to simulate interactively the distribution of vegetation and its functioning, including carbon cycling among vegetation, soil and atmosphere. ESMs's resolution is ~2º for the atmosphere and land, approximately 1º for the ocean and sea ice, 24 vertical layers in the atmosphere, 50 vertical layers in the ocean, and 20 layers in the soil.

In collaboration with the GFDL and CMI scientists, I explored interactions between historic land use and increased atmospheric CO2 concentrations and their implications for the carbon cycle and climate (Shevliakova et al. 2013, in rev). The implications of the biospheric response for the 21st Century compatible emissions were assessed using an ensemble of the CMIP5 ESMs (Jones et al 2013). Additionally, I contributed to the analysis of biological (e.g. phenology Jeong et al (2012a,b), fire Magi et al (2012)) and physical processes (e.g. precipitation over Amazon Yin et al. 2012) in the CMIP5 climate models as well to the synthesis of land-water-energy interactions for the National Climate assessment (Hibbard et al, 2013).

Publications:

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J.P. Dunne, J. John, A. Adcroft, S. M Griffies, RW Hallberg, E. Shevliakova, R.J. Stouffer, W.F Cooke, K.A. Dunne, M.J. Harrison, J.P. Krasting, S. Malyshev, P.C.D. Milly, P. Phillipps, L.T. Sentman, B.L. Samuels, M.J. Spelman, M. Winton, A.T Wittenberg, and N. Zadeh, (2012a): "GFDL's ESM2 global

coupled climate-carbon Earth System Models Part I: Physical formulation and baseline simulation characteristics. Journal of Climate, 25(19), DOI:10.1175/JCLI-D-11-00560.1.

J.P. Dunne, J. John, E. Shevliakova, R.J. Stouffer, J.P. Krasting, S. Malyshev, P.C.D. Milly, L.T. Sentman, A. Adcroft, W.F. Cooke, K.A. Dunne, S.M. Griffies, R.W. Hallberg, M.J. Harrison, H. Levy II, A.T. Wittenberg, P. Phillipps, and N. Zadeh, (2012b): "GFDL's ESM2 global coupled climate-carbon Earth System Models Part II: Carbon system formulation and baseline simulation characteristics". Journal of Climate. DOI:10.1175/JCLI-D-12-00150.1. 10/12.

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K. Hibbard, T. Wilson, K. Averyt, R. Harriss, R. Newmark, S. Rose, E. Shevliakova, V. Tidwell (2013, under public review), Chapter 10, "Water, Energy, and Land Use", The National Climate Assessment Report", http://www.globalchange.gov/what-we-do/assessment.

Progress Report Title: **Predicting the Impacts of Climate Change on Mesopelagic Ecosystems: Particle Remineralization in the Mesopelagic Zone**

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

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

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-based Management

Objectives: The goal of this project is to develop a model that incorporates biological processes to predict carbon flux in the mesopelagic zone and determine the influence of heterotrophic bacteria on nutrient distribution patterns in the deep ocean.

Methods and Results/Accomplishments:

The presence of signal molecules within sinking organic particles in the ocean suggests that bacterial quorum sensing plays a role in the remineralization of organic nutrients (Hmelo et al. 2011). Quorum sensing is used to coordinate behavior including production of exoenzymes which are used by heterotrophic bacteria to efficiently strip edible hydrolysate from particles. However, loss of exoenzymes and hydrolysate from particles due to diffusion and advection can be energetically costly for bacteria. I developed a mathematical model that incorporates both physical and biological processes to demonstrate that quorum sensing is necessary for using exoenzymes to fuel rapid bacterial growth on sinking particles. Incorporation of quorum sensing in the model was key for reproducing observed vertical attenuation of organic carbon flux, a result which suggests that remineralization rates used in earth system models are too slow in the upper mesopelagic zone when quorum sensing occurs.

The mathematical model explicitly depicts the interactions between sinking particles and heterotrophic bacteria using 9 state variables, particulate organic carbon as well as bacteria, active exoenzyme, inactive exoenzyme, and hydrolysate associated with two physical environments, dissolved and particulate. The model has a vertical range from the upper mesopelagic zone to the ocean bottom. The model is forced with particle flux and also requires vertical profiles of temperature, salinity, density, and dissolved organic carbon.

References:

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Martin, J., Knauer, G., Karl, D., and Broenkow, W. (1987). Vertex - carbon cycling in the northeast pacific. Deep-Sea Research Part A-Oceanographic Research Papers, 34(2):267–285.

Publications:

Smith, K. A., Stock, C. A., Dunne, J. P., and Sarmiento, J. L. (Feb., 2013) Modeling bacteria-particle processes in the dark ocean. Oral Presentation, ASLO Aquatic Sciences Meeting, New Orleans, LA, USA.

Smith, K. A., Stock, C. A., Dunne, J. P., and Sarmiento, J. L. (July, 2012) An ecophysiological model of particle remineralization in the deep ocean. Poster Presentation. Ocean Carbon & Biogeochemistry Summer Science Workshop, Woods Hole, MA, USA.

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), Sarah Kapnick (Princeton)

Other Participating Researchers: June Yeung, Dan Wright, Brianne Smith, Maofeng Liu, Ping Lu, Gabriele Villarini, and Mary Lynn Baeck, (Princeton), Long Yang (Visiting Graduate Student, Tsinghua)

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 (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 and heavy rainfall from mesoscale convective systems.

Methods and Results/Accomplishments:

Urbanization and heavy rainfall have been examined through numerical modeling studies and empirical studies based on high-resolution radar rainfall data sets for the New York - New Jersey metropolitan region (Yeung et al. [2013 a and b]), the Milwaukee metropolitan region (Yang et al. [2013 a and b], the Baltimore metropolitan region (Li et al. [2013]) and the Charlotte metropolitan region (Wright et al. [2013 a - c]). In Yeung et al. [2013b], Lagrangian analyses of simulated storms (based on 3-D reflectivity fields) are introduced as tools for examining organized thunderstorms. Intercomparisons of model simulations based on "simple" microphysical schemes (single moment) are shown to perform as well as simulations based on more sophisticated microphysical schemes (double moment) in terms of storm intensity (represented by maximum reflectivity and echo top height). These methods provide a useful new avenue for examining organized convective systems and assessing the performance of regional climate models in simulating clouds and precipitation. Model and observational studies of severe thunderstorm systems for the New York City metropolitan area (Yeung et al. [2013a]) highlight the influence of mountainous terrain to the west and land-water boundaries to the east on storm structure and evolution of these storm systems and demonstrate pronounced spatial heterogeneities of rainfall associated with urbanization. Analyses do not indicate that storm splitting around the urban region is a significant feature of severe thunderstorm systems (as has been shown for weaker storm systems in previous studies). Modeling studies and empirical analyses for Milwaukee (Yang et al. [2013 a and b) have focused on the combined effects of urbanization and land water boundaries. It is shown in Yang et al. [2013 a and b] that flash flood producing storms in Milwaukee have striking spatial structure and that UHI/Lake breeze circulation plays a central role in this important feature of regional rainfall climatology. Simulation studies in Li et al. [2013] are used to examine the relative importance of land surface

processes and microphysical processes for heavy convective rainfall over the Baltimore metropolitan region.

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. During the past year, we have completed similar analyses for the Charlotte metropolitan region (Wright et al. [2013a], expanded the Charlotte analyses to characterizations of the climatology of extreme rainfall and assessed the role of urban-induced spatial heterogeneities of rainfall in Baltimore on the climatology of urban flash flooding (B. K. Smith et al. [2013]). Analyses for Baltimore, Atlanta, Milwaukee and Charlotte highlight pronounced spatial heterogeneities in warm season rainfall over the urban areas and suggest possible physical mechanisms at play.

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. 2013). Hydroclimatological analyses show that clustering of heavy rainfall events is an important element of regional flood hazards (Villarini et al. [2013 a and b]). In Villarini et al. [2013b], increasing trends in heavy rainfall are documented for the upper tier of the central US. 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.

Analyses of tropical cyclones have continued in collaboration with the Hurricane Research Group at GFDL. During the preceding year, we have collaborated with Tim Marchok on simulation studies of Hurricanes Irene (2011) and Sandy (2012). We have carried out WRF simulations of Sandy and Irene using the GFDL ensembles for initial conditions. Analyses of the simulations focus on sensitivity of landfalling hurricane properties (rainfall, wind, and storm surge) to atmospheric water vapor and hurricane intensity. We have also implemented the cyclone phase space algorithms of Bob Hart to examine extratropical transition of Irene and Sandy. We will continue these analyses next year (see future plans). We have also initiated analyses of extratopical transition of Atlantic Basin hurricanes based on CM2.5 simulations. This work is being carried out in direct collaboration with Gabe Vecchi and Sarah Kapnick. This work will also continue in the coming year.

Publications:

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Smith, B. K. J. A. Smith, M. L. Baeck, G. Villarini, and D. B. Wright, The spectrum of storm event hydrologic response in urban watersheds, Water Resources Research, in review, 2013.

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.

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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, 33(3), 629-640, 2013a.

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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, 2012.

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Yeung, J. K., J. A. Smith, M. L. Baeck and E. Bou-Zeid, Lagrangian analyses of severe convective storms in the northeastern US: modeling and observational analyses, Atmospheric Research, in review, 2013a.

Yeung, J. K., J. A. Smith, M. L. Baeck and G. Villarini, Lagrangian analyses of rainfall structure and evolution for organized thunderstorms in the urban corridor of the northeastern US, Water Resources Research, in review, 2013b.

Progress Report Title: **The Nordic Seas Overflows and their Influences on Climate**

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 variability of the Nordic Seas overflows and their influences on AMOC and climate

Methods and Results/Accomplishments:

The Nordic Seas overflows, consisting of Denmark Strait (DS) and the Iceland-Scotland (IS) Channels overflows, are important components of the Atlantic Meridional Overturning Circulation (AMOC). Their variability as well as the transformation downstream has a potential importance on the AMOC. Currently representations of the overflows in climate models are crude compared with the observation and are different across the models. Two sets of climate models (CM2M and CM2G) from GFDL are used in IPCC AR5. However, there are some differences in their overflows, which provide differences in their climatology as well as variability.

Two major differences were pointed out in previous analysis on the control runs. 1) The Iceland-Scotland (IS) Channels overflows are not resolved by CM2M due to grid settings, while in CM2G there is a strong transport of dense water through these channels. 2) The numerical mixing in CM2M is strong which influences the overflow water properties and makes them inseparable from the dense water formed in the Labrador Sea. In CM2G, however, the diapycnal mixing is much smaller and there is a clear separation between the overflow water and the Labrador Sea water, and the two water masses are anti-correlated.

Perturbation experiments focused on these two differences are done using CM2G. In the first set of experiments, the pathway through IS channels are blocked mimicking the configuration in CM2M. Results show a reduction in the overflow transport but increasing entrainment, which makes the product water transport in AMOC unchanged. Also, the surface flow pattern is changed due to the shift of the entrainment region, making the model more CM2M-like. In the second set of experiments, the diffusivity downstream of the overflows is increased by increasing tidal energy. Results show that the two water masses are mixed together as in CM2M, as well as some changes in deep transport pathways and surface properties.

Progress Report Title: **Ocean Heat and Carbon Uptake under Global Warming**

Principal Investigator: Yu Zhang (Princeton Associate Research Scholar)

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 explore ocean responses to climate warming and their effects on ocean heat and carbon uptake

Methods and Results/Accomplishments:

Ocean heat uptake is explored with non-eddying (2 degree), eddy-permitting (0.25 degree) and eddy-resolving (0.125 degree) ocean circulation models in a domain crudely representing the Atlantic basin connected to a southern circumpolar channel. The model is forced with a wind stress and a restoring condition for surface temperature, both being constant (in time) in the control climate (CTL). When the restore temperature is instantly enhanced regionally, two distinct processes are found relevant for the ensuing heat uptake: heat uptake into the ventilated thermocline forced by Ekman pumping and heat absorption in the deep ocean through meridional overturning circulation (MOC). Temperature increase in thermocline occurs on the decadal timescale whereas, over most of the abyss, it is the millennial time scale that is relevant, and the strength of MOC in the channel matters for the intensity of heat uptake. Under global, uniform warming, the rate of increase of total heat content increases with both diapycnal diffusivity and strengthening southern ocean westerlies.

In models with different resolutions, ocean responses to uniform warming share similar patterns but do have important differences. The transfer by mesoscale eddies is insufficiently resolved in the eddy-permitting model, causing steep isopycnals in the channel and weak lower MOC, and this in turn leads to a weaker heat uptake in the abyssal ocean in the eddy-resolving model. Also, the reduction of the northern-hemisphere meridional heat flux (that occurs in a warmer world because of a weakening of MOC) increases with model resolution. Consequently, the cooling tendency near the polar edge of the subtropical gyre is most significant in the eddy-resolving model. Results of this project were submitted to Journal of Physical Oceanography.

