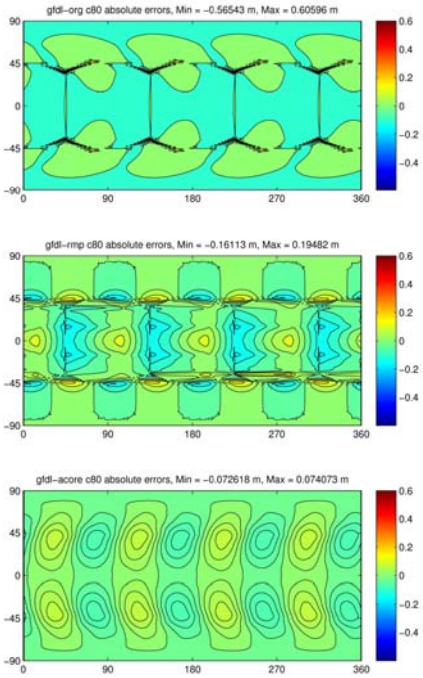
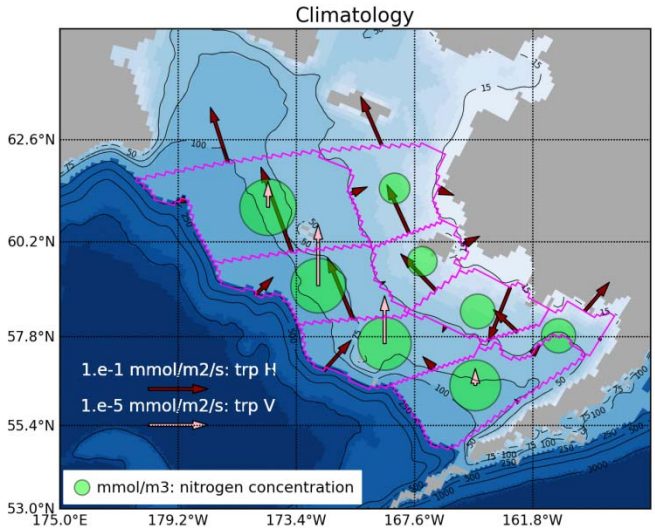


Annual Progress Report
April 1, 2013 – March 31, 2014

Cooperative Institute for Climate Science
at Princeton University
NOAA Cooperative Agreement NA08OAR4320752



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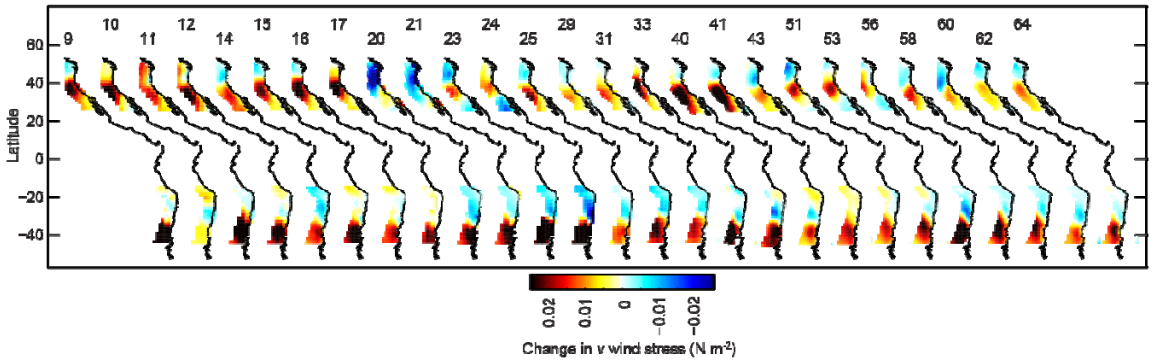

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Cooperative Institute for Climate Science
Princeton University

Annual Progress Report under cooperative agreement NA08OAR4320752

For the period April 1, 2013 – March 31, 2014

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 a 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 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. A sea-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 processes into the model, and ecosystem modeling.

Both of these are continual undertakings, 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. 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 Sea-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. 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.

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 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.

Analogous to the development of ESMs, data assimilation in ESMs has many components, and research in CICS focuses 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.

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 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 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 are being 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 and the land) where CICS has particular expertise, or that are concerned with understanding the interactions between those 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, are carried out as part of a close collaboration with GFDL.

Education/Outreach

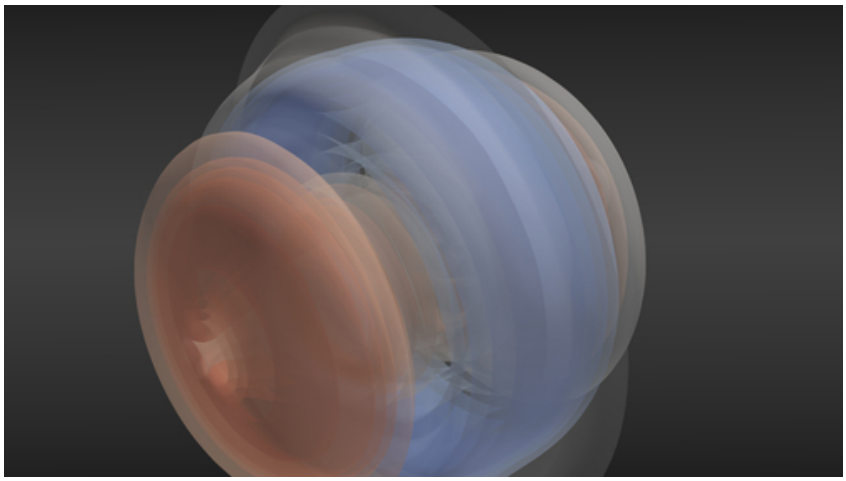
Science Action (SA)

During the 2012-2013 academic year, a pilot program for informal online education at Princeton University entitled Science Action (SA) ran in the spring term with funding support from eight centers and departments affiliated with the University, including CICS. The pilot program invited Princeton undergraduate and graduate students to form teams and trained them to concisely communicate an explanation about a topic in science or engineering, in the form of a 3-5 minute video. Specific topics were selected from three proposed themes: climate science, fusion physics, and engineering principles. After receiving guidance from Writing Mentors (recruited from the Princeton Writing Program faculty) and Science Mentors (recruited from Princeton's postdoctoral research community), students' videos were vetted by the Science Mentors to ensure scientific accuracy. The vetted videos were uploaded to a dedicated Princeton YouTube page (http://www.youtube.com/user/princetonSA/videos) and made available to the online community, as an informal University outreach to promote science education and science literacy.

A total of six student teams were formed during the pilot year of Science Action (SA1) comprised of a majority of undergraduates, graduate students, and two postdoctoral students. In total, there were 24 participants in year 1 of SA. The videos from year 1 have demonstrated several novel approaches to demystifying the complexity of an advanced scientific theory, and participants revealed in collected testimonials how they found the process of research and communication to be a compelling experience.

Art of Science

CICS co-sponsored the Art of Science 2013, a competition that explores the interplay between science and art. The 2013 competition drew 170 submissions from 24 departments across the University. The exhibit includes work by undergraduates, faculty, staff, graduate students, and alumni and consists of 43 images of artistic merit created during the course of scientific research. Entries were chosen for their aesthetic excellence as well as scientific or technical interest.



East-West, West-East
Martin Jucker, Program in Atmospheric and Oceanic Sciences

The first prize image was "East-West, West-East," a visualization of the Earth's wind patterns in shades of red and blue, by Martin Jucker, an associate research scholar in the Program in Atmospheric and Oceanic Sciences. The Art of Science 2013 images can be viewed in an online gallery http://www.princeton.edu/artofscience/gallery2013/.

Mentoring Physical Oceanography Women to Improve Retention (MPOWIR) NOAA Graduate Internship

MPOWIR, a community mentoring program designed to improve retention of female physical oceanographers, has for several years sponsored a graduate internship at NOAA laboratories, including GFDL. Every year 1-2 female physical oceanography students, enrolled in a graduate program in the USA, are selected to spend 8-10 weeks working in a NOAA lab. The program aims to expose the students to the range of work carried out at NOAA facilities, and ultimately improve the diversity of the NOAA workforce. In the summer of 2013 two students, Chen Chen from Columbia University and Jinting Zhang from University of Washington, were selected as MPOWIR interns working at GFDL with Andrew Wittenberg and Rong Zhang. Both students had a successful summer

of research at GFDL, culminating in research seminars, and leading to continuing collaboration. The NOAA funding, administered through CICS, covered all of their related travel expenses.

2014 Young Women's Conference in Science, Mathematics, Technology, and Engineering

CICS students Todd Mooring and Hannah Zanowski, CICS postdoc Allison Smith and CICS Associate Director Sonya Legg, along with colleagues from AOS and GFDL, participated in the annual Young Women's Conference organized by the Princeton Plasma Physics Laboratory on March 21st 2014. Almost 400 young women from middle and high schools in New Jersey, New York and Pennsylvania spent the day being exposed to science careers by female role models. The CICS hand-on display included density current experiments illustrating the ocean thermohaline structure, a rotating fluid tank demonstrating the large-scale atmospheric circulation, and experiments exploring ocean acidification. This outreach event also benefited the CICS student and postdoc participants by providing them with an opportunity to improve their communication skills.

Structure of the Joint Institute

Princeton University and NOAA's Geophysical Fluid Dynamics Laboratory have a successful 47-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:

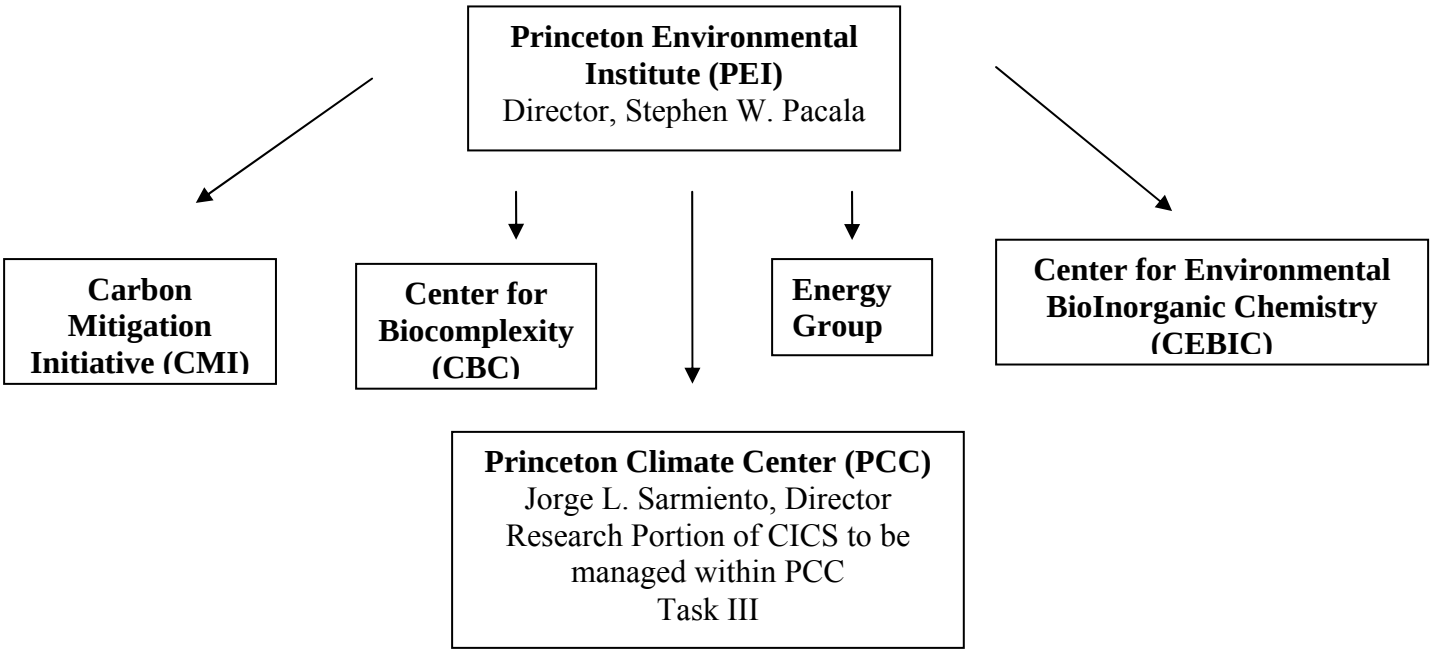
I. Administrative Activities including outreach efforts are carried out jointly by the AOS Program and Princeton Environmental Institute (PEI).

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.

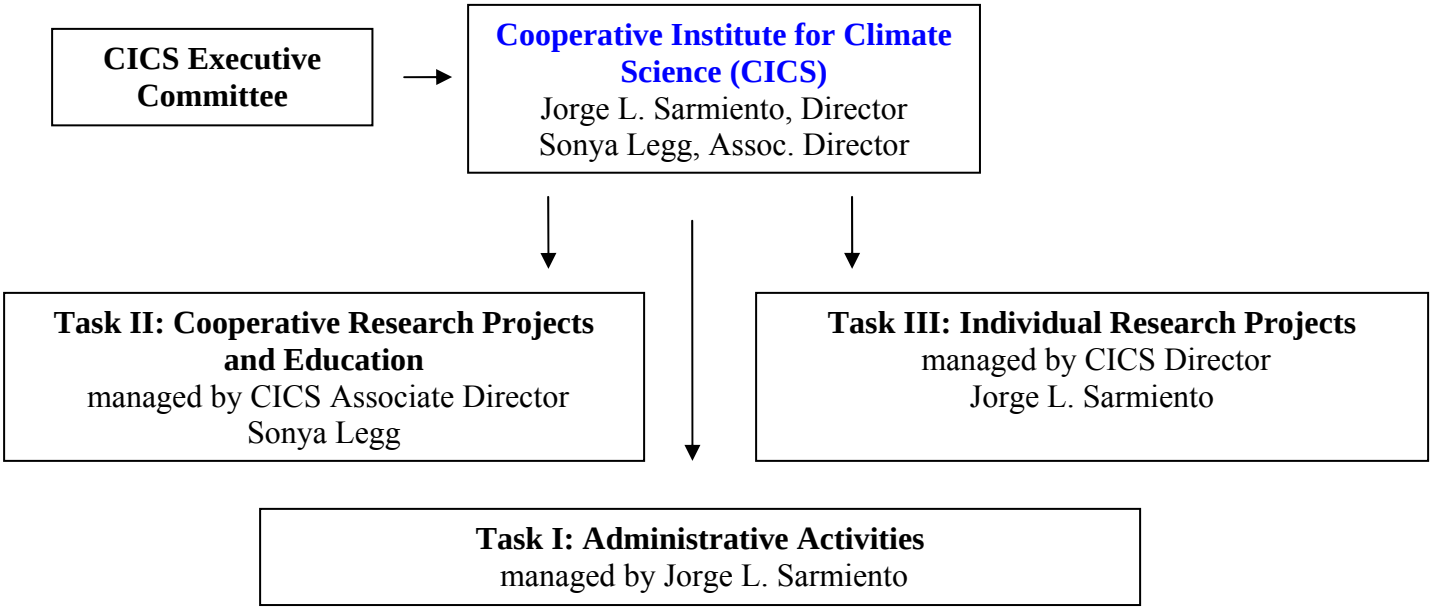
III. Principal Investigator led research projects supported by grants from NOAA that comply with the themes of CICS. These all occur within AOS and the Princeton Environmental Institute (PEI), and may also include subcontracts to research groups at other institutions on an as needed basis.

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.

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
Sonya Legg – Associate Director of CICS and 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

The following selection highlights a few of the many research advances made by CICS researchers in the past year, organized by the major themes of the cooperative institute. While space constraints do not permit us to cover the full breadth of CICS research, we aim to showcase a representative cross-section.

EARTH SYSTEM MODELING: DEVELOPMENT and ANALYSIS

Earth system model development and analysis includes a wide range of activities, from fundamental research into specific component processes of the climate system, to analysis of simulations generated by the complex models including many of these different components. Here we summarize and highlight some of the activities in model development and analysis over the past year.

Ocean Waves and Climate

Ocean waves are an example of phenomena which both respond to and influence the large scale climate, yet are too small to explicitly resolve at the coarse resolution required for global climate simulations. These small-scale phenomena must therefore be parameterized, i.e. represented in terms of the resolved quantities. CICS Postdoctoral researchers Yalin Fan and Angelique Melet have examined the interactions between two different types of waves and large-scale climate through the incorporation of new parameterizations in the climate models. Fan, in collaboration with S. Griffies and S.J. Lin at GFDL, has focused on surface waves driven by the winds, coupling a surface wave model to a global atmospheric or physical climate model. Fan shows that global warming can modify the surface wave statistics, while surface waves, through their impact on upper-ocean mixing, can influence mixed-layer depth, overturning circulation and sea surface temperature. Melet, in collaboration with R. Hallberg, S. Legg, and former CICS postdoc Maxim Nikurashin, has examined the impact of parameterizations of a different type of ocean wave, deep lee-waves driven by geostrophic flow over abyssal topography. Deep mixing generated by these waves is most pronounced in the Southern Ocean, influencing the Southern Ocean stratification and overturning. The parameterizations of wave-induced mixing examined by Fan and Melet will contribute to more accurate future versions of GFDL climate models.

Improved Atmospheric Organic Chemistry

Organic chemistry is an important component of the earth system, providing a link between the biosphere and the atmospheric physical system. Jingqiu Mao has identified a new mechanism for oxidation of isoprene, a natural emission from plants, which influences tropospheric ozone and organic nitrates. Mao has implemented this mechanism in the coupled chemistry-climate model AM3 and evaluated the model chemistry with observations, leading to a more accurate simulation of tropospheric ozone. Mao identified a previously unrecognized role of aerosols in atmospheric oxidant chemistry, which when included in AM3 shows that biomass burning, associated with emissions of trace gases and aerosols, can lead to a nonlinear impact on radiative forcing, such that low emission levels lead to a net cooling, while higher levels lead to a net warming. These improvements to the chemistry model are important for correctly predicting climate-change related feedbacks in the earth system.

Software Infrastructure for Climate Modeling

A vital component of a complex climate model development effort, involving coupling of multiple constituent models, is the software environment which allows scientific groups to coordinate development of new physics packages and algorithms. At GFDL this task is carried out by the Flexible Modeling System (FMS), developed under the leadership of V. Balaji. The runtime environment, post-processing and data archival for the long batch jobs on supercomputers needed to achieve GFDL's climate simulation goals is coordinated by the FMS Runtime Environment (FRE) which encapsulates complete model configurations in a single file. A notable achievement of the past year is the development of FRE as a distributed workflow system spanning multiple sites (GFDL, NCCS, NCRC). Another fundamental aspect of climate model software is the dynamical core; the discretization of the fluid dynamical equations separate from the parameterizations of physics and subgrid-scale phenomena. Postdoc Xi Chen, working with GFDL scientists S-J Lin and Lucas Harris, has been developing numerical improvements to the accuracy and efficiency of the GFDL cubed-sphere atmospheric dynamical core, contributing to the development of the next generation GFDL coupled climate model CM4.

Spatial and Temporal Variability of Antarctic Ice-Sheet

An important requirement for models of the present and future climate system is evaluation against observations. For an ice-sheet model capable of predicting the changes which may give rise to substantial sea-level rise, observations of the trends in ice-sheet mass are therefore essential, including observations of the spatial variability of these trends, in order to distinguish between different mechanisms for ice-sheet decline. Frederik Simons and postdoc Christopher Harig, of Princeton's department of Geosciences, have analyzed the data from the Gravity Recovery and Climate Experiment (GRACE) over the past 10 years, to show that the pattern of ice-loss is highly variable, with increased rates of loss in Western Antarctica, slight increases in rates of loss in the Antarctic Peninsula and ice-mass gain in Dronning Maud land. The increased rates of loss in Western Antarctica are associated with regions where warm ocean waters have direct access to the ice-shelves, a mechanism for ice-sheet decline being investigated by Olga Sergienko in collaboration with Robert Hallberg at GFDL.

EARTH SYSTEM MODELING: APPLICATIONS

The earth system models developed by CICS and GFDL researchers are applied to examine a variety of societally relevant problems. Here we highlight some of the most interesting and exciting applications made over the past year.

Reductions in Historical Warming due to Land-Carbon Uptake

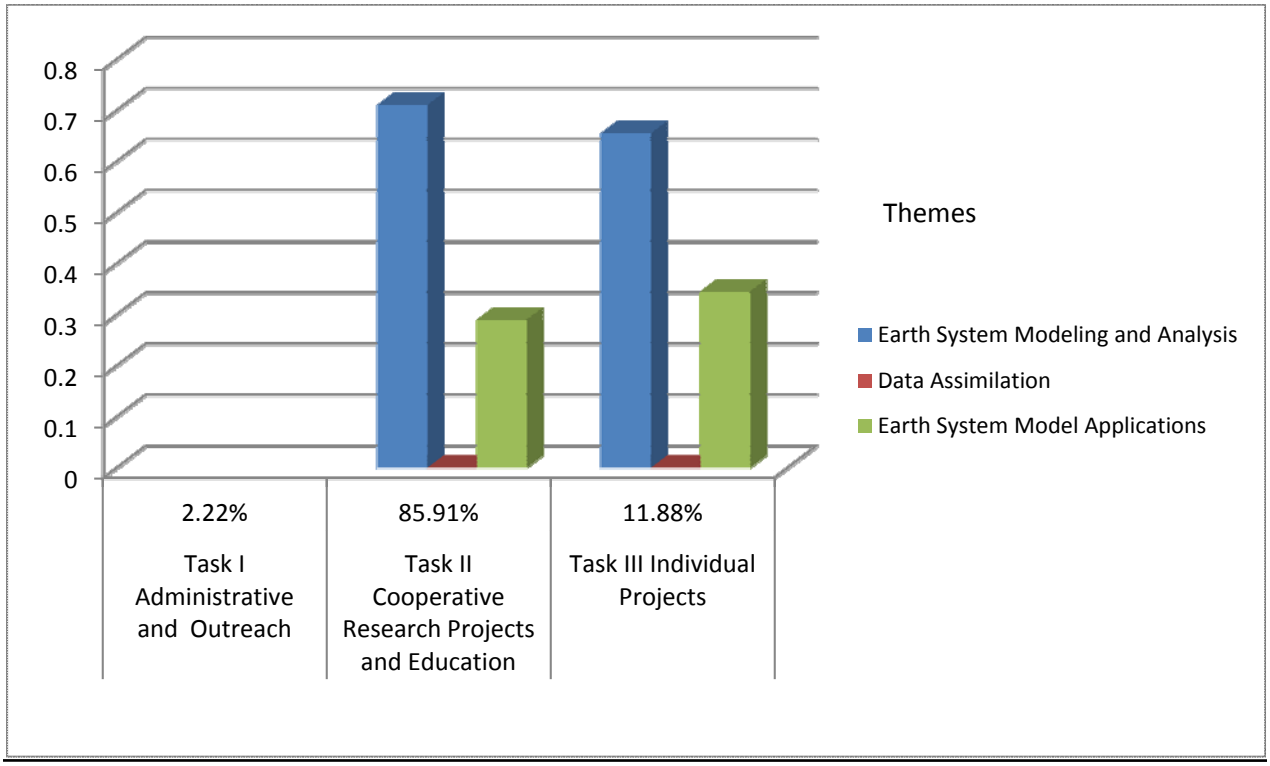
The development of NOAA's first global coupled climate-carbon earth system models, EM2M and ESM2G, was recently completed by a team involving GFDL scientists and CICS researchers, Elena Shevliakova and Sergey Malyshev. Now Shevliakova and Malyshev, with Princeton and GFDL colleagues, have applied this model to examine the role that the uptake of carbon by the terrestrial biosphere has played in modifying historical atmospheric carbon dioxide levels and hence the observed anthropogenic global warming. They find that without the enhanced vegetation growth due

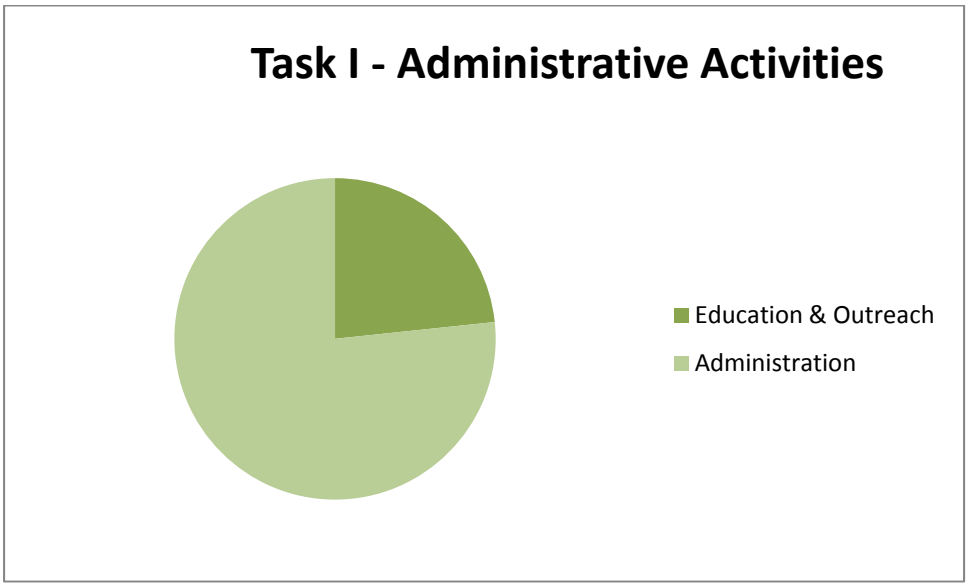
to CO2 fertilization, historical CO2 levels would have increased more rapidly, and an additional 0.3 degrees C global warming would have occurred.