An ongoing project is the investigation of heat and carbon uptake in a coupled model consisting of a 1-D energy balance atmospheric model and a fully stratified 3-D ocean circulation model. The model also contains a biogeochemistry package, simulating biogeochemical cycles of tracers including DIC, PO4, O2, etc. Ocean and atmospheric CO2 are linked through air-sea exchange, whereas atmospheric CO2 concentration is also affected by CO2 emissions. It was suggested, by some recent studies, that the century-scale global mean temperature response to CO2 emission is independent of the emission pathway (Eby et al., 2009). By examining ocean responses to two idealized CO2 emission scenarios with the same amount of the total cumulative CO2 emissions, i.e., a pulse emission event and a continuous emission path lasted over time t (in unit of years) and followed by a complete cessation, we found the pulse emission experiment is very instructive. Ocean circulation response after the complete emission of CO2

in the second scenario is lagged behind that in the pulse emission experiment with a time lag around t. In other words, the pulse emission experiment 'foresees' the ocean responses to various emission paths with identical total cumulative CO2 emissions.

References:

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Publications:

Zhang, Y., G. K. Vallis, (2013), Ocean heat uptake in eddying and non-eddying ocean circulation models. Submitted to J. Phys. Oceanogr.

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)

Other Participating Researchers: Steve Garner (GFDL) , Geoff Vallis (Princeton), 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: Parameter study of tropical cyclones in rotating radiative-convective equilibrium with mesoscale resolution

Methods and Results/Accomplishments:

Rotating radiative-convective equilibrium is studied by extracting the column physics of a meso-scale resolution global atmospheric model that simulates realistic hurricane frequency statistics (Zhao et al. 2009)and coupling it to rotating hydrostatic dynamics in doubly-periodic domains (Held and Zhao 2008). The results help in understanding the tropical cyclones simulated in the global model. The parameter sensitivities also provide a reference point for analogous future studies with cloud resolving models.

The sensitivity of the equilibrium achieved in a large square domain (2x104km on a side) to sea surface temperature (SST), ambient rotation rate and surface drag coefficient is examined. In such a large domain, multiple tropical cyclones exist simultaneously. The number, size and intensity of these tropical cyclones are investigated. The number of tropical cyclones increases with ambient rotation rate and decreases with SST and surface drag coefficient. The average intensity of tropical cyclones increases with SST and decreases with ambient rotation rate and surface drag coefficient. Potential intensity theory captures the sensitivity to SST and ambient rotation rate with reasonable accuracy but shows an over-strong sensitivity to surface drag coefficient. The mean radius of maximum surface wind, although poorly resolved, increases with SST, decreases with surface drag coefficient and increases with ambient rotation rate f for small f (but saturates or possibly reverses as f is increased further).

Two model parameters, one in the convection closure scheme and one related to sub-grid scale horizontal mixing in the dynamical core, are also perturbed, and the behavior in this idealized configuration is broadly consistent with that in the global model (Zhao et al. 2012).

The variation of rotating radiative-convective equilibrium with domain size is also studied. As domain size increases, the equilibrium evolves through four regimes: a single tropical depression, a transition regime in which a single storm intermittently develops, a single sustained storm, and finally multiple storms. The sustained storm regime shifts towards larger domain size as SST increases or f decreases.

References:

Zhao, M., I. M. Held, and S.-J. Lin, 2012: Some counterintuitive dependencies of tropical cyclone frequency on parameters in a GCM. Journal of the Atmospheric Sciences, 69 (7), 2272-2283.

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:

Earth System Model Applications

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

Principal Investigator: Claudie Beaulieu (Princeton Associate Research Scholar)

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

Other Participating Researchers: Elena Shevliakova (Princeton), David Medvigy (Princeton), Wolfgang Buermann (UCLA)

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 conclude our analysis of the shift in the mean land carbon sink that seemed to occur in 1988 by looking at land-atmosphere fluxes from observational data sets and model outputs

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 the late 1980's (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 ocean uptake estimated from several ocean models runs. 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 identifying independently regions/ecosystems in which carbon uptake is consistent with the timing and magnitude of the abrupt increase detected in our previous studies (Sarmiento et al., 2010; Beaulieu et al., 2012). In collaboration with researchers at UCLA, NASA and Princeton, a suite of simulations of primary productivity from the terrestrial biogeochemical model CASA and Upscaled FluxNet data were analyzed. Results show that globally, the net primary productivity (NPP) significantly increased of about 1 Pg C/yr after 1989. The gross primary productivity (GPP) also significantly increased of approximately 2 Pg C/yr at the same time. These estimates are consistent with the shift in net land carbon uptake detected in previous work. Three key regions seem to be contributing to the abrupt increase in productivity in the late 1980s: Northern Eurasia, Tropical Africa and Tropical South America (see Figure 1). Additional analysis performed on the meteorological forcing dataset of Sheffield et al. (2006) revealed that these changes may be climate-constrained. More specifically, our results show that the productivity changes observed in the three regions seem influenced by different climatic factors: a) warming in Northern Eurasia (from late 1980s onwards), b) increased precipitation in Tropical Africa (from late 1980s/early 1990s onwards) and c) increased solar radiation over Tropical South America (from mid-1990s onwards). Additional CASA simulations are being analyzed to study sensitivity of the results to different forcing data sets. Analysis performed on a historical simulation from the LM3V model shows similar NPP patterns, although the increase seems more gradual.

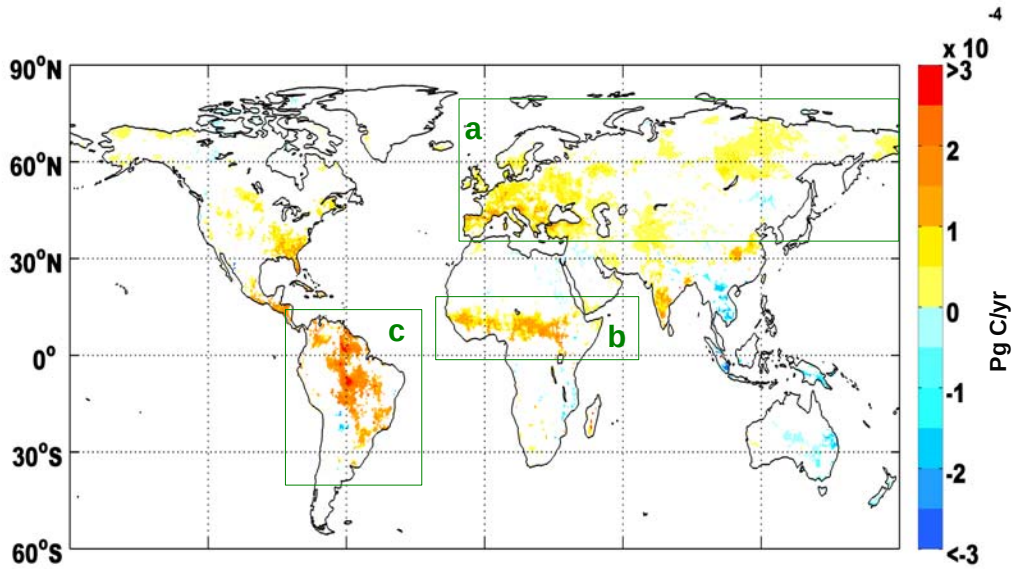


FIGURE 1: NPP differences between 1990-2008 and 1982-1989. The NPP is estimated using the terrestrial biogeochemical model CASA. Only significant differences are shown (t-test, 5% critical level). The green rectangles are highlighting three regions exhibiting a very strong signal: a) Northern Eurasia, b) Tropical Africa and c) Tropical South America.

References:

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

Sarmiento, J.L., Gloor, M., Gruber, N., Beaulieu, C., Jacobson, A.R., Fletcher, S.M., Pacala, S., Rodgers, K. (2010) Trends and regional distributions of land and ocean carbon sinks. Biogeosciences, 7, 2351-2367.

Publications:

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.

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. Naik (GFDL), D. Schwarzkopf (GFDL), V. Ramaswamy (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 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:

The role of land-surface processes in modulating the Indian monsoon annual cycle: This study (Bollasina and Ming 2012) makes use of a state-of-the-art atmospheric general circulation model, the Geophysical Fluid Dynamics Laboratory AM3, to conduct "perpetual" experiments aimed at providing new insights into the role of regional land-atmosphere processes in modulating the annual cycle of precipitation over India. The simulations, each several hundred days long, are carried out at three different stages of the annual cycle: March (the transition from wintery to pre-monsoon conditions), May (just before the monsoon onset), and July (when the monsoon is fully developed). Insolation and SSTs are held fixed at their respective monthly mean values in each experiment and, thus, there is no external time-varying forcing on the system. It is found that in the perpetual May case both precipitation and circulation are able to considerably evolve only by internal land-atmosphere processes and the mediation of soil hydrology. A large-scale equilibrium state is reached after approximately 270 days, closely resembling mid-summer climatological conditions. As a result, despite the absence of external forcing, intense and widespread monsoon rains over India are able to develop in the May-like state, highlighting the important role of land-atmosphere processes in driving the monsoon northwestward progression. These findings indicate that the land-atmosphere system, and namely the slow interaction between soil moisture and circulation, acts to delay the onset by about a month in the actual climate system, which is pivotal for the existence of desert regions to the west. Additionally, these results suggest that the land-atmosphere system in May is far from being in equilibrium with the external forcing in the actual system. The northwestward inland propagation of the precipitation front comprises a succession of 35-50 day coupled oscillations between soil moisture, precipitation, and circulation. The oscillatory regime is self-sustained and entirely due to the internal dynamics of the system. In contrast to the May case, minor changes in the precipitation regime are found when the model is initialized in early spring or mid-summer.

Long-term Advancement of the Indian Monsoon Onset: the Role of Anthropogenic Aerosols: In this study (Bollasina et al. 2013a) we investigated the impact of increased anthropogenic aerosols during the second half of the 20th century on the onset and early development of the monsoon over the Indian subcontinent by means of historical experiments with the GFDL climate model (CM3). The model has fully-interactive aerosols and chemistry, and a representation of both direct and indirect effects. We find

that aerosols may be responsible for the observed advancement of the monsoon onset over India, leading to enhanced precipitation in June over most parts of the country. Our experiments show that the earlier onset is preceded in spring by strong aerosol forcing over the Bay of Bengal and Indonesia, mostly attributable to the aerosol direct effect on radiation and the resulting increase in atmospheric stability, preventing the monsoon front from advancing toward the continent in May. The induced circulation anomalies lead to thermodynamical changes over the northwestern part of the Indian subcontinent in late May and June, including enhanced surface heating and increased near-surface moist static energy over the western semi-arid areas. As a result of this perturbation, and favored by a relative warming of sea surface temperature in the Bay of Bengal, the induced circulation anomaly reinforces the June climatological pattern, and precipitation substantially moves northwestward. These findings underscore the importance of aerosol-induced dynamical feedbacks and of regional land-surface processes for understanding the aerosol impact on the Indian monsoon.

Impact of Indian and non-Indian Anthropogenic Aerosols on the late 20th century weakening of the South Asian monsoon: A series of CM3 historical experiments has been carried out to investigate the relative role of aerosols from Indian and non-Indian sources on the long-term monsoon variations (Bollasina et al. 2013b). We show that most of the precipitation reduction over South Asia is generated by regional emissions of aerosols, especially in the early and mature monsoon season. Non-Indian aerosols also contribute during the later part of summer. Interestingly, the importance of non-Indian aerosols increases when regional temperature changes are considered. The mechanisms by which the two different aerosols sources affect the monsoon are examined.

Publications:

Bollasina, M., and Y. Ming, 2012: The role of land-surface processes in modulating the Indian monsoon annual cycle. Climate Dyn., doi:10.1007/s00382-012-1634-3.

Bollasina, Massimo, and Yi Ming, February 2013: The general circulation model precipitation bias over the southwestern equatorial Indian Ocean and its implications for simulating the South Asian monsoon**.** Climate Dynamics, 40(3-4), doi:10.1007/s00382-012-1347-7.

Bollasina, M., Y. Ming, and V. Ramaswamy, 2013: Long-term Advancement of the Indian Monsoon Onset: the Role of Anthropogenic Aerosols. To be submitted to Geophys. Res. Lett. (April 2013).

Bollasina, M., Y. Ming, D. Schwarzkopf, V. Naik, and V. Ramaswamy, 2013: Impact of Indian and non-Indian anthropogenic aerosols on the late 20th century weakening of the South Asian monsoon. To be submitted to Geophys. Res. Lett. (June 2013).

Presentations:

Mechanisms and physical processes underpinning regional hydroclimate variability and change: the paradigm of the South Asian monsoon (and beyond), School of Geosciences, University of Edinburgh, UK, 5 March 2013 (Invited).

Mechanisms and physical processes underpinning regional hydroclimate variability and change: the paradigm of the South Asian monsoon (and beyond), Department of Earth and Environmental Sciences, University of Michigan, 15 February 2013 (Invited).

Mechanisms and physical processes underpinning regional hydroclimate variability and change: the paradigm of the South Asian monsoon (and beyond), Department of Physics, University of Oxford, UK, 7 February 2013 (Invited).

Mechanisms and physical processes underpinning regional hydroclimate variability and change: the paradigm of the South Asian monsoon (and beyond), Department of Meteorology, University of Reading, UK, 31 January 2013 (Invited).