Ocean Ecosystems and Climate

A considerable research activity on ocean ecosystem response to climate change has developed at Princeton University and nearby Rutgers University, much of this with outside funding. As part of an ongoing growth of interest in this topic CICS is capitalizing on this work through investments in a range of areas. One of these is high resolution regional circulation (ROMS) and lower trophic level models of the impact of climate variability and change on the Bering Sea and California current region by Curchitser at Rutgers, and complementary work in the California Current Large Marine Ecosystem by fisheries ecologist, Ryan Rykaczewski (who was a post-doc at Princeton and is now a faculty member at the University of South Carolina). Meanwhile, Cheryl Logan (also a former post-doc and now at California State University Monterey Bay) developed an improved empirical algorithm for predicting coral bleaching events and is now applying these to predict how climate warming and ocean acidification will affect coral reefs in the future. At a more fundamental level, Prof. Simon Levin of Princeton University is developing improved models of dynamic phytoplankton stoichiometry and virus impacts on plankton populations. Post-doc Allison Smith has developed a mechanistic model of particulate organic matter cycling by bacteria in the mesopelagic including the effect of quorum sensing.

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. Educational outreach activities included funding for a MPOWIR supported graduate students. Princeton University matching funds also co-supported Science Action and the Art of Science.

Project Titles

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

Education/Outreach Projects

- Science Action
- Art of Science
- Mentoring Physical Oceanography Women to Improve Retention (MPOWIR) NOAA Graduate Internship
- 2014 Young Women's Conference in Science, Mathematics, Technology, and Engineering

Earth System Modeling and Analysis Projects

- Hybrid Ocean Model Development (Alistair Adcroft)
- Flexible Modeling System (FMS) (V. Balaji)
- Equilibration of a Primitive Equation GCM in the Limit of Zero Large Scale Friction (Junyi Chai)
- Development of GFDL Cubed-Sphere Dynamic Core with Horizontal Remap Algorithm and Non-Staggered Riemann Solver Based Numerical Scheme (Xi Chen)
- Roles of Wind and Precipitation Nonlinearities in ENSO Asymmetries (Kityan Choi)
- Downscaling of Climate Models and Ecosystems Implications (Enrique Curchitser – Rutgers)
- Air-Sea Interaction in an Ocean with Mesoscale Eddies, Ocean Surface Waves, and Tropical Cyclones (Yalin Fan)
- Variations and Trends in Local and Global Radiative Fluxes, and their Relation to Processes of the Hydrological Cycle (Stephan Fueglistaler)
- Parameterizing Eddy Transports in Eddy-Permitting Ocean Models (Malte Jansen)
- Ocean Mixing Processes and Parameterization (Sonya Legg)
- Top-Down Controls on Marine Microbial Diversity and its Effects on Primary Productivity in the Oceans (Simon Levin)
- Urban Model Development (Dan Li)
- The Fluctuation-Dissipation Theorem in a Two-Layer Model of Quasi-Geostrophic Turbulence (Nicholas Lutsko)
- Ozone and Secondary Organic Aerosols over Southeast U.S. (Jingqiu Mao)
- Internal-Wave Driven Mixing in the Ocean: Parameterizations and Climatic Impacts (Angélique Melet)
- Baroclinic Wave Activity in the Martian Atmosphere (Todd Mooring)
- Internal Wave Mixing in Continental Slope Canyons (Robert Nazarian)
- Embedding Curator Infrastructure into FMS Runtime Environment (Serguei Nikonov)
- Processes that Control Climate Change over the Southern Hemisphere (Isidoro Orlanski)
- Development of an Ice-Sheet Model (Olga Sergienko)
- Land Carbon Dynamics and Climate Change (Elena Shevliakova)
- Mapping Antarctica's Mass Loss in Space and Time (Frederik J. Simons)
- Regional Climate Studies Using the Weather Research and Forecasting Model (James Smith)
- Biophysical Models and the Spatial Ecology of Temperature and Oxygen in the Mesopelagic Zone of the Global Ocean (Katherine Allison Smith)
- The Response of a Turbulent Boundary Layer to a Step Change in Stabilizing Surface Heat Flux (Alexander Smits and Elie Bou-Zeid)

Earth System Modeling and Analysis Projects continued

- Improving Microphysical Parameterization in Numerical Models (Kara J. Sulia)
- Processes of Dense Water Formation and Transport in the North Atlantic and their Influences on the Climate (He Wang)
- Implementation of Ice Nucleation Scheme in Mixed-Phase Clouds (Yuxing Yun)
- Decadal Variability and Prediction (Liping Zhang)

Data Assimilation Projects

- Creation of GLODAPv2: A Next Generation Data Product for Model Initialization, Comparison and/or Assimilation (Robert Key)

Earth System Model Applications Projects

- Central Asian Climate: Aridity and Orography (Jane Baldwin)
- Dynamical Responses of the Tropical Atmosphere to Anthropogenic Forcing (Spencer Hill)
- Assessing the Hydroclimate in High-Resolution GCMs (Sarah Bancroft Kapnick)
- Climate Versus Emission Drivers of Tropospheric Ozone Variability and Trends (Meiyun Lin)
- Stratospheric Circulation Changes in Response to Natural and Anthropogenic Forcings (Pu Lin)
- Modeling the Effects of Climate Change and Ocean Acidification on Global Coral Reefs (Cheryl Logan)
- Diurnal Land/Atmosphere Coupling Experiment (DICE) (Sergey Malyshev)
- Remote and Regional Impacts of East Asian Aerosol/Climate Interactions (Geeta Persad)
- Using Models to Improve our Ability to Monitor Ocean Uptake of Anthropogenic Carbon (Keith Rodgers)
- NOAA/GFDL Earth System Model Downscaling in the California Current Large Marine Ecosystem (Ryan Rykaczewski)
- Climate Response to Saharan Dust Perturbations (Jeffrey Strong)
- Signal Tracking of Antarctic Open-Ocean Polynyas (Hannah Zanowski)

Progress Reports:

Earth System Modeling and Analysis

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

Principal Investigator: Alistair Adcroft (Princeton Research Oceanographer)

CICS/GFDL Collaborator: Robert Hallberg (GFDL), Stephen Griffies (GFDL), Malte Jansen (Princeton)

Other Participating Researchers: Mehmet Ilicak (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:

In December 2012, I was asked to lead the Ocean Working Group whose task it is to build the ocean component of the GFDL's next coupled model, CM4. OWG efforts initially align with the development of the new ocean model MOM6, which unifies the capabilities of MOM5 and GOLD, and which also began at the end of 2012. The lion's share of 2013 has been devoted to both these development efforts.

In addition to model development, work has progressed on two new parameterizations. In conjunction with Malte Jansen, the mesoscale eddy kinetic energy (MEKE) energetics framework is being revisited and extended. With Robert Hallberg's "eddy-resolution switch", we hope to model the unresolved eddy energy in an eddy-permitting model, which will greatly improve the fidelity of the contemporary class of intermediate-resolution models. In collaboration with Ilicak and Legg, we have submitted a paper on a new framework that accounts for the sub-grid scale heterogeneity of boundary layer physics. This framework extends one-dimensional parameterizations to an imaginary dimension along which we model the sub-grid scale variations in stratification. It has the potential to allow deep-water formation on small-scales even in a coarse resolution model that might be stably stratified in the mean.

My paper on a porous barrier representation of topography was accepted with commendations from the reviewers! I have since been extending the concept in preparation for implementing the ideas in a 3D general circulation model (i.e. MOM6). Fig. 1 shows how porous barriers will allow a GCM to more faithfully represent the transport and exchange of water masses where they are under the control of unresolved topography.

Publications:

A framework for parameterization of open-ocean deep convection. Ilicak, M., Adcroft, A., and Legg, S., 2014: Ocean Modelling. Submitted.

An Order-invariant Real-to-Integer Conversion Sum. Hallberg, R., and Adcroft, A., 2014: Parallel Computing. accepted.

Atlantic Watermass and Circulation Response to Persistent Freshwater Forcing in Two Coupled General Circulation Models. Harrison, M., Adcroft, A., and Hallberg, R., 2014: Climate Dynamics, 42 (1-2), p. 59-68, http://dx.doi.org/10.1007/s00382-013-1798-5.

Representation of topography by porous barriers and objective interpolation of topographic data. Adcroft, A., 2013: Ocean Modelling, 67, p. 13-27, http://dx.doi.org/10.1016/j.ocemod.2013.03.002.

Sensitivity of 21st Century global-mean steric sea level rise to ocean model formulation. Hallberg, R., Adcroft, A., Dunne, J., Krasting, J. and Stouffer, R., 2013: Journal of Climate, 26(9), doi:10.1175/JCLI-D-12-00506.1.

Routes to Energy Dissipation for Geostrophic Flows in the Southern Ocean. Nikurashin, M., Vallis, G., and Adcroft, A., 2013: Nature - Geosciences, 6, p. 48-51, http://dx.doi.org/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., 2013: J. Climate, 26 (7), 2247-2267, http://dx.doi.org/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., 2013: J. Climate, 26, 231-245, http://dx.doi.org/10.1175/JCLI-D-12-00121.1.

Figures:

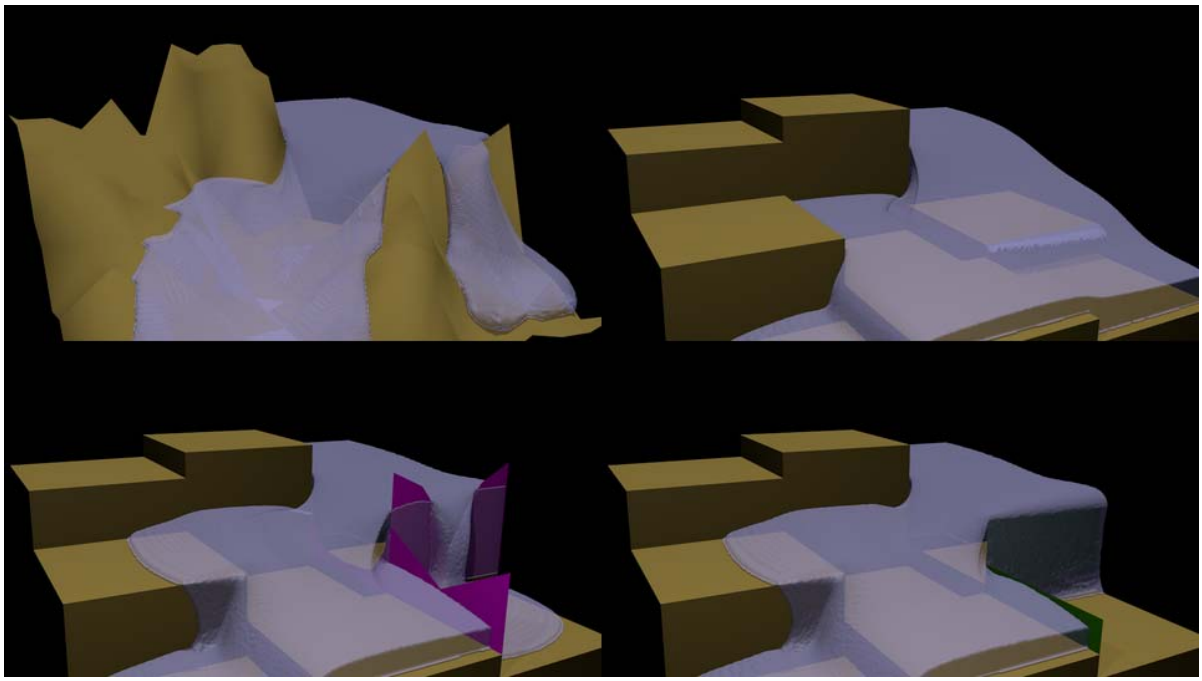


Fig. 1: A cartoon of how a deep water-mass could traverse some complex topography, and three illustrations of how models might represent that topography and water mass evolution.

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

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

CICS/GFDL Collaborator: Gabriel Vecchi (GFDL), Alistair Adcroft (Princeton), Isaac Held (GFDL), Keith Dixon (GFDL), Tony Rosati (GFDL), S-J Lin (GFDL), Jorge Sarmiento (Princeton), Stefan Fueglistaler (Princeton), Sergey Nikonov (Princeton), Karen Paffendorf (Princeton)

Other Participating Researchers: Karl Taylor (DoE/PCMDI), Max Suarez (NASA/GMAO), Steve Hankin (NOAA/PMEL), George Philander (Princeton), Steve Pacala (Princeton), Bryan Lawrence (Reading), Paul Kushner (U Toronto), Duane Waliser (UCLA)

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); 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 international Summer School on Ocean Modeling, Hyderabad, India, July 2013, sponsored by International Centre for Theoretical Physics (ICTP), Trieste; keynote address at Parallel Computing Technologies (ParCompTech) Conference, Bangalore, India, February 2013; Perfect-model framework for evaluation of statistical downscaling unveiled at NCPP Workshop, August 2013; and fully-automated seasonal forecast system delivers quasi-operational forecast starting March 2014, with monthly updates to follow from here on.

References:

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

Publications:

Moine, M.-P., et al., 2013: Development and exploitation of a controlled vocabulary in support of climate modelling. Geoscientific Model Development Discussions, 6 (2), 2967–3001, doi:10.5194/gmdd-6-2967-2013.

Guilyardi, E., V. Balaji et al., 2013: Documenting Climate Models and Their Simulations. Bull. Amer. Met. Soc., 94 (5), 623–627.

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

Balaji, V., R. Redler, and R. Budich, 2013: Earth System Modeling - Volume 4: IO and Postprocessing. Springer Berlin Heidelberg, doi: 10.1007/978-3-642-36464-8.

Balaji, V., 2013c: 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., 2013a: Input/Output and Postprocessing. Earth System Modelling - Volume 4, SpringerBerlin Heidelberg, SpringerBriefs in Earth System Sciences, 1–2, DOI: 10.1007/978-3-642-364648 1.

Siebers, B. and V. Balaji, 2013: Data Storage. Earth System Modelling - Volume 4, Springer BerlinHeidelberg, SpringerBriefs in Earth System Sciences, 21–24, DOI: 10.1007/978-3-642-36464-8 4.

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.: Coupling technologies for Earth System Modelling, Geosci. Model Dev., 5, 1589-1596.

Progress Report Title: **Equilibration of a Primitive Equation GCM in the Limit of Zero Large Scale Friction**

Principal Investigator: Junyi Chai (Princeton Graduate Student)

CICS/GFDL Collaborator: Isaac Held (GFDL), Malte Jansen (Princeton)

Other Participating Researchers: Geoffrey Vallis (Exeter)

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: Aiming to understand how the large scale surface friction affects the equilibration of baroclinic eddies by exploring the zero friction limit, which leads to a surprising but elegant solution to the primitive equations --This may be relevant for understanding the difference in mid-latitude circulation between Southern and Northern hemispheres which have different bottom roughness; therefore, different strength of bottom friction.

Methods and Results/Accomplishments:

The mean state of terrestrial atmosphere in the extra-tropics is largely controlled by the equilibration of baroclinic eddies (Schneider and Walker 2006). Therefore, an understanding on the equilibration of baroclinic eddies is crucial for a general circulation theory. In numerical general circulation models (GCMs), a bottom friction which acts at large scale is needed to ultimately remove the kinetic energy from eddies and zonal mean flows. As GCMs can only resolve large scale quasi two-dimensional motions, little energy is lost to the grid-scale filter due to the inverse cascade. Therefore a large scale energy sink is needed to close the energy cycle. In reality, the surface friction may present a parameterization of small scale three-dimensional turbulent boundary layer processes that cascade kinetic energy to smaller and smaller scales until eventually the energy is dissipated by molecular viscosity.

Surprisingly, and in contrary with pure two-dimensional turbulence driven with a steady energy injection rate, the idealized primitive equation GCM can equilibrate without large scale bottom friction. The equilibrate state has no eddy activities, but only strong zonal winds that extend to the surface. In fact, the mechanism for the GCM to equilibrate can be understood as the magnitude of zonal wind will keep increasing in the absence of friction, until the barotropic governor effect is so strong that the baroclinic instability is totally suppressed. The temperature field in the equilibrium state is the same as the prescribed equilibrium temperature. A theoretical understanding for this state arises from considering the entropy budget (Held 2007). The large scale radiative damping decreases the entropy of the flow, as the warmer equatorial region gets heated and polar region gets cooled. The decrease in entropy is balanced by the creation of entropy due to surface friction. When surface friction does not exist, the entropy creation is zero, so that the entropy sink and the related poleward heat transport needs to become zero, so there is no baroclinic instability. This seems a plausible explanation. The only difficulty is how to make an analogous entropy budget for a shallow water system and see why the shallow water system can equilibrate by damping height perturbation but still allow eddies to exist. The entropy budget is validated by numerical simulations. It suggests that the above zero friction solution may not be only limited to the idealized GCM but may be relevant for more realistic bottom friction and radiations.

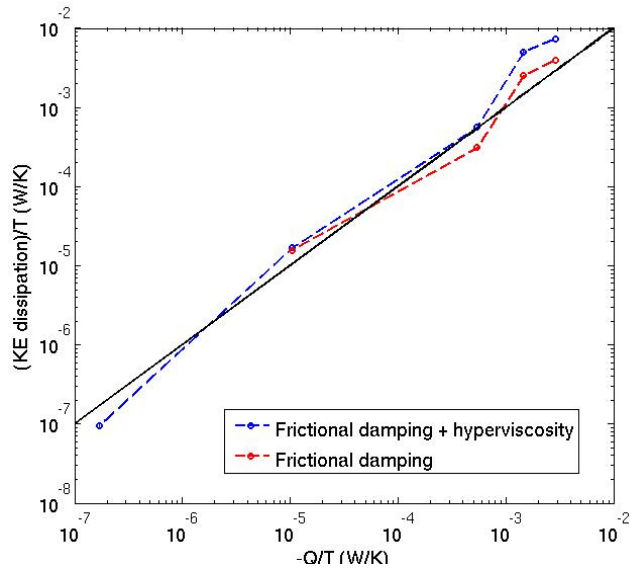


Figure 1: Entropy budget: entropy sink vs. production.

References:

Held, Isaac M., 2007: Progress and problems in large-scale atmospheric dynamics. In The Global Circulation of the Atmosphere, T. Schneider and A. Sobel, eds., Princeton, NJ, Princeton University Press, 1-21.

Schneider, T., and C. C. Walker, 2006: Self-organization of atmospheric macroturbulence into critical states of weak nonlinear eddy-eddy interactions. J. Atmos. *Sci.*, 63, 1569-1586.

Publications:

Chai, J. and Vallis, G. K., 2014. The role of criticality on the horizontal and vertical scales of extratropical eddies in a dry GCM, accepted by J. Atmos. Sci.

Chai, J. and Vallis, G. K., 2013., The spontaneous emergence of coherent vortices in primitive equation GCMs, poster presentation in AGU Fall Meeting.

Chai, J. and Jansen, M., 2014, Equilibration of a primitive equation GCM in the limit of zero large scale friction, in preparation.

Progress Report Title: **Development of GFDL Cubed-Sphere Dynamic Core with Horizontal Remap Algorithm and Non-Staggered Riemann Solver Based Numerical Scheme**

Principal Investigator: Xi Chen (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Shian-Jiann Lin (GFDL), Lucas Harris (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: Applying remap algorithm with GFDL's current cubed-sphere dynamic core will improve the model's accuracy at the location where the "tiles" of the cubed-sphere surfaces are connected. Applying the Riemann solver based numerical scheme to the model will increase the robustness of the model without artificial diffusion added to the system.

Methods and Results/Accomplishments:

A cubed-sphere grid system provides much better uniform grid point distribution compared to the conventional lat-lon grid system. The GFDL cubed-sphere dynamical core implements the Finte-Volume Method (FVM) with centered-5-point stencil discretization based on the numerical scheme developed by Lin (2004), Putman and Lin (2007). However, the curvilinear coordinates of the cubed-sphere at the location where two tiles connect are not continuous. Thus, the centered-5-point stencil numerical scheme needs to be modified into a one-sided numerical scheme at tile edges. The modified numerical scheme is not sufficient to provide desirable accuracy, as the tile-edge imprint can be observed, and the convergence rate of the error measurement is downgraded from 2 to 1.3 (Harris and Lin 2012) in an idealized shallow water zonal static flow test.

A remap algorithm to the extended "ghost cells" at the edges of the tiles could provide the extra grid cells which are required in a centered FVM. Thus, the numerical treatment is consistent at both the tile edges and inner region. However, a 2D remap scheme could be numerically expensive, which is not desirable for a massively parallel computation. With an equal-angular gnomonic cubed-sphere grid generation scheme, the cell centers of one tile's ghost cells can be aligned with cells of this tile's neighbor along a great circle that parallel to this tile's edge. Thus the 2D remap scheme can be simplified into 1D. Using this 1D remap scheme, the edge imprints of the cubed-sphere are alleviated, and the overall order of accuracy is restored to 2nd order.

The current GFDL dynamic core implements staggered grid definition for horizontal winds. This approach simplifies the flux calculation between two control volumes. It is also convenient to calculate the value of vorticity at the volume center. However, this numerical scheme is more diffusive than some non-staggered methods. On the other hand, many non-staggered schemes use Riemann solvers to calculate fluxes, which are computationally expensive. To develop a non-staggered numerical scheme, an approximate Riemann solver is created based on Chen (2013). This approximate Riemann solver assumes atmospheric flow speed is smaller than acoustic (or gravity) wave speed, and no significant acoustic (gravity) wave speed discontinuity at the interface of control volumes. The new scheme is computationally comparable to GFDL's current dynamic core, and less diffusive.

The attached figure shows the results of case 2 in the Whilliamson (1992) shallow water tests. The results display the difference of the height field between day 5 and day 0 of a steady state zonal flow. The first row is the result from the current GFDL model, the second row is the result from the GFDL model with a horizontal remap algorithm. The third row is the result from a non-staggered numerical scheme.

References:

Chen, X., N. Andronova, B. Van Leer, J. E. Penner, J. P. Boyd, C. Jablonowski, and S.-J. Lin, 2013: A control-volume model of the compressible euler equations with a vertical lagrangian coordinate. Monthly Weather Review, 141 (7), 2526–2544.

Harris, L. M. and S.-J. Lin, 2012: A two-way nested global-regional dynamical core on the cubed-sphere grid. Monthly Weather Review, 141 (1), 283–306

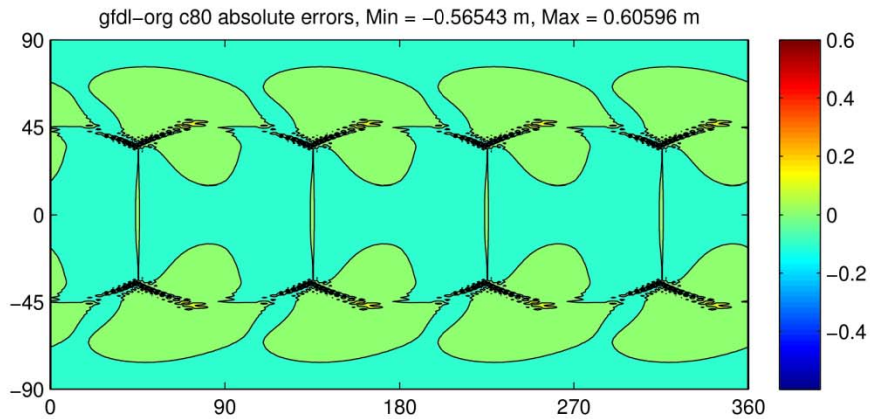
Lin, S.-J., 2004: A "vertically Lagrangian" finite-volume dynamical core for global models. Mon. Wea. Rev., 132, 2293–2307.