Mechanisms and physical processes underpinning regional hydroclimate variability and change: the paradigm of the South Asian monsoon (and beyond), Department of Atmospheric and Oceanic Sciences, McGill University, Canada, 25 January 2013 (Invited).

Anthropogenically-forced variability of the South Asian summer monsoon, SEAS Colloquium in Climate Science, Department of Applied Physics and Applied Mathematics, Columbia University, NY, 13 September 2012 (Invited).

The South Asian summer monsoon: an ideal test bed for investigating physical processes and feedbacks in the climate system, Department of Earth, Atmospheric, and Planetary Science, Purdue University, West Lafayette, 10 September 2012 (Invited).

The South Asian summer monsoon: an ideal test-bed for exploring (observed/simulated) physical processes in the climate system, Department of Earth System Science, University of California, Irvine, 15 May 2012 (Invited).

Multi-faceted forced variability of the South Asian summer monsoon, Department of Atmospheric and Oceanic Science, University of Maryland College Park, 10 May 2012 (Invited).

Asian monsoon in AM3, Joint GFDL-NCAR Atmospheric Modeling Meeting, Princeton, 4 May 2012.

Progress Report Title: **Ocean Heat Transport and Atmospheric Feedbacks on Global Climate**

Principal Investigator: David Brayshaw (Princeton Visiting Research Fellow/University of Reading Assistant Professor)

CICS/GFDL Collaborator: Geoff Vallis (Princeton)

Other Participating Researchers: Tim Merlis (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: To develop an improved fundamental understanding of the atmosphere's response to imposed changes in ocean heat transport

Methods and Results/Accomplishments:

A series of axisymmetric aqua-planet simulations were performed with a leading UK climate model (HadGAM1) featuring a slab (q-flux) ocean. These simulations were performed in the UK using UK computing resources but were designed and run while the PI was based in GFDL/Princeton. The simulations suggested that an oceanic poleward heat transport (format: 2nd Legendre polynomial, ~0.8PW peaking in the midlatitudes) induces an atmospheric feedback that generates a substantial global-average surface warming. The study is highly idealized and is intended to study the processes involved rather than being directly relevant to "real world" boundary conditions.

Partner experiments using the "Idealised Moist" GFDL model (see Frierson et al 2006, but now including an interactive moisture LW optical depth component developed by Merlis) were then configured and used to separate out various components of the atmospheric response in HadGAM1 (SW albedo, SW optical depth, LW optical depth – and the "isolated" response to the ocean heat transport when the other components are not allowed to vary).

This research is still ongoing. However, the indications are that the feedback relationship between SW albedo and LW optical depth is crucial in amplifying the initial "isolated" perturbation caused by the ocean heat transport. A repeat of the HadGAM simulation using the GFDL HIRAM model exhibited similar behaviour to the HadGAM model – although its overall global surface temperature response was somewhat weaker (approximately 50% of the magnitude).

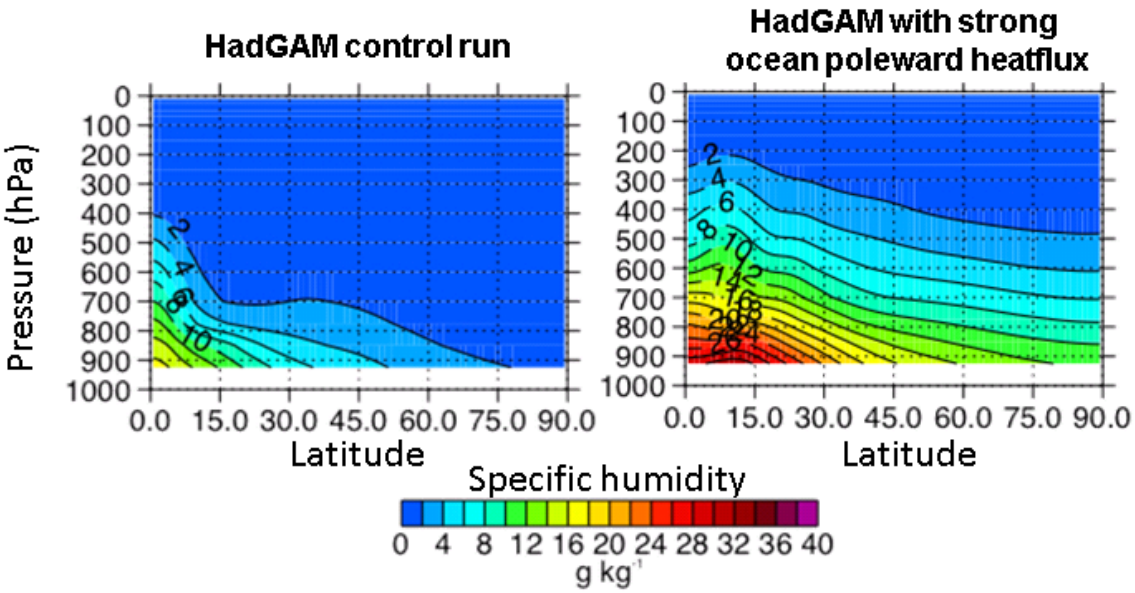


Figure: Zonally-averaged specific humidity in the control run (no ocean heatflux) and the strongly perturbed ocean heat flux experiment. The increase in atmospheric water vapour acts to increase the long-wave optical depth in the perturbed experiment.

References:

Frierson, Dargan M. W., Isaac M. Held, Pablo Zurita-Gotor, 2006: A Gray-Radiation Aquaplanet Moist GCM. Part I: Static Stability and Eddy Scale. J. Atmos. Sci., 63, 2548–2566. doi: http://dx.doi.org/10.1175/JAS3753.1.

Publications:

Brayshaw, D., Atmospheric Feedback from Ocean Transport, informal seminar, Lamont-Doherty Earth Observatory, Columbia University, 10 July 2012.

Brayshaw, D., Atmospheric Feedback from Ocean Transport, informal seminar, University of Washington, 30 July, 2012.

Brayshaw, D., Atmospheric Feedback from Ocean Transport, informal seminar, University of Reading, 10 December, 2012.

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 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). 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. 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.

Publications:

Chen, J.-H., and S.-J. Lin, 2012: Seasonal predictions of tropical cyclones using a 25-km resolution general circulation model. 26, 380–398. J. Climate. 26, 380–398.

Progress Report Title: **The Asymmetry of the Duration and Sequencing of ENSO**

Principal Investigator: Kityan Choi (Princeton Graduate Student)

CICS/GFDL Collaborator: Gabriel Vecchi (GFDL), Andrew Wittenberg (GFDL), Isaac Held (GFDL), Gabriel Lau (GFDL)

Other Participating Researchers: Stefan 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: Evaluate the role of atmosphere nonlinearity in the ENSO asymmetry, using coupled models (CM2.1, CM2.5) and atmospheric models (AM2, HiRAM)

Methods and Results/Accomplishments:

The asymmetries of ENSO were examined using observational records, coupled climate models (CM2.1 and CM2.5) and a simplified dynamical framework. Three asymmetries between El Nino and La Nina are identified in models and observations: duration, sequencing and amplitude. The duration asymmetry is the tendency of cold events to last longer than warm events. The amplitude asymmetry involves warm events tending to be stronger. The sequencing asymmetry involves tendency of warm events to be followed by cold events more readily than the reverse. The Central Equatorial Pacific wind stress anomalies also exhibit an asymmetric response to sea surface temperature anomalies in models and observations. Using a modified delayed-oscillator conceptual model, we parameterize the impact of the wind stress asymmetric response and we demonstrate that a larger (smaller) coupling efficiency during warm (cold) events can lead to the above-mentioned asymmetries in a consistent way. The duration asymmetry is robust across the parameter space we have explored. The sequencing asymmetry can be obtained only if there is stochastic external forcing. The amplitude asymmetry will have the same sign as that observed if the positive feedback is strong compared to the negative feedback.

In the conceptual model, the difference in the wind stress response during warm and cold conditions also lead to a time mean state that is warmer than the equilibrium state; in other words, cold events are closer to the equilibrium state than the warm events are. Since the equilibrium state(s) of the nature is unknown, computing anomalies from the climatology has been a conventional approach in analyzing ENSO strength and duration in observations and models. The time mean state, however, cannot be acquired a priori and it changes as nonlinearities substantiate. Therefore, when the mean climate state is a necessary reference for analysis (e.g. in what conditions an event is considered to have terminated), we suggest that numerical model experiments studying nonlinearities be examined not only by subtracting the control experiment directly from the perturbed experiments, but also by comparing results of perturbation experiments after removing the climatology for each setup.

We have submitted a manuscript of this work to the Journal of Climate. The manuscript is currently under revision.

Following up the above-mentioned studies, we use AM2 and HiRAM to investigate the nonlinear wind stress response by imposing the composite of the sea surface temperature (SST) anomalies during El Nino onto the SST climatology. We invert the sign of the anomalies and scale the anomaly amplitudes to

larger and smaller values, keeping the spatial pattern unchanged. We found that the wind stress anomalies for the inverted El Nino case indeed show a weaker strength than the El Nino case. Such nonlinearity is stronger in AM2 than in HiRAM. The difference in the response between these two models warrants further investigations.

Publications:

Presentations:

Choi, K.-Y., G. Vecchi, 2012: A proposed mechanism for ENSO asymmetries. AGU Fall Meeting.

Choi, K.-Y., G. Vecchi, 2012: Mechanisms of the ENSO Asymmetry. AMS 18th Conference on Air-Sea Interaction.

Progress Report Title: **Towards Accurate Predictions of Regional Precipitation Change Due to Anthropogenic Aerosol and Greenhouse Gas Emissions**

Principal Investigator: Spencer Hill (Princeton Graduate Student)

CICS/GFDL Collaborator: Yi Ming (GFDL), Leo Donner (GFDL), Isaac Held (GFDL), Gabriel Lau (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: Improve predictions of 21st century precipitation changes due to human activities, in particular emissions of aerosols and greenhouse gases, at regional scales

Methods and Results/Accomplishments:

Despite some confidence in large scale temperature and precipitation trends in the coming decades associated with human-induced climate change, changes at more regional scales remain poorly constrained. This hinders climate adaptation efforts. Spatially heterogeneous aerosol forcing in particular complicates things, introducing a real practical need for better characterizing the climate response to the combined forcings of aerosols and greenhouse gases.

We have focused on the effect of these forcing agents on Earth's surface temperature, which then excites changes in precipitation. Specifically, by imposing sea surface temperature (SST) anomalies representative of pre-industrial (PI) to present day (PD) aerosol emissions in an atmosphere-only general circulation model (AGCM), we have demonstrated that cooling of the northern hemisphere (NH) relative to the southern hemisphere (SH) due to the predominantly NH aerosol emissions causes a southward shift of the intertropical convergence zone (ITCZ) in the AGCM. This contrasts the case with greenhouse gas-representative SST anomalies (which are more symmetric about the equator), in which the ITCZ doesn't exhibit an obvious shift in either direction. Understanding this behavior requires an understanding of the tropical Hadley cell "gross moist stability" (GMS), a measure of the efficiency of Hadley cell energy transport. Though often assumed constant, GMS exhibits statistically significant seasonally varying changes in the aerosol case, which we have shown to be consistent with theory developed in *Held 2001*.

References:

Ming, Y. and V. Ramaswamy 2009; 2011 Journal of Climate; Held, I. M. 2001 Journal of Climate.

Publications:

Hill, S A., and Yi Ming, August 2012: Nonlinear climate response to regional brightening of tropical marine stratocumulus**.** Geophysical Research Letters, 39, L15707, doi:10.1029/2012GL052064.

Hill, S. A., Y. Ming, L. J. Donner, N.-C. Lau, and I. M. Held. "Seasonally dependent changes to Hadley cell gross moist stability caused by anthropogenic aerosols." In preparation for submission to Geophysical Research Letters.

Hill, S. A., Y. Ming, L. J. Donner, N.-C. Lau, and I. M. Held. "Tropical hydrological responses to mean and spatially varying components of forced sea surface temperature changes." In preparation for submission to Journal of Climate.

Progress Report Title: **Assessing the Hydroclimate in a High-Resolution Global Coupled Model Framework**

Principal Investigator: Sarah Kapnick (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Thomas Delworth (GFDL)

Other Participating Researchers: Chris Milly (USGS), Sergey Malyshev (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 (60%)
Weather & Water Goal: Serve Society's Needs for Weather and Water Information (40%)

Objectives: To better understand global and regional hydroclimate variability, its expected future change, and impacts.

Methods and Results/Accomplishments:

My research to date has largely focused 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). I validated the use of CM2.5 for exploring global snowfall, snowpack, and snow covered area using various reanalysis products. I show that in comparison to its coarser predecessor, CM2.5 better captures mean annual climatologies of snow variables and the seasonal cycle of snow covered area. I also looked at the climate change aspects of snow variables in a 2xCO2 environment and found global reductions in snowfall, but regions where snowfall uniquely increases due to increased precipitation. This work is currently in press (Kapnick and Delworth 2013) and was also picked up by various media outlets, including the Associated Press (and their partner organizations), World News with Diane Sawyer, CNN.com, and others. We created a special figure over the United States for the media summary (Figure 1).

Using the results from this first completed project, I developed two other projects with regional focuses that I am currently preparing as two papers. The first is a study of hydroclimate seasonal cycle variability over North America. It explores how changes in the timing and magnitude of snowfall affect snowpack, snowcover, runoff, and soil moisture. The second study looks at the Himalaya region identified in the submitted paper on global snowfall variability. The Karakoram region in the present climate has observed glacier expansion or steadfast mass, whereas the regions to the southeast exhibit glacier retreat (Bolch et al., 2012). Given the results of the idealized simulation in Kapnick and Delworth 2013, I am curious if differences in snowfall variability and temperature sensitivity can be used to explain the differences in glacier response. Using a presently available 3-member ensemble of CM2.5 simulations from 1860 to 2100, I explore how snowfall has varied in the past and future climate. This work highlights

the importance of high-resolution to reproduce the distribution and magnitude of hydrologic variables and presents a unique opportunity to model regional variability on long time scales.

References:

Bolch, T. et al., 2012: The state and fate of Himalayan glaciers. Sciences, 336, 310-314.

Delworth, T. et al., 2012: GFDL's CM2.5 Global Coupled Climate Models. Part I: Formulation and Simulation Characteristics, J. Climate, 25, 2755–2781.

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

Kapnick, S., T. Delworth 2013: Controls of Global Snow Under a Changed Climate. J. Climate. doi:10.1175/JCLI-D-12-00528.1, in press.

Publications:

Kapnick, S., T. Delworth 2013: Controls of Global Snow Under a Changed Climate. J. Climate. doi:10.1175/JCLI-D-12-00528.1, in press.

Talks (Posters noted):

Kapnick, S., The Snowfall Shuffle: Changes in Global Distributions of Snow in Response to Climate Change, NOAA Headquarters, Silver Springs, Maryland. March 12, 2013.

Kapnick, S., Changes in Global Snow Under 2xCO2, Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York. March 8, 2013.

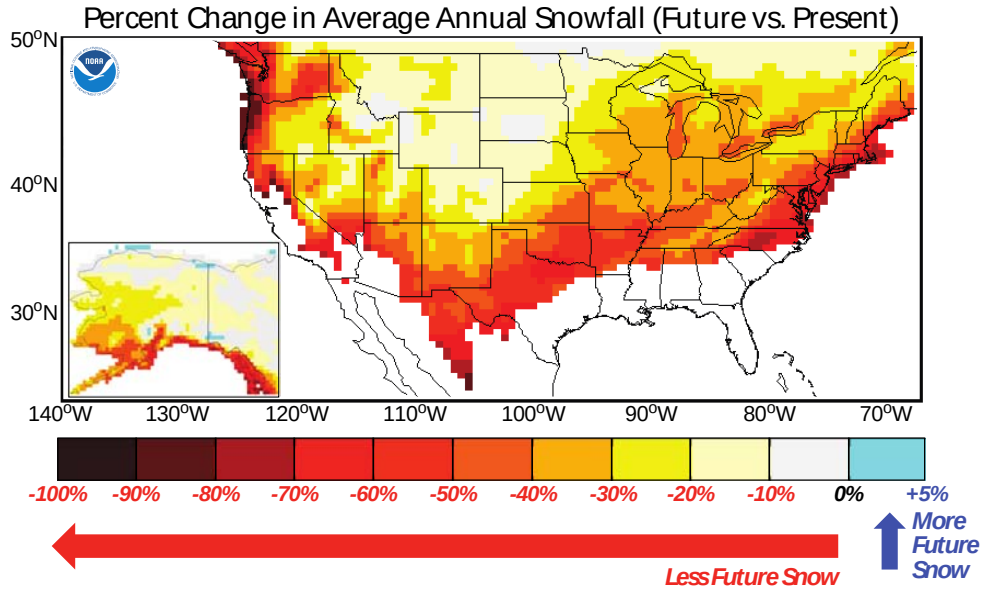
Kapnick, S., Controls of Global Snow Under a Changed Climate, Department of Geology and Geophysics, Yale University, New Haven, Connecticut. January 24, 2013.

Kapnick, S., Controls of Global Snow Under a Changed Climate, America Geophysical Union Annual Meeting, San Francisco, California. December 6, 2012. (Poster)

Kapnick, S., Why the Future will have More February Skiing But Fewer Summer Pool Parties, DISCCRS VII Symposium, Colorado Springs, Colorado. October 15, 2012.

Kapnick, S., Controls of Global Snowfall Under a Changed Climate, NCCR Summer School on Water and Climate, Ascona, Switzerland. September 12, 2012. (Poster)

Figure 1: Percent change in snowfall after CO2 doubling when compared to the 1990-control simulation.



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

Principal Investigator: Cheryl Logan (Princeton Contractor/Assistant Professor, California State University, Monterey Bay)

CICS/GFDL Collaborator: John Dunne (GFDL)

Other Participating Researchers: Simon Donner (UBC), Mark Eakin (NOAA/NESDIS)

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

Objectives: Assess sensitivity of global coral reefs to bleaching under thermal stress of climate warming

Methods and Results/Accomplishments:

We have compared a suite of alternative mechanistically derived empirical algorithms for the sensitivity of global coral reef ecosystems to thermally-induced bleaching based on comparison of a variety of available sea surface temperature productions with the global reefbase database of bleaching observations to provide a revised algorithm for NOAA's Coral Reef Watch bleaching prediction system (Logan et al., 2012). Through this work, we were able to determine that the historical maximum monthly mean served as the most robust proxy for coral sensitivity to bleaching, and that multidecadal data products peaked in representativeness at approximately the one month timescale and 0.5 spatial scale resolution due to sampling limitations.

We then applied a suite of alternative algorithms with respect to underlying assumptions of coral acclimation and adaptation to changes in thermal stress both historically and under future climate change projections using downscaled output from GFDL's Earth System Model (ESM2M; Logan et al., submitted). These physiologically derived bleaching prediction methods refine future bleaching projections, and advance population and community modeling efforts. We use bias-corrected global SST output from ESM2M to evaluate implications of the new representative concentration pathways (RCPs) used by the 5th IPCC Assessment to coral bleaching trajectories. Results provide a range of future bleaching frequencies, some of which dramatically improve the outlook for reef-building corals.

References:

Logan, C. A., J. P. Dunne, C. M. Eakin, and S. D. Donner, 2012: A framework for comparing coral bleaching thresholds In Proceedings of the 12th International Coral Reef Symposium, Cairns, Australia, 9-13 July 2012, 1-5.

Logan, C. A., J. P. Dunne, C. M. Eakin, and S. D. Donner, submitted: Incorporating adaptation and acclimatization into future projections of coral bleaching. Global Change Biology.

Publications:

Logan, C. A., J. P. Dunne, C. M. Eakin, and S. D. Donner, 2012: A framework for comparing coral bleaching thresholds In Proceedings of the 12th International Coral Reef Symposium, Cairns, Australia, 9-13 July 2012, 1-5.

Logan, C. A., J. P. Dunne, C. M. Eakin, and S. D. Donner, submitted: Incorporating adaptation and acclimatization into future projections of coral bleaching. Global Change Biology.

Progress Report Title: **GFDL Data Portal Post IPCC Adaptation**

Principal Investigator: Serguei Nikonov (Princeton Professional Technical Specialist)

CICS/GFDL Collaborator: V.Balaji (Princeton), Aparna Radhakrishnan (DRC/GFDL), Kyle Olivo (DRC/GFDL), Hans Vahlenkamp (NCAR/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: Execution of IPCC AR5 showed strong and weak sides of developed infrastructure for publishing experiments on GFDL data portal and delivering data to scientific community. The goal is to improve it making stress on universality - system should be easily used for not IPCC projects. It was also important to investigate and compare different RDBMSs to choose potential candidate for curator database and migrate to chosen. Another objective was to bind Curator system tighter to FMS Runtime Environment for increasing throughput performance and expanding system usage to whole GFDL community.

Methods and Results/Accomplishments:

During the past year, we accomplished the following: the Curator system with GFDL Data Portal infrastructure showed good performance in IPCC AR5 and GFDL Summer School on Atmospheric Modeling; the Curator infrastructure was accepted for wide lab community usage; the best RDBMS candidate for curator database was chosen - IBM DB2; the Curator database was migrated to IBM DB2 without changing SQL structure; and mapper was ported and thoroughly tested.

Additionally, we participated in ESGF (Earth System Grid Federation) project. Full ESGF Node is installed and all GFDL IPCC AR5 data was republished there.

Finally, preliminary design investigations were made for deep incorporation of the Curator system into FRE.

Publications:

Basic principles of designing climate data portals on example of GFDL Data Portal. S.Nikonov. May 2012. Special seminar at Division of Physical Sciences and Engineering, King Abdullah University of Science and Technology (KAUST). Thuwal, Kingdom of Saudi Arabia.

Global Data Infrastructure and the Earth System Grid Federation. S.Nikonov, K.Olivo, A.Radhakrishnan. Poster presentation. May 2012 PICSciE Conference. Princeton University, NJ.

Progress Report Title: **Contrasting Features of Scattering and Absorbing Aerosol 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, and 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 investigate the significance of interhemispherically asymmetrical scattering and absorbing aerosol radiative forcings on climate conditions

Methods and Results/Accomplishments:

Human activities have greatly increased the amount of aerosols in the atmosphere since the Industrial Revolution. Anthropogenic aerosol emissions are comprised of optically scattering and absorbing particles—with the principal concentrations being in the Northern Hemisphere—and yield negative and positive global-mean radiative forcings, respectively. Aerosols also influence cloud properties, yielding additional negative radiative forcings. Aerosols have therefore both counteracted and contributed to global warming over the 20th Century, and will continue to do so in the future.

My work focuses principally on investigating the contrasting features between scattering and absorbing aerosol radiative forcings and the accompanying climate responses by employing the NOAA Geophysical Fluid Dynamics Laboratory CM2.1 global climate model. Anthropogenic sulfate and black carbon are used as proxies of a strong scatterer and a strong absorber. Optical properties in CM2.1 are validated by comparisons with ground-based, aircraft, and satellite measurements in industrialized and biomass burning regions.

In the global-mean, we find that sulfate exerts a -1.12 W/m^2 top-of-atmosphere (TOA) direct radiative forcing (DRF), and black carbon exerts a 0.86 W/m^2 TOA DRF. Spatial distributions of forcings show similar magnitudes with opposite signs, demonstrating the powerful balance between scattering and absorbing aerosol perturbations of the energy balance. The quantitative roles of cloud coverage, surface albedo, and relative humidity in governing the magnitudes of TOA DRFs are determined; clouds and high albedo surfaces considerably weaken sulfate forcings and strengthen black carbon forcings. Sulfate forcings are considerably strengthened by hygroscopic growth.

A distinct contrast is evident in the responses of key thermal, hydrological, and dynamical climate variables to the positive and negative particulate forcings. The effects on zonal-mean precipitation, atmospheric circulation, and heat transport include patterns of changes north and south of the equator that are governed by the sign of the aerosol forcing and the initiation of an interhemispheric forcing asymmetry. The aerosol-induced changes in the variables are in contrast to the response of the more globally uniform and hemispherically symmetric well-mixed greenhouse gas forcing. The presence of opposing forcings and responses between the aerosol scatterers and absorbers hides the effects of individual aerosol types on regional climate.

Accomplishments include publishing a paper in October 2012, presenting my research at the AGU Fall Meeting in December 2012, working on two additional manuscripts, and writing a dissertation thesis. I have also received the Emerging Alumni Scholars Award for "the excellence of your dissertation project, your ability to communicate in an engaging manner to a broad public outside your discipline, and on the merits of your distinguished career at Princeton."

Publications:

Ocko, IB, and P Ginoux, Important aspects of aerosol optics revealed by comparing collocated ground-based, aircraft, and satellite measurements with model data, in prep (2013).

Ocko, IB, V Ramaswamy, and Y Ming, Contrasting climate responses to the scattering and absorbing features of anthropogenic aerosol forcings, in prep for submission to Journal of Climate (2013).

Ocko, IB, and V Ramaswamy, Climate responses to gases and aerosols from 1860 to 2000, AGU Fall Meeting, San Francisco, CA, 2012.

Ocko, IB, V Ramaswamy, PA Ginoux, Y Ming, LW Horowitz, Sensitivity of scattering and absorbing aerosol direct radiative forcing to physical climate factors, J. Geophys. Res., 117, doi:10.1029/2012JD018019 (2012).