Putman, W. M. and S.-J. Lin, 2007: Finite-volume transport on various cubed-sphere grids. Journal of Computational Physics, 227 (1), 55–78.

Publications:

Chen, Xi, Shian-Jiann Lin, and Lucas M. Harris. A computationally efficient Riemann solver based shallow water model on the cubed-sphere. In American Geophysical Union Fall Meeting, San Francisco, CA, USA, December 9-13 2013.

Chen, Xi, Shian-Jiann Lin, and Lucas M. Harris. A computationally efficient Riemann solver based shallow water model on the cubed-sphere. Journal of Computational Physics, to be submitted.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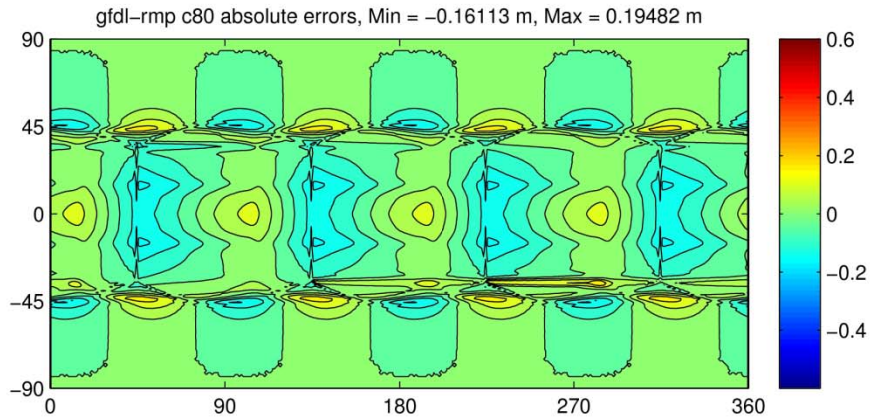
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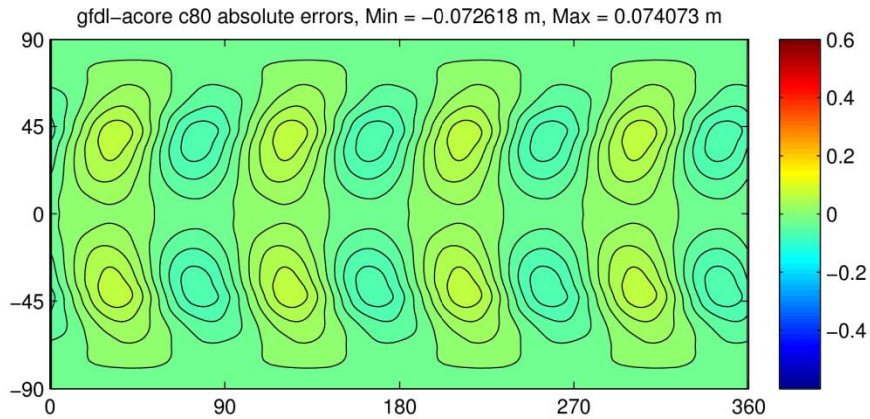
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Progress Report Title: **Roles of Wind and Precipitation Nonlinearities in ENSO Asymmetries**

Principal Investigator: Kityan Choi (Princeton Graduate Student)

CICS/GFDL Collaborator: Gabriel Vecchi (GFDL), Andrew Wittenberg (GFDL), Isaac Held (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: To understand the characteristic differences between El Nino and La Nina

Methods and Results/Accomplishments:

We systematically quantified the asymmetries in the El Nino-Southern Oscillation (ENSO) in the models participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5). The models under pre-industrial conditions exhibit a wide range of amplitude asymmetry with most underestimating the observed positive asymmetry. Most models agree with the observations that La Nina tends to last longer and El Nino is more readily followed by La Nina.

Among the many contributors to the asymmetry, we investigated the nonlinear equatorial Pacific zonal wind response to ENSO (Choi et al 2013, Dommenget et al 2013). We found that nonlinear zonal wind responses in the models are very well correlated with the nonlinear precipitation responses associated with ENSO. By driving a linear shallow water model with the nonlinear precipitation response as the heating anomaly in the atmosphere, we can reproduce the nonlinear zonal wind response from the nonlinear precipitation response. This suggests that the nonlinear zonal wind response is driven by the precipitation (elevated heating in the atmosphere), as is supported by a previous study by Chiang et al (2001).

As further understanding of the precipitation is crucial to the understanding of the wind response and thus the ENSO asymmetry characteristics, we investigated which characteristics of the precipitation to ENSO are responsible for the nonlinear zonal wind response. Realizing that the precipitation anomalies are largely due to the redistribution of the climatological precipitation, we decompose the precipitation anomalies into three components that can be directly added to recover the total precipitation anomalies: (1) zonal redistribution, (2) meridional redistribution, (3) other. We found that the zonal redistribution component of the precipitation response explains most (about 80%) of the nonlinear zonal wind response to the total precipitation anomalies and the meridional redistribution component, albeit contributing significantly to the total precipitation anomalies, plays a secondary role in the zonal wind response.

This work is published in the Journal of Climate in December 2013 and presented in the Ocean Science Conference in February 2014.

References:

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the Atmospheric Sciences 58, no. 11 (June 2001): 1371–1394. doi:10.1175/1520-0469(2001)058<1371:RROEHA>2.0.CO;2.

Dommenget, Dietmar, Tobias Bayr, and Claudia Frauen. Analysis of the Non-Linearity in the Pattern and Time Evolution of El Niño Southern Oscillation. Climate Dynamics, June 2013, 1–23. doi:10.1007/s00382-012-1475-0.

Publications:

Choi, Kit-Yan, Gabriel A. Vecchi, and Andrew T. Wittenberg. ENSO Transition, Duration, and Amplitude Asymmetries: Role of the Nonlinear Wind Stress Coupling in a Conceptual Model. Journal of Climate 26, no. 23 (December 2013): 9462–9476. doi:10.1175/JCLI-D-13-00045.1.

Choi, Kit-Yan, Gabriel A. Vecchi, and Andrew T. Wittenberg. Nonlinear wind response and ENSO asymmetry. Ocean Science Conference 2014, Honolulu, Hawaii.

Progress Report Title: **Downscaling of Climate Models and Ecosystems Implications**

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

CICS/GFDL Collaborator: Charles Stock (GFDL)

Other Participating Researchers: Gaelle Hervieux (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 highly productive continental shelves and elucidate potential linkages between these mechanisms and climate variability and change

Methods and Results/Accomplishments:

We utilized nested bio-physical ocean models for both retrospective simulations 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. For the Bering Sea, a high-resolution retrospective ocean-ice simulation (1958-2008) was forced by CORE II atmospheric forcing and SODA ocean boundary conditions for physics and WOA for the biological fields. This simulation was diagnosed to understand climate impacts on Bering Sea physics and the delivery of offshore nutrients to highly productive shelf waters. For the California Current, a prototype dynamical downscaling of GFDL's ESM2M was conducted based on the RCP8.5 scenario. It is worth noting that the downscaled projection included the effects of both basin-scale physical and biogeochemical trends along the domain boundary and linked two distinct ecosystem models.

Notable accomplishments are as follows:

Bering Sea: 1) 1958-2008 ROMS hindcast simulation has been completed and extensive model-data validation has taken place and analyses of the Bering Sea circulation and sea ice variability have been 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) A third manuscript examining variability in nutrient resupply to the surface waters of the Bering Sea during winter is in preparation, lead-authored by the postdoc funded through this project (Hervieux, Fig. 1). Passive tracer, age tracer, and nutrient transport diagnostics were developed for this analysis to elucidate and quantify patterns of nutrient exchange.

California Current: 1) An enhanced version of the CoSINE ecosystem model - including carbon and oxygen chemistry - was coupled and tested within ROMS. 2) Atmospheric, oceanic and biogeochemical boundary forcing was drawn from GFDL's ESM2M RCP8.5 projection contributed to the CMIP5 and used to force the high-resolution regional physical-biological simulation. 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 a manuscript is in preparation.

Future/Ongoing Work: The regional simulations developed under this project continue to be analyzed by both the investigators on the project and additional collaborators to understand interactions between basin-scale climate variability and change and these important shelf ecosystems.

We view the physical-biological downscaling component a "proof-of-concept" for a sustained dynamical climate downscaling capacity for U.S. shelf ecosystems. We have identified a number of key improvements needed to realize this goal and are taking steps to address these. First, we are implementing the GFDL COBALT model into the ROMS framework to provide a seamless transition between basin- and shelf-scale ecosystem responses. Second, we are also investigating the use of higher resolution global atmospheric configurations to force the regional model and further improve regional simulation skill.

Publications:

Hervieux, G., Curchitser, E., Castruccio F., and Stock C., (in prep). Pathways of winter resupply of nitrate to the surface waters of the Bering Sea.

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.

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Fiechter, J., E.N. Curchitser, C.A. Edwards, F. Chai and F. Chavez, 2014. Air-sea CO2 fluxes in the California Current: Impacts of model resolution and coastal topography. Global Biogeo- chemical Cycles. Accepted.

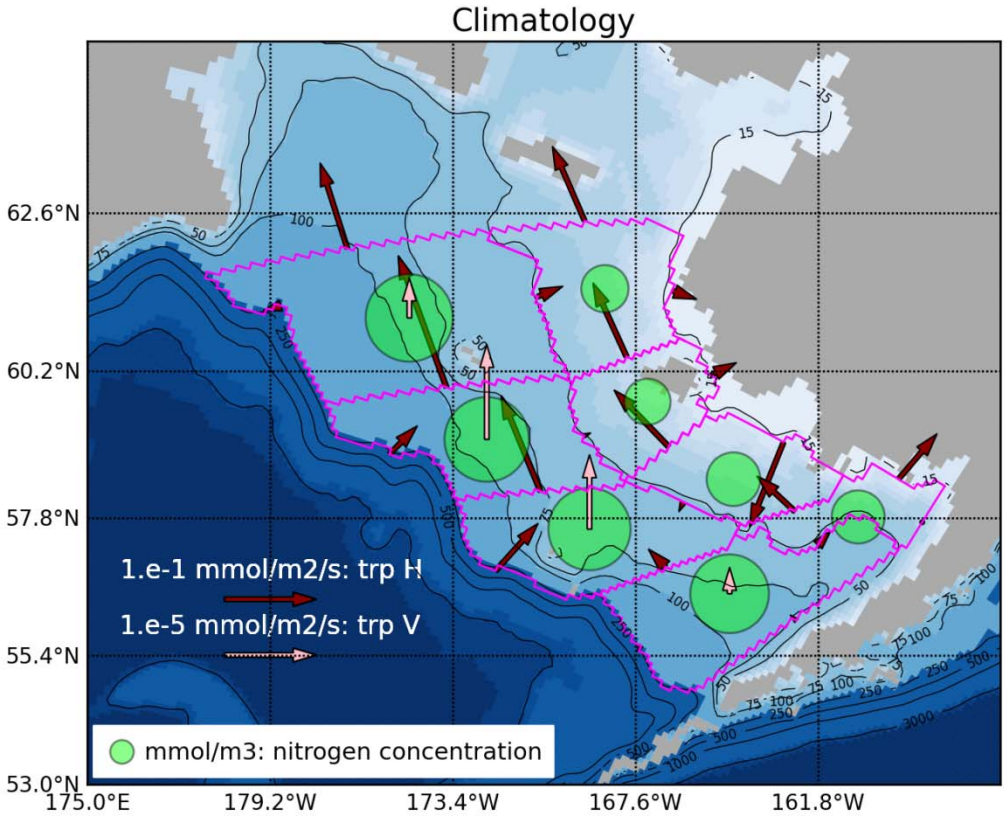

Fig 1: a) Annual nitrate inventories (mmol/m3) and transport for the surface (0-50m) Bering Sea. Red (pink) arrows represent the horizontal (vertical) flux of nitrogen (mmol/m2/s) between the boxes. A northward (southward) pink arrow means a positive (negative) transport "entering" the upper 50m.

Progress Report Title: **Air-Sea Interaction in an Ocean with Mesoscale Eddies, Ocean Surface Waves, and Tropical Cyclones**

Principal Investigator: Yalin Fan (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Stephen Griffies and Mike Winton (GFDL)

Other Participating Researchers: Hendrik Tolman (NCEP)

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 swell and wind sea seasonal variations and their response to global warming; investigate the effect of Langmuir turbulence and non-breaking wave parameterizations in global climate simulations

Methods and Results/Accomplishments:

Two separate studies were conducted during the past year: 1. The seasonal structure of the wind sea and swell from a 29-year surface gravity wave climatology produced by Fan et al. (2012) using the GFDL coupled atmosphere-wave model is analyzed. The swell energy fraction analysis shows that swell dominates most of the World Ocean basins for all four seasons, and the Southern Ocean swells dominate swell in the global ocean. The swells are loosely correlated with the surface wind in the mid-latitude storm region in both hemispheres, while their energy distribution and propagation direction do not show any relation with local winds, and vary significantly with season due to nonlinear interactions.

The same GFDL coupled system as Fan et al. (2012) is then used to investigate the projected future change in wind sea and swell climate through a time-slice simulation. Robust responses found in the wind seas are associated with modified climate indices. A dipole pattern in the North Atlantic during the boreal winter is associated with more frequent occurrence of the positive NAO phases under global warming; and the wind sea energy increase in the Southern Ocean is associated with the continuous shift of SAM towards its positive phase. Swell responses are less robust due to nonlinearity. The only consistent response in swells is the strong energy increase in the western Pacific and Indian Ocean sector of the Southern Ocean during the austral winter and autumn.

2. Detailed modeling experiments and analysis are done in terms of the impact of parameterized Langmuir turbulence and non-breaking wave mixing in global climate simulations. Three numerical experiments are conducted using the Langmuir parameterization suggested by McWilliams & Sullivan (2000) and Smyth et al (2002), and non-breaking wave parameterization suggested by Qiao et al (2004) following the Delworth et al (2006) 1990 simulations. We found the Smyth et al (2002) scheme works the best for our coupled system through adding ocean stratification effect to their parameterization compare to the McWilliams & Sullivan scheme. It improves the simulated winter Mixed Layer Depth (MLD) in our simulations, with mixed layer deepening in the Labrador Sea and shoaling in the Weddell and Ross Seas. Enhanced vertical mixing through parameterized Langmuir turbulence, coupled with enhanced lateral transport associated with parameterized mesoscale/submesoscale eddies, are found to be key elements for improving mixed layer simulations. Secondary impacts include strengthening the Atlantic Meridional Overturning Circulation and reducing the Antarctic Circumpolar Current. The Qiao et al

(2004) non-breaking wave parameterization is the third scheme we assess. It adds a wave orbital velocity to the Reynolds stress calculation, and provides the strongest summer mixed layer deepening in the Southern Ocean among the three experiments, but with weak impacts during winter. This study is accepted for publication by Journal of Climate.

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Publications:

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Fan, Y. And S. M. Griffies, 2013: Ocean surface gravity waves and climate modeling. 13Th wave workshop, Banff, Canada.

Fan, Y. And S. M. Griffies, 2013: Ocean surface gravity waves and climate modeling. Joint GOV-WGNE workshop on short to medium range coupled prediction for the atmosphere-wave-sea-ice-ocean, NCEP, Maryland.

Progress Report Title: **Variations and Trends in Local and Global Radiative Fluxes, and their Relation to Processes of the Hydrological Cycle**

Principal Investigator: Stephan Fueglistaler (Princeton Assistant Professor)

CICS/GFDL Collaborator: Claire Radley (Princeton), Leo Donner, Yi Ming, and Isaac Held (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 (50%)
Weather & Water Goal: Serve Society's Needs for Weather and Water Information (50%)

Objectives: Improve understanding of the effect of global constraints on local variability of radiative fluxes, rainfall and cloud cover

Methods and Results/Accomplishments:

Earth's hydrological cycle and the global energy balance are tightly coupled. An interesting observation is that the variance of the global averages of key quantities such as rainfall, atmospheric humidity and cloud albedo is much smaller (orders of magnitude) than 'local' variance (local in the sense of a station measurement, or grid cell in a model). This is true both for 'typical' fluctuations as well as 'extreme events'.

Our analyses so far have focused on variability associated with El-Nino/Southern Oscillation (ENSO). From an observational perspective, the variations of the general circulation due to ENSO provide an ideal "experiment" to study the relation between local and global variance for three reasons. First, the amplitude of the local changes (for example top of atmosphere, TOA, radiative fluxes) is very large and can be measured reasonably accurately. Second, the events have a long enough time scale to be clearly identifiable, and a short enough time scale that multiple events have occurred in the relatively short period of global observations from satellites.

In a recent paper (Radley et al., *J.Clim, in press*), we show that for some variables such as cloud cover, model biases in the base state translate into corresponding biases in response to ENSO in such a way that the model's distribution function of the anomalies during ENSO is a scaled version of the anomalies in the observations, whereby the scaling factor is given by the tropical mean bias of the model. While this scaling greatly improves the agreement between the model's and the observation's probability distribution functions of the ENSO anomalies, we find that it cannot explain the model's tropical mean bias in the response to ENSO.

Currently, we explore the behavior of tropical high clouds (deep convective clouds) in response to changes in sea surface temperatures (SSTs). We use the GFDL Atmospheric General Circulation Model AM2, and analyze the model's cloud field in model runs using SST modifications ranging from uniform changes to enhancing/attenuating gradients.

Publications:

Radley, C., S. Fueglistaler, L. Donner, Clouds and radiative balance changes in response to ENSO in observations and models, J. Clim. in press, 2014.

Conference presentations:

Radley, C., Cloud and radiative balance changes in response to ENSO in observations and models, talk, Gordon conference Radiation and Climate, New London, NH, 2013.

Radley, C., S. Fueglistaler, L. Donner, Cloud and radiative balance changes in response to ENSO in observations and models, poster, SPARC General assembly, Queenstown, New Zealand, 2014.

Progress Report Title: **Parameterizing Eddy Transports in Eddy-Permitting Ocean Models**

Principal Investigator: Malte Jansen (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Isaac Held (GFDL), Robert Hallberg (GFDL), Alistair Adcroft (Princeton)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: Improving the parameterization of subgrid meso-scale eddy effects in eddy permitting ocean models

Methods and Results/Accomplishments:

During my time as a Princeton AOS Postdoctoral Associate, I set up and analyzed a series of idealized numerical simulations of a turbulent oceanic flow at varying resolutions. The goal was to better understand the limitations of ocean models at eddy permitting resolutions.

The simulations used a two-layer, "Phillips-model", configuration of GFDL's newest ocean model, MOM6. Simulations were performed at a range of resolutions ranging from "eddy resolving" to barely "eddy permitting." At eddy resolving resolutions, the simulations adequately capture the effect of meso-scale eddies, which are understood to be a major contributor to the large scale transport of heat and tracers in the ocean. At eddy permitting resolutions, the model is able to produce some meso-scale variability resembling ocean eddies, but it is not able to properly resolve the meso-scale eddies at all relevant scales. As a result the eddy energy, as well as the eddy heat transport, are too weak as compared to higher resolution reference simulations.

The simulations were analyzed in detail to better understand the reasons for the break-down of the eddy statistics at eddy permitting resolutions. It was found that the viscous parameterization, used to parameterize the effects of subgrid-scale eddies, tends to spuriously dissipate a large amount of energy at eddy permitting resolutions. As a result, even eddies significantly larger than the grid-scale are much too weak. These results pointed to the need of a new parameterization for subgrid-scale eddy effects, which does not spuriously dissipate large amounts of energy. I have since developed an approach for such a parameterization, which has been tested successfully in an idealized (quasi-geostrophic) model. The implementation of a similar parameterization in MOM6 is currently in preparation.

Publications:

Jansen, M. F.: Energetically consistent sub-grid eddy parameterization for eddy permitting ocean models. Ocean Sciences Meeting, February 2014. (Abstract ID:15485)

Jansen, M.F. and I.M. Held: Energetically Consistent Parameterization of Sub-Gridscale Eddies. Submitted to Ocean Modelling.

(Most of the work for these publications was done while I was funded through the NOAA Climate and Global Change Fellowship Program.)

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, 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), Maarten Buijsman (UNO), Mehmet Ilicak (UBergen)

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, particularly in the 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 and Maarten Buijsman, now at University of New Orleans, focuses on the local mixing at tall steep topography. Developments of the past year include the publication of a paper describing the enhancement of dissipation by resonance at multiple steep ridges (Klymak et al, 2013), and the acceptance for publication of a paper describing the influence of 3-dimensional flow and complex topography on this resonance (Buijsman et al, 2014). Legg has explored the implementation of the Klymak et al 2010 scheme in climate models, and examined the sensitivity of the estimated dissipation to the algorithms for estimating tidal and topographic parameters at the model grid scale. This work has been shared with the Internal Wave Driven Mixing Climate Process Team, and following further refinement will be implemented in the GFDL climate model.

A continuing focus of the past year has been the fate of large-scale internal waves upon reflection from sloping topography. Process simulations of wave breaking at finite amplitude topography were extended to variable stratification and 3-dimensional ridges and seamounts, and an article describing this parameter space survey was recently published (Legg 2014). 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, with two manuscripts published in the past year (Melet et al 2013, 2014). Currently, Melet and Legg are focusing on the impact of low-mode wave-breaking on the large-scale ocean circulation, using the results of Legg (2014) as guidance, and another manuscript is in preparation. The work of Legg (2014) is also being extended to more complex geometries, such as continental slope canyons, by CICS student Robert Nazarian, under Legg's supervision. 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 been renewed until 2015.

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 ready to submit (Wang et al, 2014).

Mehmet Ilicak carried out a study, in collaboration with Legg, of the impact of a parameterization of heterogeneous ocean convection on the large-scale circulation, documented in a paper under review in Ocean Modeling (Ilicak et al, 2014).

Legg has been actively participating in MOM6 development, including providing feedback on choice of parameterizations. Together with Bonnie Samuels, Legg has carried out a study of the sensitivity of large-scale ocean circulation in CM2G to different parameterizations of ocean mixing, and will repeat these simulations using MOM6 in the next few months, as a baseline for new parameterization development and climate model tuning.

References:

Klymak, J, Sonya Legg, and R Pinkel, September 2010: A simple parameterization of turbulent tidal mixing near supercritical topography. Journal of Physical Oceanography, 40(9), DOI:10.1175/2010JPO4396.1.

Publications:

Melet, Angelique, Robert W Hallberg, Sonya Legg, and K Polzin, March 2013: Sensitivity of the Ocean State to the Vertical Distribution of Internal-Tide Driven Mixing. Journal of Physical Oceanography, 43(3), DOI:10.1175/JPO-D-12-055.1.

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Legg, Sonya, January 2014: Scattering of low-mode internal waves at finite isolated topography. Journal of Physical Oceanography, 44(1), DOI:10.1175/JPO-D-12-0241.1.

Buijsman, M C., J Klymak, and Sonya Legg, et al., March 2014: Three Dimensional Double Ridge Internal Tide Resonance in Luzon Strait. Journal of Physical Oceanography. DOI:10.1175/JPO-D-13-024.1..

Melet, Angelique, Robert W Hallberg, Sonya Legg, and M Nikurashin, March 2014: Sensitivity of the Ocean State to Lee Wave Driven Mixing. Journal of Physical Oceanography. DOI:10.1175/JPO-D-13-072.1.

Ilicak, M., S. Legg and A. Adcroft, 2014: A framework for parameterization of heterogeneous ocean convection. Submitted to Ocean Modelling.

Wang, H., S. Legg and R. Hallberg, 2014: Representations of the Nordic Sea Overflows and their large scale impact in climate models. To be submitted to Ocean Modelling.

Legg, S.; Melet, A.; Klymak, J. M.; Hallberg, R. W.; Parameterizations of local and remote mixing by internal tides and the impact on ocean circulation (Ocean Sciences 2014, Abstract ID: 14233).

Buijsman, M. C.; Legg , S.; Klymak, J. M.; Kang, D.; Nonlinear internal wave generation and dissipation at the double ridge in Luzon Strait (Ocean Sciences 2014, Abstract ID: 15089).

Wang, H.; Legg, S. A.; Hallberg, R. W.; Representations of the Nordic Seas overflows and their large scale climate impact in coupled models (Ocean Sciences 2014, Abstract ID: 16246).

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 (GFDL), John Dunne (GFDL)

Other Participating Researchers: Juan A. Bonachela (EEB, Princeton), Steve D. Allison and Adam C. Martiny (University of California, Irvine), Michael Follows and Oliver Jahn (Massachusetts Institute of Technology)

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:

We have devoted this year's work to accomplishing the future goals pointed out in our last report, namely i) polish the two-nutrient version of our model for flexible phytoplankton nutrient uptake, ii) integrate it in a global biogeochemical model and, iii) understand better the ecological and evolutionary consequences of the different life-history strategies for marine viruses infecting phytoplankton.