Progress Report Title: **Spontaneous Superrotation in Idealized Atmospheric Models**

Principal Investigator: Samuel Potter (Princeton Graduate Student)

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

Other Participating Researchers: Thomas Spengler (University of Bergen)

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 characterize the tropical variability of idealized atmospheric models and understand what climates are amenable to greater tropical wave activity and, consequently, superrotation

Methods and Results/Accomplishments:

My main tool is the GFDL spectral dynamical core, an idealized primitive equation model with highly idealized physics. I am currently wrapping up research on why atmospheric dynamical cores with large thermal Rossby numbers (in my case, this is a planet with small radius) superrotate. Using spectral diagnostics I have shown that the dry dynamical core has strong Kelvin wave activity, which in the case of the large thermal Rossby number atmosphere leads to strong equatorward momentum fluxes. This Kelvin wave signal can be seen in Earth's atmosphere as well. My next step is to adapt an idealized moist model to ask similar questions (e.g. Frierson 2007). The main addition to the moist model is a Betts-Miller convection scheme that allows for more complex tropical variability. Studying the moist model will hopefully lead to a better understanding of the type of atmospheric circulations that may have come about during extreme hothouse climates of the past.

As a side project I have recently submitted and had accepted a paper on barotropic Rossby wave reflection in the atmosphere based on a class project I had done several years ago.

References:

Frierson, DMW, 2007: The Dynamics of Idealized Convection Schemes and Their Effect on the Zonally Averaged Tropical Circulation. JAS.

Publications:

Potter, SF, GK Vallis, and JL Mitchell: Spontaneous superrotation and the role of Kelvin waves in an idealized dry GCM, JAS, In Preparation.

Potter, SF, T Spengler, and IM Held: Barotropic Rossby waves in sheared flow and validity of the WKB approximation, JAS, Accepted.

Progress Report Title: **Will Non-Linearities in the Buffering Capacity of Seawater Dominate the Ocean Carbon-Climate Feedback over the 21st Century?**

Principal Investigator: Keith Rodgers (Princeton Research Scholar)

CICS/GFDL Collaborator: John Dunne (GFDL)

Other Participating Researchers: Thomas Froelicher (Princeton)

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: The purpose of this work is to understand the mechanisms that will contribute to a positive carbon-climate feedback over the 21st century. This is being pursued through the use and application of GFDL's Earth System Model ESM2M.

Methods and Results/Accomplishments:

Will there be a positive feedback between the ocean carbon cycle and the physical climate system over the 21st century? The current generation of Earth System Models exhibit such a feedback, with ocean carbon uptake being reduced by ~20% due to warming of the climate system (Friedlingstein et al. 2006). Such changes are typically attributed to changes in subduction rates due to increased stratification (Friedlingstein et al., 2006) or to increased winds over the Southern Ocean driving changes in the natural carbon cycle of the ocean (Le Quéré et al., 2007).

However, it is also known that the carbon chemistry of the ocean poses an impedance to uptake of carbon from the atmosphere that increase with carbon concentrations. This is usually defined in terms of the Revelle Factor (Revelle and Suess, 1957). In addition to the DIC-dependence of the Revelle Factor, there is also a temperature dependence. It has long been expected that the changes in the carbonate buffering capacity of seawater will change under anthropogenic carbon emissions, and thereby contribute to an ocean carbon/climate feedback. In fact, recent work with the GFDL ESMs has demonstrated that this has important impacts on the seasonal cycle of carbon (Rodgers et al., 2013). However, to date it has proven difficult to quantify this effect with simplified models.

In this project we are using the current generation of ESMs from GFDL to evaluate in a unified framework the relative importance of physical state perturbations and changes in the buffering capacity of seawater in driving carbon-climate feedbacks described by Friedlingstein et al. (2006). This is being evaluated through a suite of perturbation studies with GFDL's ESM2M (Dunne et al., 2013), with the reference simulation being a concentration RCP8.5 projection of future climate change. The central hypothesis of this work is that chemical saturation of the subtropical cells, characterized by a rapid turnover time (1-2 decades) will pose a first-order control on 21st century carbon-climate feedbacks. The implications for future acidification of the ocean will also be investigated.

References:

Dunne, J.P., et al. (2013), GFDL's ESM2 global coupled climate-carbon Earth System Models Part II: Carbon system formulation and baseline simulation characteristics, Journal of Climate, in press.

Friedlingstein, P. et al. (2006), Climate-carbon cycle feedback analysis: Results from the C4MIP-Model Intercomparison, Journal of Climate, 19, 3337-3353.

Le Quéré et al. (2007), Saturation of the Southern Ocean CO2 sink due to recent climate change, Science, 316, 1735-1738.

Revelle, R., and H.E. Suess (1957), Carbon dioxide exchange between atmosphere and ocean and the question of an increase of atmospheric CO2 during the past decades, Tellus.

Publications:

Plancherel, Y., K.B. Rodgers, R.M. Key, A.R. Jacobson, and J.L. Sarmiento (2012), Role of regression model selection and station distribution on the estimation of oceanic anthropogenic carbon change by eMLR, Biogeosciences Discussion, 9, 14589-14638.

Abstract accepted for ICDC9 in Beijing in June 2013 (Oral presentation)

Rodgers, K.B. et al. (2013), Large changes in seasonality of the surface ocean carbon cycle under anthropogenic climate change, ICDC9 Abstract.

Progress Report Title: **NOAA/GFDL Earth System Model Downscaling in the California Current Large Marine Ecosystem**

Principal Investigator: Ryan Rykaczewski (Princeton Contractor/University of South Carolina Assistant Professor)

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

Other Participating Researchers: Enrique Curchitser (Rutgers)

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 (85%)
Ecosystem Goal: Protect, Restore, and Manage the Use of Coastal and Ocean Resources through Ecosystem-based Management (15%)

Objectives: We are investigating the ability of one-way downscaled earth system model (ESM) output to accurately represent climatological variability in the California Current Large Marine Ecosystem (CCLME). Once the limitations and caveats of this downscaling are better recognized, we intend to analyze projections of future change in the region and understand the differences between the coarser GFDL model and the higher resolution downscaled product.

Methods and Results/Accomplishments:

Previous investigation of the response of the CCLME to future climate change using ESM 2.1 highlighted unexpected biogeochemical trends not apparent in physical model projections (Rykaczewski and Dunne, 2010). However, the climatological conditions of the CCLME are relatively poorly represented by the coarse ESM 2.1; the region is dominated by coastal upwelling, a process poorly resolved in current global models. Here, we have begun applying a downscaling strategy through which ESM 2m boundary conditions are used to force a ROMS simulation of the CCLME (with the expertise of project collaborator Enrique Curchitser at Rutgers).

Thus far, we have compiled a list of properties useful for assessing model performance; specifically, the ability of the model to represent the fingerprint of basin-scale processes on the CCLME regional domain. A theme of this project is model application with the goal of applying results to ecosystem-based management strategies, and so comparison of model output with available high-quality data is an essential component. We have identified the California Cooperative Oceanic Fisheries Investigations (CalCOFI) dataset as the most appropriate data source against which model climatology can be compared.

An early accomplishment related to this project has been multi-model (IPCC AR5 generation) analysis of projected changes in atmospheric temperature and pressure gradients in the CCLME as an explicit test of the Bakun (*Science*, 1990) upwelling intensification hypothesis. Model projections are inconsistent with Bakun's hypothesis. These results are being prepared for publication and have been presented at a number of scientific conferences (noted below). This result motivates further investigation of the basin-scale influence on regional biogeochemical properties, as the importance of local atmospheric processes on the CCLME is not as dominant as previously hypothesized.

References:

Bakun, A. (1990) Global climate change and intensification of coastal ocean upwelling. Science 247 (4939):198-201, doi:10.1126/science.247.4939.198.

Rykaczewski, R.R., and Dunne, J.P. (2010) Enhanced nutrient supply to the California Current Ecosystem with global warming and increased stratification in an earth system model. Geophysical Research Letters 37:L21606, doi:10.1029/2010GL045019.

Publications:

Rykaczewski, RR, JP Dunne, and CA Stock. February 2013. Climate change and marine ecosystems: Issues of scale and challenges for the community. ICES Working Group on Interactive Physical-biological and Ecosystem Modeling. Paris, France.

Rykaczewski, RR. February 2013. Responses of ecosystem processes to long-term climate Change. American Association for the Advancement of Science, Annual Meeting. Boston, MA, USA.

Rykaczewski, RR. November 2012. Linkages between the Carbon Cycle and Biota in the Global Ocean. Sea Around Youth Symposium. Yokosuka, Japan.

Progress Report Title: **Predicting the Impacts of Climate Change on Mesopelagic Ecosystems: Respiratory Niches in the Pelagic Ocean**

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

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

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-based Management

Objectives: Habitats are determined by a complex array of physical and biological factors. The fundamental niche is the geographic area with tolerable conditions for an organism but the size of the fundamental niche is often much larger than the space occupied by an organism, the realized niche (Hutchinson, 1957). The primary objective is to establish and compare respiratory niches for tuna and determine future changes to the respiratory niches using projections from IPCC-class climate models.

Methods and Results/Accomplishments:

Globe-traveling tuna utilize many different regions and depths in the ocean while foraging for food. Predicting the effects of climate change on habitat utilization in the physically and chemically complex three-dimensional ocean environment requires identification of underlying physiological mechanisms influenced by environmental conditions. Hemoglobin-oxygenation is hypothesized to be one of these underlying mechanisms. Oxygen extraction from seawater and delivery to tissues, a fundamental process which depends on hemoglobin, is a necessity for tuna survival. All of the environmental factors associated with hemoglobin-oxygenation are predicted to change in the future: temperature is predicted to increase with climate change, oxygen is predicted to decrease as increases in temperature cause water column stratification to increase, and carbon dioxide is predicted to increase with ocean acidification. It is hypothesized that these changes will result in habitat compression for tuna, but the magnitude and biogeography of the compression will be different among the species of tuna. The P_{50} depth, the depth at which 50% of hemoglobin is oxygenated, is being used as the threshold restricting tuna habitat utilization in global datasets and IPCC-class earth system model results. Preliminary results from two earth system models indicate that future climate change will have neutral to negative impacts on the habitat size of *Thunnus albacares*, the yellowfin tuna, by 2100 (Fig. 1).

References:

Hutchinson, G. (1957). Concluding remarks. Cold Spring Harbor Symposium on Quantitative Biology, 22:415–427.

Publications:

Smith, K. A., Carter, B., Dunne, J. P., and Sarmiento, J. L. (Jan., 2013) Predicting the effect of multiple stressors on respiratory niches in the pelagic ocean over the next century. Oral Presentation, Society of Integrative and Comparative Biology Meeting, San Francisco, CA, USA.

Smith, K. A. (Dec., 2012) Changing climate, changing habitats: Predicting the future for marine organisms. Invited Seminar. University of Rhode Island, Kingston, RI, USA.

Smith, K. A., Dunne, J. P., Carter, B., and Sarmiento, J. L. (May, 2012) Predicting future habitat changes above oxygen minimum zones. Oral Presentation. Symposium on the Effects of Climate Change on the World's Oceans, Yeosu, Korea. (*Best Presentation Award)

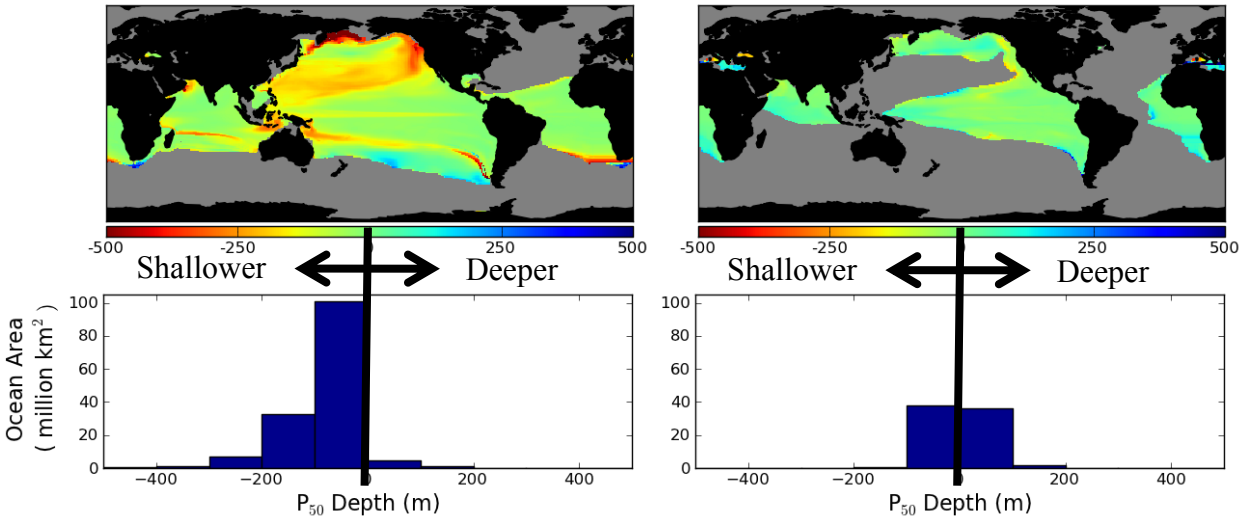


Figure 1: The predicted changes in P_{50} depth for *Thunnus albacares* in the next century using results from NOAA GFDL Earth System models ESM2M (left panel) and ESM2G (right panel). ESM2M results suggest that there will be habitat compression, mostly decreasing vertical ranges by 0-100 m, for this species while the ESM2G results suggest that there will be no overall change.