Concerning the first two points, the principal investigators, together with collaborators, have recently published the model (J. A. Bonachela, S. D. Allison, A. C. Martiny, and S. A. Levin, 2013) and presented it in this year's Ocean Sciences Meeting as well as during numerous research visits. The model describes how phytoplankton cells allocate resources differently under various environmental conditions in order to acclimate to diverse nutrient availability by regulating protein synthesis. Specifically, the model represents in a mechanistic way the synthesis of proteins used to take up nitrogen and phosphorus. Because the two nutrient pools play key roles in protein synthesis and growth, our model represents the important link between the two nutrients. The aim of this model is to represent in a realistic way the changes to phytoplankton stoichiometry observed under different environmental conditions.

This model is being tested experimentally (C. Mouginot, J. A. Bonachela, J. Vrugt, A. C. Martiny, and S. A. Levin, in preparation 2014) and has been already integrated into the Darwin model, a global model for oceanic biogeochemistry developed at M.I.T., as a result of the collaboration with the creators of such global model. The Darwin is a an ideal global model for this integration, due to its trait-based representation of phytoplankton ecotypes and its stochastic initialization of such trait values; then, the final community structure emerges from the biotic and abiotic interactions present in each region of the globe. Our goal is to understand to what extent is phytoplankton nutrient uptake strategies responsible for the observed global patterns of nutrient ratios. The integrated model is now under an intense testing, both in 1d configurations (i.e. water column) and 3d simulations. This effort will transform the Darwin

into the first model of its kind able to account for dynamic changes of the (interacting) phytoplankton nitrogen and phosphorus pools as a result of phytoplankton plasticity and the various strategies of cells to acclimate to changing environments (J. A. Bonachela, O. Jahn, M. Follows, A. C. Martiny, and S. A. Levin, in preparation 2014).

Because marine phytoplankton viruses use the uptake proteins as a gateway for infection, there exists an important trade-off between growth and survival (i.e. between increasing the number of such proteins in order to increase uptake and, therefore, growth rate, and decreasing infection probability). Thus, our next goal will be understanding how those global patterns are affected by the presence of viruses.

As a previous step, we have studied the ecological and evolutionary aspects linked to the two most standard models for phytoplankton-virus interaction (J. A. Bonachela and S. A. Levin, 2014). These two models represent in a very different way the viral lytic cycle. The goal was to understand how those differences affect the ecological and evolutionary outcomes of the two models. This is a key task in order to identify the best candidate to use for long-term predictions in global models as the Darwin. In addition, those differences can be also associated with different infection strategies for the virus: pure lytic cycle, delaying offspring release, against a continuous release through buddying. Therefore, this study serves to compare the ecological and evolutionary consequences of using one or the other strategy. As we show in (J. A. Bonachela and S. A. Levin, 2014), the continuous (buddying) release is advantageous from the point of view of competition, but the lytic (delayed) strategy converges faster to the evolutionary stable strategy.

The final integration of the virus description into our modification to the Darwin can potentially mean a breakthrough in the modeling of biogeochemical cycles, as it will include the two most important sources of top-down regulation for phytoplankton (zooplankton and viruses) together with realistic descriptions of the most important bottom-up sources of regulation (nutrients such as nitrogen, phosphorus and iron), in a fully dynamic environment.

References:

M. J. Follows, S. Dutkiewicz, S. Grant, S. W. Chisholm, Science 315, 1843 (2007).

Publications:

J. A. Bonachela, S. D. Allison, A. C. Martiny, and S. A. Levin, Biogeosciences 10, 4341 (2013).

J. A. Bonachela, S. D. Allison, A. C. Martiny, and S. A. Levin, Ocean Sciences Meeting (2014).

C. Mouginot, J. A. Bonachela, J. Vrugt, A. C. Martiny, and S. A. Levin, in preparation (2014).

J. A. Bonachela, O. Jahn, M. Follows, A. C. Martiny, and S. A. Levin, in preparation (2014).

J. A. Bonachela and S. A. Levin, J. Theor. Biol. 345, 32 (2014).

Progress Report Title: **Urban Model Development**

Principal Investigator: Dan Li (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Elena Shevliakova (Princeton), Sergey Malyshev (Princeton), S.J. Lin (GFDL)

Other Participating Researchers: Chris Milly (USGS)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: Develop and assess an urban scheme into GFDL's land model LM3

Methods and Results/Accomplishments:

The current LM3 does not include any urban representation. Hence it cannot represent the impacts of urbanization on the local/regional climate and cannot be used to assess the impacts of climate change in urban areas. However, given the substantial expansion of urban land and the significant growth of urban population, developing an accurate urban representation in the land surface model is becoming imperative. I am currently implementing a state-of-the-art urban representation into GFDL's land model LM3. The urban representation is largely based on urban canopy models that have been used in numerical weather prediction models like the Weather Research and Forecasting model (Chen *et al.*, 2011). This urban representation has yet to be fully implemented and evaluated. I expect that when the urban representation is available, it will open up new opportunities for studying the impacts of climate change on cities and the impacts of urbanization on local/regional climate change.

References:

Chen F, Kusaka H, Bornstein R, Ching J, Grimmond C S B, Grossman-Clarke S, Loridan T, Manning K W, Martilli A, Miao S G, Sailor D, Salamanca F P, Taha H, Tewari M, Wang X M, Wyszogrodzki A A and Zhang C L 2011 The integrated WRF/urban modelling system: development, evaluation, and applications to urban environmental problems International Journal of Climatology 31 273-88.

Publications:

Development and evaluation of an urban representation in GFDL's GCM (in preparation).

Progress Report Title: **The Fluctuation-Dissipation Theorem in a Two-Layer Model of Quasi-Geostrophic Turbulence**

Principal Investigator: Nicholas Lutsko (Princeton Graduate Student)

CICS/GFDL Collaborator: Isaac Held (GFDL), Sonya Legg (GFDL), Stephan Fueglistaler (Princeton), Steve Garner (GFDL)

Other Participating Researchers: Tim DelSole (George Mason/COLA)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: To better understand how the Fluctuation-Dissipation Theorem can be used in a climate context; Also, to gain insight into how the internal variability of a two-layer quasi-geostrophic model can be used to understand it's response to perturbations

Methods and Results/Accomplishments:

The Fluctuation-Dissipation Theorem (FDT) is a method for using the internal variability of a system to estimate how the system will respond to a small forcing or perturbation, assuming this response is linear. This is a powerful tool, and is particularly appealing in the context of climate change, for which we are interested in quantities such as climate sensitivity which could potentially be estimated using the FDT (e.g. Cooper and Haynes, 2011; Gritsun and Branstator, 2007). As such, an extensive mathematical formalism has been developed to fit the FDT to the conditions commonly found in climate systems (Majda et al., 2005; Majda et al., 2010).

However, recent efforts to apply the FDT to atmosphere-only global climate models (AGCMs) have been ambiguous, with some successes (Gritsun and Branstator, 2007) and some less successful efforts (Ring and Plumb, 2008). Furthermore, even in the successful cases the FDT estimates were more qualitatively than quantitatively correct and even by this metric the results deteriorated lower in the troposphere, for reasons which are not understood (Majda et al., 2010). Another concerning feature of these works is that no sensitivity tests were conducted, likely for reasons of computational expense, and so the robustness of these results is questionable.

In this project, we have applied the FDT to a two-layer model of quasi-geostrophic turbulence. This system is more complex than the highly idealized systems which were used to develop the mathematical formalism, but are less complex than AGCMs and so can be run quickly and inexpensively. The two-layer model in the set-up which we are investigating is also considered to be the simplest model of the annular modes, which are the dominant mode of variability in the mid-latitude troposphere (Zurita-Gotor et al., 2013) and so we are also hoping to gain insight into the annular modes as part of this work. As such, it provides a test-case for the FDT in which there is significant complexity and which is scientifically interesting, but simple enough that extensive sensitivity tests can be conducted.

The results so far have been encouraging. The FDT has been shown to give accurate estimates of the model's response to several different perturbations, and these estimates are robust to a number of sensitivity tests. Our results also indicate that the issues which have been found with regards to the lower troposphere are due to the friction caused by the Earth's surface, which causes the response of the lower

layer to become more barotropic. Remarkably, the FDT is able to account for this effect in some cases, though this effect does add a significant source of error and complexity to the problem. Our work also appears to confirm the conjecture that the auto-correlation time-scale of the annular modes is crucial for determining their response to perturbations (Gerber et al., 2008). This is concerning as many dry atmosphere models overestimate this time-scale (Gerber et al., 2008).

References:

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Gritsun, A. and Branstator, G. (2007) Climate Response Using a Three-Dimensional Operator Based on the Fluctuation–Dissipation Theorem. J. Atmos. Sci., 64, 2558–2575.

Majda, A., Abramov, R. and Grote, M. (2005) Information theory and stochastics for multiscale nonlinear systems, CRM monograph series 25, American Mathematical Society.

Majda, A., Gershgorin, B. and Yuan, Y. (2010) Low Frequency Response and Fluctuation-Dissipation Theorems: Theory and Practice, J. Atmos. Sci., 67, 1186-1201.

Ring, M. J., and R. A. Plumb (2008) The response of a simplified GCM to axisymmetric forcings: applicability of the fluctuation-dissipation theorem. J. Atmos. Sci., 65, 3880–3898.

Zurita-Gotor, P., Blanco-Fuentes, J. and Gerber, E. P. (2013) The impact of baroclinic eddy feedback on the persistence of jet variability in the two layer model. J. Atmos. Sci., 71, 410-429.

Progress Report Title: **Ozone and Secondary Organic Aerosols over Southeast U.S.**

Principal Investigator: Jingqiu Mao (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Larry Horowitz (GFDL), Fabien Paulot (Princeton), Songmiao Fan (GFDL)

Other Participating Researchers: Arlene Fiore (Columbia)

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 interaction between natural and anthropogenic emissions over Southeast U.S.

Methods and Results/Accomplishments:

Methods: We mainly use global chemistry models and field observations to understand the fundamental chemical processes that may significantly impact climate and air quality.

Accomplishments: (1) We have a proposal funded from NOAA Climate Program Office, "Impact of organic nitrate chemistry on air quality and climate: past, present and future atmospheres," with total amount of $392,881. Mao is the PI on this proposal. (2) We developed a new isoprene oxidation mechanism and this work is published in JGR. This mechanism represents the best knowledge on isoprene oxidation and has been adopted as the standard mechanism for a global model GEOS-Chem (www.geos-chem.org). This work is highlighted on NOAA CPO website: (http://cpo.noaa.gov/ClimatePrograms/EarthSystemScience/AtmosphericChemistryCarbonCycleandClimate/AC4Archive/TabId/543/ArtMID/1405/ArticleID/210/AC4-funds-research-that-proposes-revised-mechanism-for-isoprene-chemistry.aspx) (3) This new isoprene mechanism is now implemented in AM3 and evaluated with observations from SENEX aircraft campaign. The AM3 simulation results were also provided to the SENEX team and included in the SENEX data archive. (4) 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. (5) 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. (6) 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. (7) Submitted a proposal on organic aerosols to EPA.

Publications:

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Ren, X., van Duin, D., Cazorla, M., Chen, S., Mao, J., Zhang, L., Brune, W. H., Flynn, J. H., Grossberg, N., Lefer, B. L., Rappenglück, B., Wong, K. W., Tsai, C., Stutz, J., Dibb, J. E., Thomas Jobson, B., Luke, W. T., and Kelley, P. (2013), Atmospheric oxidation chemistry and ozone production: Results from SHARP 2009 in Houston, Texas, Journal of Geophysical Research: Atmospheres, 118(11), 5770-5780.

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Mao, J., Fan, S., Jacob, D. J., and Travis, K. R. (2013), Radical loss in the atmosphere from Cu-Fe redox coupling in aerosols, Atmos. Chem. Phys., 13(2), 509-519. (3rd most cited paper in ACP in 2013, out of 740 papers).

Presentations:

University of Maryland, College Park, MD, "Uncertainties in the atmospheric oxidation of biogenic volatile organic compounds (BVOCs) : implications for air quality and climate" (03/2014) (Invited).