Progress Report Title: **Climate Response to Saharan Dust Perturbations**

Principal Investigator: Jeffrey Strong (Princeton Graduate Student)

CICS/GFDL Collaborator: Gabriel Vecchi (GFDL)

Other Participating Researchers: Thomas Delworth, Paul Ginoux, and Thomas Knutson (GFDL)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

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

Objectives: To understand the sensitivity of the climate system to realistic variations in both the atmospheric loading of Saharan-borne mineral dust and its optical properties

Methods and Results/Accomplishments:

North Africa is the largest source of global dust, contributing 55% of the total 1500-2000 Tg of global annual emissions (Ginoux et al., 2012). These large emissions of mineral dust strongly influence the radiative balance in the regional climate. Simultaneously, this dust is predominantly transported over the tropical North Atlantic into the main development region of Atlantic tropical cyclones due to the climatological easterlies over North Africa. This mass transport has been shown to influence the development of Atlantic tropical cyclones (Dunion & Velden, 2004). However, this source of dust undergoes significant multidecadal scale fluctuations in emissions with nearly a 5x increase in dust emissions between the 1960's and the 1980's followed by a more recent decrease in emissions (Prospero & Lamb, 2003). Simultaneously, our understanding of the optical properties of African mineral dust is continuously evolving as mineral composition varies considerably across the domain of a typical Saharan dust plume (Balkanski et al., 2007).

Using the GFDL's CM2.1 model, we are investigating how these variations in atmospheric loading and optical properties of North African mineral dust affect the climate system, with particular emphasis on conditions pertinent to Atlantic tropical cyclogenisis. A series of four experiments were conducted: Two 150-year free-running controls with constant insolation, atmospheric gases, and land cover values representative of 1990 conditions and two 50-year, 21-member ensemble perturbations from their respective control run, initialized at 5-year intervals, where atmospheric dust loading was reduced to simulate an 80% decrease in dust emissions over North Africa. Each pair of experiments used two different optical properties: One where the dust had the CM2.1 standard, predominantly absorbing optical properties and one where the dust had a newer, predominantly scattering optical regime

Initial results show considerable sensitivity to various optical properties (Figure). In the case of predominantly absorbing dust, upon their removal we see a marked weakening of the Sahel monsoon. This is explained via a strong net energy divergence over North Africa which leads to a drying of the atmospheric column by anomalous land-breezes. In the case of the predominantly scattering dust we observe a significant increase in the strength of the Atlantic Meridional Overturning Circulation, similar to those following strong volcanic eruptions, which then rapidly decreases upon the removal of the dust. Finally, both experiments show mixed results in terms of the necessary conditions for tropical cyclone development. The removal of the predominantly absorbing dust causes a decrease in the moist static stability and an increase in sea surface temperature over the North Atlantic. Conversely, the removal of

the predominantly scattering dust causes a decrease in vertical wind shear and an increase in mid-level moisture. It then becomes pertinent to examine what a dust perturbation with more moderate optical properties will do to the tropical climate.

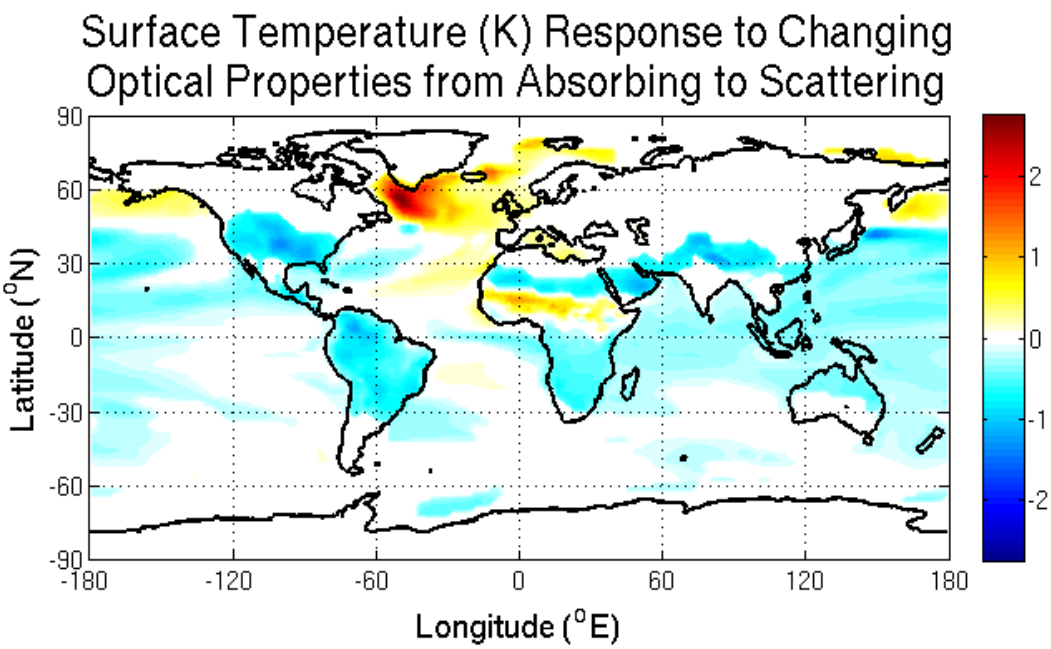
References:

Balkanski, Y., M. Schulz, T. Claquin, and S. Guibert (2007): Reevaluation of Mineral Aerosol Radiative Forcings Suggests a Better Agreement with Satellite and AERONET Data, Atmos. Chem. Phys., 7(1), 81-95, doi:10.5194/acp-7-81-2007.

Dunion, J. P. and C. S. Velden (2004): The Impact of the Saharan Air Layer on Atlantic Tropical Cyclone Activity, Bull. Amer. Meteor. Soc., 85, 353-365, doi:10.1175/BAMS-85-3-353.

Ginoux, P., J. M. Prospero, T. E. Gill, N. C. Hsu, and M. Zhao (2012): Global-Scale Attribution of Anthropogenic and Natural Dust Sources and their Emission Rates Based on MODIS Deep Blue Aerosol Products, Rev. Geophys., 50(3), RG3005, doi:10.1029/2012RG000388.

Prospero, J. M. and P. J. Lamb (2003): African Droughts and Dust Transport to the Caribbean: Climate Change Implications, Science, 302(5647), 1024-1027, doi:10.1126/science.1089915.



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

Principal Investigator: Geoffrey Vallis (Princeton Senior Research Geoscientist/Princeton Faculty)

Other Participating Researchers: Pablo Zurita-Gotor (Madrid), Sophie Zhang (Princeton), Antoine Venaille (Lyons), Martin Jucker (Princeton), Stephan Fueglistaler (Princeton), Max Nikurashin (Tasmania)

Theme: Earth System Model Applications

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

NOAA Goals: 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. One goal is to understand how the circulation of the atmosphere and ocean respond to warmer climate. Another goal is to understand the processes that maintain the large-scale circulation of the atmosphere and ocean.

Methods and Results/Accomplishments:

In a paper recently published in Nature Geosciences, we described the results of some very high resolution numerical simulations that modeled the passage of energy in the ocean from the input via wind forcing to the dissipation via breaking internal waves.

In a paper in review in the Journal of the Atmospheric Sciences, we described a new formulation of an idealized model of the stratosphere. The model will better enable studies of how ozone hole recovery and global warming affect the circulation of the troposphere.

Finally, we have explored the differences and similarities between ocean heat uptake and carbon uptake. These processes will determine the relative importance of the short and long term response to increased greenhouse gases, and the relative levels of the so-called transient and equilibrium climate sensitivity.

Publications:

Ilicak, M. and Vallis, G.K., 2012. Simulations and phenomenology of horizontal convection. Tellus A, 64, 1–17. doi:http://dx.doi.org/10.3402/tellusa.v64i0.18377.

Jucker, M., Fueglistaler, S. and Vallis, G.K., 2012. Maintenance of stratospheric structure in an idealized general circulation model. J. Atmos. Sci. 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., 69, 3251–3263. doi: http://dx.doi.org/10.1175/JAS-D-11-0300.1.

Nikurashin, M., Vallis, G.K. and Adcroft, A., 2012. Routes to energy dissipation for geostrophic flows in the southern ocean. Nature Geosciences, 6, 48–51. doi: doi:10.1038/ngeo1657.

Nikurashin, M. and Vallis, G.K., 2012. A theory of deep stratification and interhemispheric overturning circulation and associated stratification. J. Phys. Oceanogr., 42, 1652–1667.

O'Rourke, A. and Vallis, G.K., 2012. Jet interaction and the influence of a minimum phase speed bound on the propagation of eddies. J. Atmos. Sci. Submitted.

Venaille, A., Vallis, G.K. and Griffies, S.M., 2012. The catalytic role of the beta effect barotropization of inviscid fluids. J. Fluid Mech., 709, 490–515. doi: http://dx.doi.org/10.1017/jfm.2012.344.

Progress Report Title: **Signal Tracking of Antarctic Open-Ocean Polynyas**

Principal Investigator: Hannah Zanowski (Princeton Graduate Student)

CICS/GFDL Collaborator: Jorge Sarmiento (Princeton), Robert Hallberg (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: The objective of this research is to answer the following three questions: What are the underlying dynamics and mechanisms responsible for transport of the polynya signal? Where does the water from the polynya travel upon exiting the Weddell Sea? Could the Weddell Polynya of the 1970s be partially responsible for warming in the abyssal Pacific?

Methods and Results/Accomplishments:

To answer the three questions above, we have developed a set of idealized simulations using a two layer version of GOLD that models the polynya signal. The setup of the simulations is such that a negative buoyancy forcing of 1.3×10^{-3} m^2/s^3 (calculated from heat flux data from Gordon et al., 2007) is applied at the surface over an approximately 200,000km^2 region which is similar in size to the Weddell Polynya of the 1970s. The downwelling water has an associated tracer so that we are able to track the polynya signal as it spreads into the abyssal oceans. All of the simulations have been run for at least 50 years, but the results shown here focus on the signal after 40 years since it has been about 40 years since the Weddell Polynya of the 1970s. The six simulations I have completed thus far are as follows:
1. Flat ocean of 5km depth with a 3km layer interface; 2. Ocean with realistic seafloor topography and a 3km layer interface; 3. Same as 2) but with a 5km interface; 4. Same as 3) but with the buoyancy forcing in the Ross Sea; 5. Same as 3) but with time-dependent buoyancy forcing; and 6. Same as 2) but with time-dependent buoyancy forcing and with Orkney Passage deepened.

Simulations 1) and 2) have assisted in my understanding of the mechanisms by which the signal can travel. So far we have found that the signal spreads by two mechanisms. The first mechanism is propagation through waves that develop as a result of the downwelling in the forcing region. For the flat ocean there are both Kelvin waves and Rossby waves which are responsible for propagating the thickness perturbations around the oceans, but for the ocean with realistic seafloor topography, topographic Rossby waves become important for propagating the signal out of the Weddell Sea, while Kelvin waves are now only found at the equator. The second mechanism is spreading of the signal through advection by boundary currents that are set up by the waves propagating away from the forcing region. The advection of the signal is important for understanding how tracers, such as CFCs, could spread as a result of entering the deep ocean through the polynya.

Simulations 3) - 6) have assisted in my understanding of the oceanographic aspects that impact the spatial structure of the polynya signal as it spreads into the abyssal oceans. The seafloor topography, the depth to which the signal sinks before leaving the Weddell Sea, and the magnitude and temporal structure of the buoyancy forcing all impact the pathways along which the polynya signal can spread. Thus far we have found that after 40 years, it is unlikely that the advective signal from the polynya would be able to reach the abyssal Pacific (Figure 1), and as a result the warming in the abyssal Pacific is most likely not due to the Weddell Polynya of the 1970s. However, given that the tracer in figure 1 remains

concentrated in the Weddell Sea region and partially in the South Atlantic, the Weddell Polynya could still be responsible for some of the warming (Johnson and Doney, 2006) discovered there.

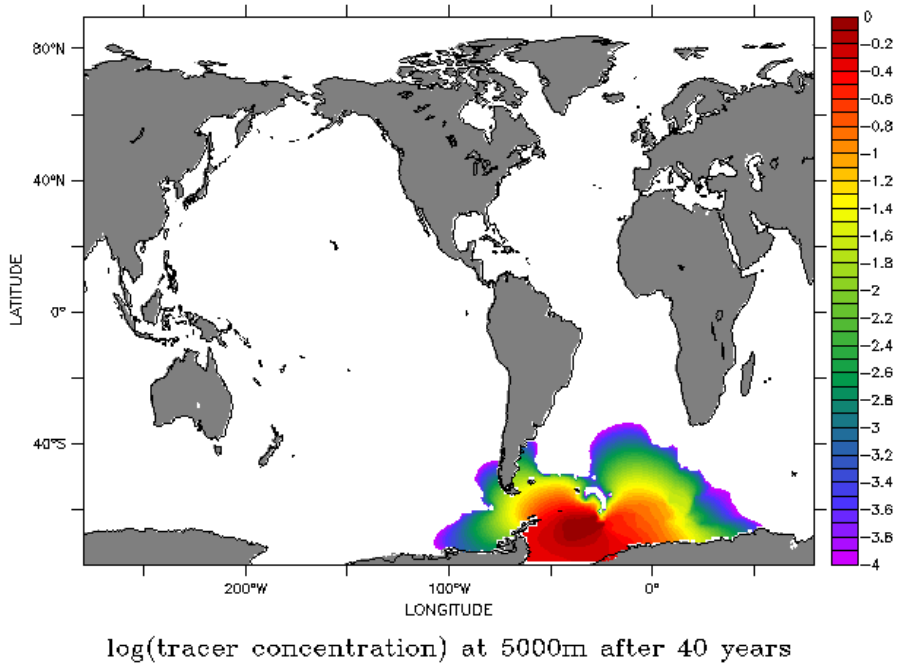


Figure 1: Log of the tracer concentration at 5km after 40 years for the time-dependent buoyancy forcing simulation. The buoyancy forcing is such that it is on for the first three months of the first three years of the simulation and then zero for all time after.

References:

Gordon, A.L., M. Visbeck, and J.C. Comiso, 2007: A Possible Link between the Weddell Polynya and the Southern Annular Mode. J. Clim.,20, 2558-2571.

Johnson, G.C., and S.C. Doney, 2006: Recent western South Atlantic bottom water warming. Geophys. Res. Lett.30, L14614, doi:10.1029/2006GL026769.

Progress Reports:

Education/Outreach

Progress Report Title: **Cooperative Institute for Climate Science Professional Development Summer Institute in Weather and Climate July 16-20, 2012**

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

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

Task I: Administration & Outreach

NOAA Sponsor: Brian Gross (GFDL)

Education/Outreach

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

Objectives: In support of the Cooperative Institute for Climate Science's (CICS) intent to educate society about the complexity of understanding and predicting climate and environmental consequences, we designed and delivered professional development for New Jersey teachers to improve their students' understanding of weather and climate. This work is a collaboration of Princeton University science and education professors as well as local educators: Dr. Steven Carson, formerly of the Geophysical Fluids Dynamics Laboratory and currently a middle school science teacher in Princeton Township, New Jersey; and Dr. Anne Catena, Ed.D., Program in Teacher Preparation at Princeton University. The instructional team also included Greg Peters, a middle school teacher in an "urban rim" school district, Ewing, NJ. Mr. Peters works with students identified as under-represented groups.

Methods and Results/Accomplishments:

The teachers explored the fundamentals of Earth's climate as a system and the interaction of land, ocean and atmosphere through hands-on activities and demonstrations. Topics included air pressure, temperature, seasons, the greenhouse effect, humidity, clouds, wind, the Coriolis effect, storms, and colors in the sky. Discussions focused on understanding climate change and the need to plan remediation in respect to the public's understanding. One teacher commented "Knowing more about weather and climate makes us all better citizens and teachers". Teachers indicated that the material and resources included in this program will impact their own teaching and their students' understanding.

Twelve teachers of grades 3-8 participated in the seminar representing seven different school districts. In addition two pre-service teachers from Princeton University participated to further their understanding of content and instruction.

Teacher Feedback:

"Knowing more about weather and climate makes us all better citizens and teachers."

"Any teacher grades 2-12 would benefit from this course. I enthusiastically recommend this institute!!"

"Great instructor, Steve Carson, with engaging, informative models."

"I'm now better informed; made me more data-based and provided great models to use."

Temperature readings outside of Guyot Hall

Teachers conducting wind experiment

Researcher Steve Carson flanked by Quest 2012 Teachers

Progress Report Title: **Geostrophic Turbulence and Active Tracer Transport in 2 Dimensions Workshop March 13-15, 2013**

Principal Investigator: Isaac Held (GFDL/Princeton Lecturer with rank of Professor)

Other Participating Researchers: Peter Constantin (Princeton), Bill Young (Scripps Institution of Oceanography)

Task I: Administration & Outreach

NOAA Sponsor: Brian Gross (GFDL)

Education/Outreach

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

Objectives: The goal of this interdisciplinary workshop was to familiarize mathematicians and atmosphere/ocean scientists with ongoing research outside of their fields, and possibly fertilize new work within both groups.

Methods and Results/Accomplishments:

Many idealized models of atmospheric and oceanic flows reduce to the two-dimensional (2D) advection of a tracer that in turn determines the flow field. The classic example is non-divergent 2D flow on a plane (or a sphere), where the tracer is the vertical (or radial) component of the vorticity. Of special interest is the "geostrophic turbulence" generated in systems with two interacting active tracers, representing flow at the tropopause and the earth's surface in the simplest atmospheric case. Another example of special interest is surface quasi-geostrophic (SQG) flow, in which the state of the system is completely determined by the temperature at the surface. SQG flows bear some formal resemblance to 3D incompressible flows – for example, dimensional arguments suggest a -5/3 kinetic energy spectrum for the direct turbulent cascade to small scales, just as in 3D. SQG has developed into a model problem for those interested in singularity formation in 3D Euler or Navier-Stokes. The possible formation of singularities in SQG remains unsolved. There is also interest in possible blow-up of active scalar equations with more singular constitutive laws and in questions relating to long time behavior in the limit of small dissipative mechanisms.

The workshop provided the opportunity for mathematicians and AOS scientists to find some common ground, and exposed participants to new methods and models that will possibly fertilize new work within both groups. Approximately one dozen graduate students and post-docs attended from several U.S. universities, and 5 graduate students presented posters.

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 (NWS/NCRFC), Aizhong Ye (Beijing Normal University), Xing Yuan (Princeton), Joshua Roundy (Princeton)

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.

Methods and Results/Accomplishments:

We have updated the Princeton seasonal hydrologic forecast system by incorporating NLDAS-2 observation, replacing dynamical climate forecast model from CFSv1 to CFSv2, and re-calibrating the VIC model against over 1700 USGS streamflow gauges (Figure 1). We have investigated the role of downscaling precipitation and bias-correcting streamflow on the ensemble seasonal hydrologic forecast, and found that the proposed post-processing method is critical for more reliable and skillful streamflow forecast (Figure 2). We have also conducted a set of comprehensive hydrologic hindcasts over the CONUS region during 1982-2008, using climate forcing from ESP, CFSv1 and CFSv2. The hindcast is equivalent to 9720-year VIC simulation at 1/8 degree over CONUS. Validation over 1734 USGS gauges indicates that CFSv2-based streamflow forecasts is the most skillful during the first month, but all three approaches can hardly exceed the climatological forecast without post-processing (Figure 3). We are now exploring the contribution from multiple climate forecast models to the hydrologic prediction.

Publications:

Yuan, X., E. F. Wood, J. K. Roundy, and M. Pan, 2013: CFSv2-based seasonal hydroclimatic forecasts over conterminous United States. J. Climate, doi:10.1175/JCLI-D-12-00683.1, in press.

Yuan, X., and E. F. Wood, 2012: Downscaling precipitation or bias-correcting streamflow? Some implications for coupled general circulation model (CGCM)-based ensemble seasonal hydrologic forecast. Water Resour. Res., 48, W12519, doi:10.1029/2012WR012256.

Xia, Y. et al., 2012: 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. Geophys. Res., 117, D03109, doi:10.1029/2011JD016048.

Xia, Y. et al., 2012: 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. Geophys. Res., 117, D03110, 10.1029/2011JD016051.

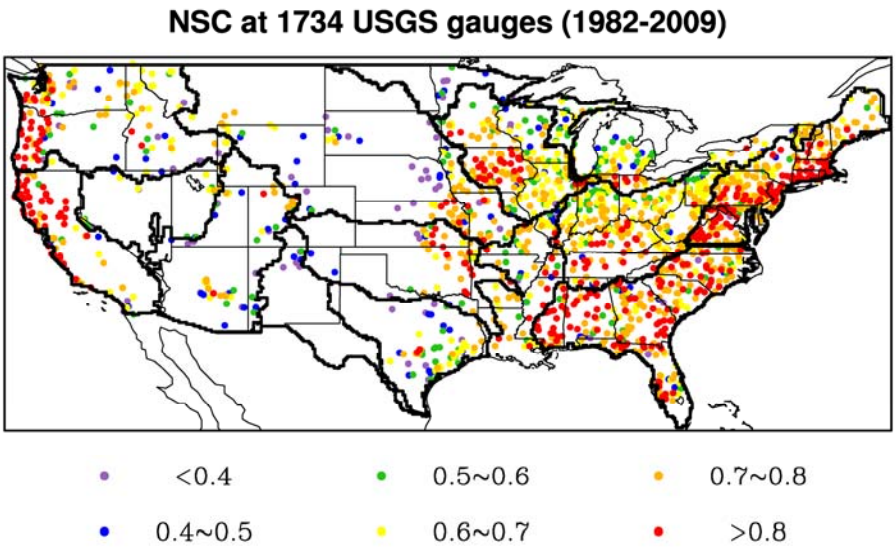


Figure 1. Nash-Sutcliffe efficiency coefficients (NSE) for monthly streamflow simulated by the re-calibrated water-budget VIC model at 1734 USGS gauges. (Yuan et al., *J Clim.*, 2013)

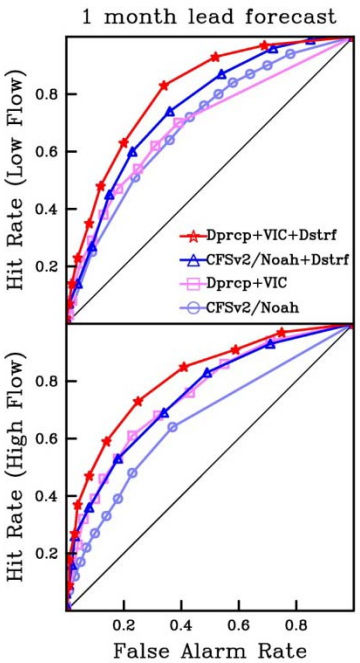


Figure 2. ROC diagrams for low- and high-streamflow month-1 forecasts averaged over Ohio basin. (Yuan and Wood, *WRR*, 2012)

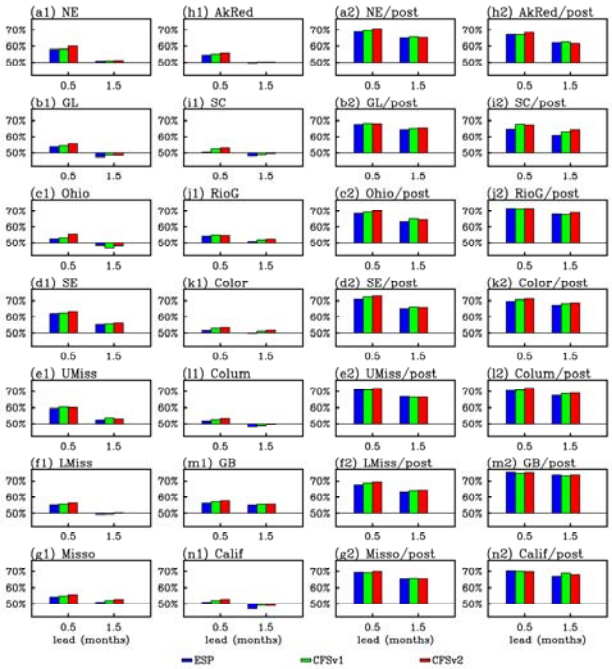


Figure 3. Percentages of positive *RPSS* for monthly streamflow forecasts without (a1-n1) and with (a2-n2) post-processing averaged over the 14 large basins. The reference forecast is climatology. (Yuan et al., *J Clim.*, 2013)

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

Principal Investigator: Eric F Wood (Princeton Professor)

Other Participating Researchers: Kingtse Mo (NCEP/CPC), Joshua Roundy (Princeton), Jonghun Kam (Princeton)

NOAA Sponsor: Kingtse Mo (NCEP/CPC)

Theme: Earth System Model Applications

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

Objectives: The 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 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. The primary mechanism we are investigating is the land-atmospheric coupling and the role this coupling plays in the development, continuation and recovery of drought. In our recent work we have developed a Coupling Drought Index (CDI) based on the classification of coupling state into wet or dry regimes. The classification of coupling is based on two summary statistics of the atmospheric boundary layer and top layer soil moisture. The advantage of this new classification is that is data driven and can be used to evaluate models or observations. All combinations of model, reanalysis and remote sensing data used to classify coupling indicate that the CDI is spatial and temporal consistent with the U.S. Drought monitor (Figure 1, Roundy et al. 2012).

Our recent work has extended this to look at the ability of the CFS forecasts to capture the consistent mechanism of coupling as compared to the reanalysis. To do this we analyzed the CDI over CFS hindcast period (1982-2009) and compare it with the reanalysis to better understand the ability to forecast drought. The results indicate that the forecasts show a more negative CDI (more wet coupling) as compared to the reanalysis for most of the continental United States (Figure 2, Roundy et al. 2013). The more negative CDI in the CFS forecasts indicates an increase in wet coupling and a decrease in dry coupling. The dry coupling state is associated with higher sensible heat fluxes and atmospheric warming by the land surface, which are important mechanisms of drought production and persistence. This suggests that it is unlikely that the CFS forecasts system can consistently predict summer time droughts, though individual events and ensembles may be different.

Publications:

Roundy, J. K., C. R. Ferguson, and E. F. Wood, 2012: Temporal variability of land-atmosphere coupling and its implication to drought over the Southeast United States. J. Hydrometeorology, (in press).

Roundy, J. K., C. R. Ferguson, and E. F. Wood, 2013: Impact of land-atmospheric coupling in CFSv2 on drought prediction J Climate Dynamics, (in review).

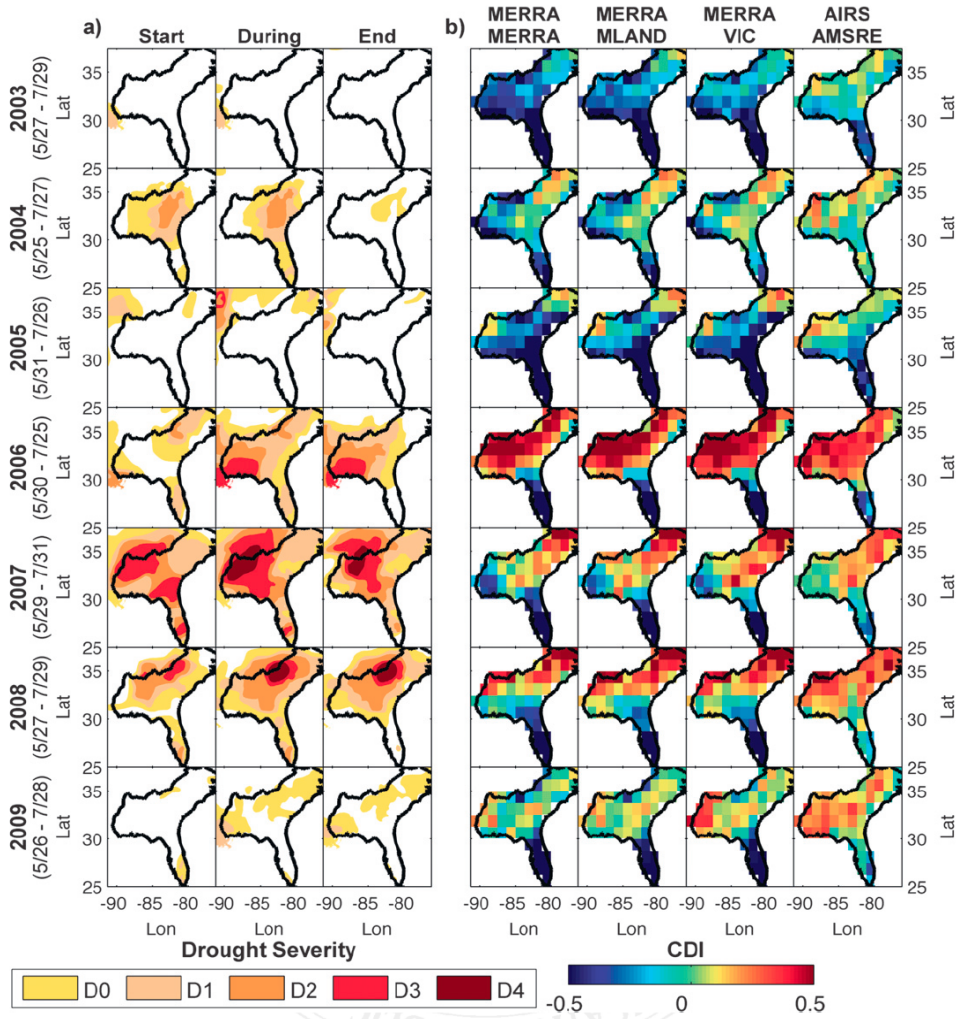


Figure 1 - The spatial and temporal variability of the 2003-2009 June-July (a) drought severity for the start, during and end of the time period and the (b) derived Coupling Drought Index (CDI) using various input datasets.

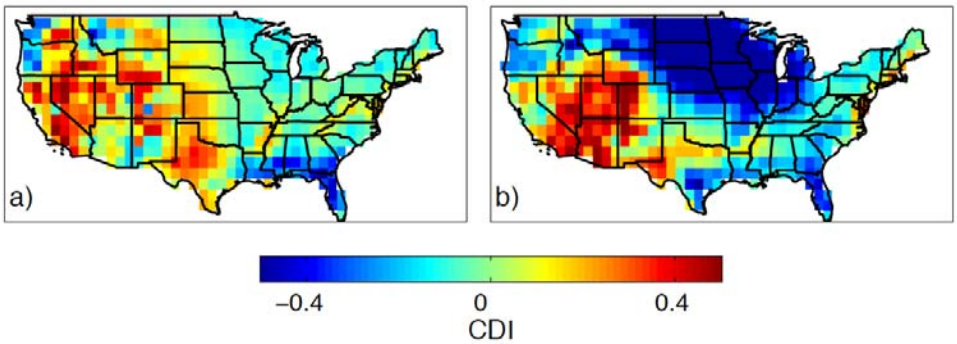


Figure 2 - The 28 year average CDI for the Summer months (June-September) over the Continental U.S. for a) the CFSR, b) Forecast initiated at 00Z May 31.

	JI Lead Author					NOAA Lead Author					Other Lead Author				
	FY 09	FY 10	FY 11	FY 12	FY 13	FY 09	FY 10	FY 11	FY 12	FY 13	FY 09	FY 10	FY 11	FY 12	FY 13
Peer-reviewed	14	31	30	30	34	2	3	2	5	8	6	21	29	31	28
Non Peer-reviewed	14	13	3	41*	64*	2	4	2	2*		2	7	2	2*	4*
Chapters in books	1	1													
Ph.D. Thesis		2	3	2	1										

**Including Presentations*

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Task I: Administrative Activities and Outreach Supported Personnel

Name	**Rank**
Carson, Steve	QUEST Summer Institute Instructor
Childers, Katelin	MPOWIR Graduate Student
Peters, Gregory	QUEST Summer Institute Lead Teacher
Sarmiento, Jorge L.	CICS Director
	CICS Associate
Vallis, Geoffrey K.	Director

Departures - Task II and Task III

Jan Huey Chen – August 1, 2012: UCAR Project Scientist at Naval Research Laboratory, CA

David Paynter – May 21, 2012: NOAA/GFDL

Ph.D. Defenses

Student: June Yeung
Advisor: James Smith – September 2012
Dissertation: Summertime Convective Rainfall in the New York City-New Jersey Metropolitan Region
Current Affiliation: ENVIRON International, Associate

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
Brayshaw, David	Visiting Associate Research Scholar	Vallis
Bollasina, Massimo	Postdoctoral Research Associate	Ming
Chai, Junyi	Graduate Student	Vallis
Chen, Jan-Huey	Postdoctoral Research Associate	SJ Lin
Choi, Kityan	Graduate Student	Vecchi
Fan, Yalin	Associate Research Scholar	Lin
Hill, Spencer	Graduate Student	Ming
Kapnick, Sarah	Postdoctoral Research Associate	Delworth
Keeley, Sarah	Visiting Associate Research Scholar	Winton
Legg, Sonya	Research Oceanographer	GFDL Director
Lin, Meiyun	Associate Research Scholar	Fiore
Logan, Cheryl	Professor at CSUMB	Dunne
Malyshev, Sergey	Professional Specialist	Pacala
Mao, Jingqiu	Associate Research Scholar	Horowitz
Melet, Angelique	Postdoctoral Research Associate	Hallberg
Mooring, Todd	Graduate Student	Vallis
Nikonov, Sergey	Professional Technical Specialist	Balaji
Ocko, Ilissa	Graduate Student	Ramaswamy
Orlanski, Isidoro	Sr. Research Meteorologist	GFDL Director
Persad, Geeta	Graduate Student	Ramaswamy
Potter, Sam	Graduate Student	Vallis
Radley, Claire	Graduate Student	Fueglistaler
Rykaczewski, Ryan	Professor-University of South Carolina	Dunne/Stock
Sergienko, Olga	Associate Research Scholar	Hallberg
Shevliakova, Elena	Professional Specialist	Pacala
Strong, Jeffrey	Graduate Student	Vecchi
Vallis, Geoffrey	Sr. Research Geoscientist	GFDL Director
Wang, He	Graduate Student	Legg
Zhang, Sophie	Associate Research Scholar	Vallis
Zhou, Wenyu	Graduate Student	Held

Task III: Individual Research Projects Supported Personnel

Name	**Rank**	**Advisor**
Beaulieu, Claudie	Associate Research Scholar	Sarmiento
Bonachela Fajardo, Juan	Postdoctoral Research Associate	Levin
Castruccio, Frederic	Postdoctoral Associate	Curchitser
Hervieux, Gaelle	Postdoctoral Associate	Curchitser
Jeong, Su-Jong	Postdoctoral Research Associate	Medvigy
Rodgers, Keith	Research Scholar	Sarmiento
Smith, K. Allison	Postdoctoral Research Associate	Sarmiento
Wright, Daniel	Graduate Student	Smith
Yeung, June	Graduate Student	Smith
Zanowski, Hannah	Graduate Student	Sarmiento

Shadow Awards: Individual Research Projects Supported Personnel

Name	**Rank**	**Advisor**
Kam, Jonghun	Graduate Student	Wood
Roundy, Joshua	Graduate Student	Wood
Ye, Aizhing	Visiting Associate Research Scholar	Wood
Yuan, Xing	Associate Climate Specialist	Wood

Personnel				
Category	Number	B.S.	M.S.	Ph.D.
Faculty	5	1	-	4
Research Scientist	5	-	-	5
Visiting Scientist	3	-	-	3
Postdoctoral Research Associate	8	-	-	8
Professional Technical Staff	4	-	-	4
Associate Research Scholar	7	-	-	7
Administrative	0	-	-	-
Total (≥ 50% support)	**21**			**21**
Undergraduates	0	-	-	-
Graduate Students	17	6	10	1
Employees that receive < 50% NOAA funding (not including graduate students)	12	1	-	11
Located at the Lab (include name of lab)	GFDL-25	3	5	17
Obtained NOAA employment within the last year	1			1

***Note:** includes shadow award personnel

CICS FY'13 List of Awards for Institutional Award NA08OAR4320752

Amount	PI	Project Title
$ 51,413[*19]	Jorge L. Sarmiento	Administration (Task I) *GFDL-Brian Gross*
$ 8,995[*19]	Jorge L. Sarmiento	Administration (Task I) MPOWIR *GFDL-Brian Gross*
$ 6,240[*19]	Jorge L. Sarmiento	Administration (Task I) QUEST *GFDL-Brian Gross*
$ 40,000 [*18]	Keith Rodgers	Using Models to improve our ability to monitor ocean uptake of anthropogenic carbon (Task III) *COD-Joel Levy*
$ 38,042 [*19]	James A. Smith	Regional Climate Studies Using the Weather Research and Forecasting Model (Task III) *GFDL-Brian Gross*
$ 11,701 [*19]	Claudie Beaulieu	Detection and Attribution of abrupt and gradual changes in the carbon system (Task III) *GFDL-Brian Gross*
$ 61,135 [*19]	K. Allison Smith	Predicting the impacts of climate change on mesopelagic ecosystems (Task III) *GFDL-Brian Gross*
$ 45,673 [*19]	David Medvigy	Large-scale variations in forest phenology and their impacts on surface water, energy, and carbon fluxes over North America (Task III) *GFDL-Brian Gross*
$ 69, 625 [*19]	Alexander Smits Elie Bou-Zeid	The Response of a turbulent boundary layer to a step change in stabilizing surface heat flux (Task III) *GFDL-Brian Gross*
$ 52,091 [*19]	Stephan Fueglistaler Claire Radley	Variations and trends in local and global radiative fluxes, and their relation to processes of the hydrological cycle (Task III) *GFDL-Brian Gross*
$ 46,713 [*19]	Robert M. Key	Creation of GLODAPv2: A next generation data product for model initialization, comparison and/or assimilation (Task III) *GFDL-Brian Gross*
$ 58,088 [*19]	Frederick Simons	Mapping Antarctica's mass loss in space and time (Task III) *GFDL-Brian Gross*
$ 76,085 [*19]	Jorge Sarmiento Hannah Zanowski	Signal tracking of Antarctic open-ocean polynyas (Task III) *GFDL-Brian Gross*
($ 12,791 [*9])	Lars Hedin Stephen Gerber	Terrestrial Carbon-Nitrogen Interactions in the Earth System (Task III) *GFDL-Brian Gross*
$2,552,179 [*19]	Geoffrey K. Vallis	Cooperative Research Projects and Education (Task II) *GFDL-Brian Gross*

Amendment No./PI	**Amount**	**Project Title**
Amendment #18: PI: Keith Rodgers	$40,000	Using Models to Improve our Ability to Monitor Ocean Uptake of Anthropogenic Carbon
Amendment #19: PI: Jorge Sarmiento Co-PI: Geoff Vallis	$3,065,189	CICS-Princeton: Year 5 Task I: $110,010 ($43,362 rebudgeted to Task III) Task II: $2,752,179 ($200,00 rebudgeted to Task III) Task III: $203,000