Yale University, New Haven, CT, "Uncertainties in the atmospheric oxidation of biogenic volatile organic compounds (BVOCs) : implications for air quality and climate" (02/2014) (Invited).

AGU Fall meeting, San Francisco, "Simulation of ozone and its precursors over the southeast US with a high-resolution chemistry-climate model" (12/2013).

North Carolina State University, Raleigh, NC, "Heterogeneous chemistry and its potential impact on climate" (11/2013) (Invited).

Chip Levy's retirement symposium, Princeton, NJ, "A missing sink for radicals" (08/2013).

GFDL lunch seminar, Princeton, NJ, "Two puzzles of atmospheric chemistry over the Southeast US" (07/2013).

SENEX Science meeting, Nashville, TN, "Simulating isoprene oxidation in GFDL AM3 model" (06/2013).

GEOS-Chem user meeting, Harvard University, "Ozone and organic nitrates over the eastern US: sensitivity to isoprene chemistry" (05/2013.

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

Principal Investigator: Angélique Melet (Princeton Postdoctoral Research Associate)

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

Other Participating Researchers: M. Nikurashin (U. Tasmania), C. Muller (CNRS), B. Arbic (U. Michigan), P. Timko (Bangor U.), J. Nycander (Stockholm U.), S. Falahat (Stockholm U.), J. Goff (U. Texas)

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 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:

Over the last year, I've been working on four different studies. *Internal tide generation by abyssal hills:* Internal tides are generated by interaction of barotropic tides with rough topography. Their breaking provides most of the mechanical energy required to maintain the deep ocean stratification and circulation. Existing estimates of the energy flux converted from the barotropic to internal tides rely on topographic products that do not resolve scales below 10 km, dominated by abyssal hills. In this study, we used a statistical realization of abyssal hill roughness to analytically compute the conversion of tidal energy due to abyssal hills based on linear theory. We show that globally, abyssal hills are responsible for O(0.1) TW of energy conversion, which represents 10% of the global energy flux into internal tides due to larger scales of topography resolved in standard topographic products. However, the contribution of abyssal hills to internal tide generation is comparable to that due to larger scales of topography over mid-ocean ridges. [*Melet et al. 2013, JGR*].

Energy flux into lee waves under a changing climate: Lee waves are generated through interactions of geostrophic flows with rough bathymetry, and are dominated by the Southern Ocean. Last year, we showed that lee wave driven mixing specifically impacts the ocean state and should be parameterized in climate models [*Melet et al. 2014, JPO*]. Yet, we used a static estimate for the energy flux into lee waves. In this study, we use linear theory and outputs from GFDL's CM2G climate model to compute a time varying energy flux into lee waves over the 1861-2100 period using historical and RCPs forcings. We show that the global energy flux into lee waves decreases under a warming climate. We also suggest a physically based parameterization of the energy flux into lee waves that could be used in climate models.

Impact of low mode internal tide dissipation on the ocean state: Only the local dissipation of internal tides is currently parameterized in climate models. However, a significant fraction of internal tide energy is radiated away from their sources as low modes, and is dissipated either in the ocean basins, continental slopes or continental shelves. In this study, we study the impact of low mode energy dissipation on the ocean state as a function of where low mode internal tide dissipate in an idealized setting (e.g. dissipation of low modes in ocean basins only, on continental slopes or continental shelves

only). The parameterization of low mode energy dissipation provides enhanced mixing in the thermocline. We show that the vertical location of mixing matters more than its horizontal distribution for global simulations and that mixing on continental shelves is important to large-scale circulation mostly through impact on dense overflows (e.g. AABW).

Sensitivity of 21st century sea level rise to ocean vertical mixing: Study led by Robert Hallberg. GFDL's CM2G model is used to investigate the sensitivity of sea level rise to ocean vertical mixing. A series of simulations is run with increasing values of additional uniform, constant diffusivities (0, 0.1, 0.2, 0.4, 0.6, 0.8 cm^2/s) under pre-industrial radiative forcing, and 1% per year increase of CO_2 until doubling/quadrupling pre-industrial levels. It is shown that increased levels of vertical mixing broaden the thermocline, result in a warmer ocean and stronger steric sea level rise. This study highlights the need for reducing the levels of spurious, numerically induced mixing in ocean models, and for physically based parameterizations of vertical mixing in such models [*Melet, Hallberg, Samuels, poster at Ocean Science, 2014*].

References:

Climate Process Team: http://www-pord.ucsd.edu/~jen/cpt

Publications:

A. Melet, R. Hallberg, S. Legg, M. Nikurashin, 2014. Sensitivity of the ocean state to Lee wave driven mixing. Journal of Physical Oceanography, doi: 10.1175/JPO-D-13-072.1.

A. Melet, M. Nikurashin, C. Muller, S. Falahat, J. Nycander, P. Timko, B. Arbic, J. Goff, 2013. Abyssal hill roughness impact on internal tide generation: Linear theory. Journal of Geophysical Research - Oceans, vol 118 (11), pp. 6303-6318, doi: 10.1002/2013JC009212.

S. Legg, A. Melet, J. Klymak, R. Hallberg. Parameterizations of local and remote mixing by internal tides and their impact on ocean circulation, Oral presentation at the Ocean Science meeting, Honolulu (USA), Feb. 2014.

A. Melet, R. Hallberg, S. Legg, M. Nikurashin. Internal wave driven mixing: Parameterizations and climatic impacts, Oral presentation at the Knowledge for the Future Assembly (IAPSO), Gothenburg, Sweden, Jul. 2013.

A. Melet, R. Hallberg, B. Samuels. Sensitivity of 21st century sea level rise to ocean vertical mixing, Poster at the Ocean Science meeting, Honolulu (USA), Feb. 2014.

Progress Report Title: **Baroclinic Wave Activity in the Martian Atmosphere**

Principal Investigator: Todd Mooring (Princeton Graduate Student)

CICS/GFDL Collaborator: R. John Wilson (GFDL), Isaac Held (GFDL)

Other Participating Researchers: Geoffrey K. Vallis (Exeter)

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: Enhance our understanding of baroclinic wave activity in the Martian atmosphere, using a reanalysis dataset to better characterize its properties and numerical model experiments to understand why the waves are so regular compared to those on Earth

Methods and Results/Accomplishments:

Traveling baroclinic waves in the Martian atmosphere have been a subject of study for several decades (e.g. Ryan et al. 1978, Barnes 1980, Banfield et al. 2004). CICS funding supported part of a larger project addressing several aspects of the waves, including an investigation of the dynamical causes of their impressive regularity (e.g. Ryan et al. 1978, Leovy 1979) and an improved empirical characterization of the waves' properties based on a reanalysis dataset (Lewis et al. 2007).

Early researchers examining Martian surface weather observations noticed significant quasiperiodic behavior with timescales of several Mars days, in contrast to terrestrial weather variability which has less well-defined timescales (e.g. Collins et al. 1996). The cause of this phenomenon remains unclear, with two major hypotheses being Mars's large (relative to Earth) value of the ratio of the Rossby deformation radius to the planetary radius (Leovy 1979) and the comparatively short radiative damping time of the Martian atmosphere (Barnes 1986). During the CICS-supported period, work on this aspect of the project focused on a getting a two-layer quasigeostrophic model working for use in wave regularity studies, although it has since been decided to conduct the research primarily or exclusively with a GCM.

Some preparatory work for the characterization of baroclinic waves in Mars reanalysis was also done during the CICS-supported period. Most notably, the meridional, vertical, and seasonal distribution of transient eddy activity as manifested in the temperature field was assessed to better scope the survey of baroclinic wave activity. The survey itself was also begun, including some computations of spectra in phase speed-zonal wavenumber space. A more recent continuation of the survey has shifted to computing eddy variance-covariance maps and more spatially localized diagnostic quantities after (Wallace et al. 1988). The survey is expected to, among other things, yield a concise description of the tendency of Martian baroclinic eddies to follow the contours of topography.

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Progress Report Title: **Internal Wave Mixing in Continental Slope Canyons**

Principal Investigator: Robert Nazarian (Princeton Graduate Student)

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

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: My primary research objective is to better understand the roles that continental slope canyons play in internal-wave driven mixing, and to represent this process in a more accurate ocean/climate GCM parameterization.

Methods and Results/Accomplishments:

In order to tackle this problem, I have begun a study of the parameter space of internal waves interaction with canyon topography. This parameter study has a two-pronged approach: ray-tracing theory and high-resolution GCM simulations. First, the ray-tracing theory follows the propagation of a remotely generated internal wave into the canyon topography, and the subsequent reflections off the topography. Based on linear theory, the reflected wavenumbers can be calculated from various properties of the incoming wave and canyon geometry, with larger wavenumbers conducive to instability and mixing. Thus, this ray-tracing algorithm allows us to monitor the change in wavenumbers upon subsequent topographical reflections (and therefore hint at regions of instability), as well as to explore scenarios in which the wave is trapped in the canyon topography.

The second approach employed in this study is high-resolution numerical modeling using the MITgcm. Specifically, we use the MITgcm to simulate a remotely generated internal wave propagating through a continental slope canyon region, tracking the energy flux in time. From the divergence of the energy flux, we are working to identify specific canyon geometries that are conducive to higher energy dissipation via mixing. While initial model simulations have a relatively simple V-shaped geometry, future simulations will more closely mirror observed submarine canyons.

Once the parameter space has been adequately studied, and the driving parameters of internal wave-driven mixing in canyon regions are identified, we will formalize the appropriate parameterization for ocean global circulation models and implement in one of GFDL's ocean models.

Progress Report Title: **Embedding Curator Infrastructure into FMS Runtime Environment**

Principal Investigator: Serguei Nikonov (Princeton Professional Technical Specialist)

CICS/GFDL Collaborator: V.Balaji (Princeton), Aparna Radhakrishnan (Engility/GFDL), Kyle Olivo (Engility/GFDL), Hans Vahlenkamp (NCAR/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 make the Curator Infrastructure an integral part of FRE and to be accepted by the scientific community as natural part of the model simulation process. This goal entails the system compliance to a set of conditions such as usability tradeoff - positive balance between new features arsenal and usage complexity, FRE and Curator mutual utilization and Curator performance, scalability and sustainability improvements.

Methods and Results/Accomplishments:

The IBM DB2 based Curator infrastructure was designed and developed. This comprised adjusting or rewriting a whole Curator set of applications – constituents, to make them able to communicate with DB2. Also, an important part of our work was the investigation of DB2 capability to work on a virtual machine to assess possible performance degradation.

We worked on improving Curator usability based on results of a survey conducted among the users. As a result, user interaction with the system was significantly simplified. Also, some long expected capabilities were developed, such as ensembles of experiments processing in the Curator system.

FRE Curator infrastructure development has been continuing to comply with ongoing changes in FRE XML schema, keeping interaction of FRE-Curator tandem intact.

We participated in the design of new version of FRE, including the investigation of the applicability of a new technique with developing demonstrative/trial applications (SCONS, CYLC) and data processing modules.

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

Principal Investigator: Isidoro Orlanski (Princeton Senior Meteorologist)

CICS/GFDL Collaborator: Isaac Held, Fanrong Zeng, and Andrew Wittenberg (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:

Poleward Shift and Change of Frontal Activity in the Southern Hemisphere over the Last 40 Years: Several studies have documented the poleward shift of the midlatitude westerly jet of the Southern Hemisphere during the last decades of the twentieth century, mainly during the warm season. In this work, the consistency between this change and the seasonal changes in frontal activity and precipitation are explored. The authors also attempt to identify the correlation between frontal activity and precipitation changes. Frontal activity is defined using the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) dataset for the period 1962–2001 as the temperature gradient times the relative vorticity at 850 hPa. Considering cyclonic systems only, an enhancement of the frontal activity at high latitudes in the last two decades is apparent. However, the pattern of frontal activity change is not zonally symmetric, with the zonal asymmetries consistent with the climate change signal of the zonal anomaly of the 300-hPa geopotential height.

The pattern of precipitation change, showing midlatitude drying and high-latitude moistening, is consistent with the pattern of the frontal activity change, explaining to a large extent both the zonal mean and asymmetric rainfall changes. This consistency is also found in terms of the year-to-year variability of the zonal mean at both mid- and high latitudes. However, the frontal activity has a complex relationship with rainfall (not every frontal system is associated with rainfall events), and this consistency is unclear over some specific regions.

Results presented here highlight the robust link between the change in the asymmetric component of the upper-level circulation, the frontal activity, and rainfall over the mid- to high latitudes of the Southern Hemisphere. Our study shows that frontal activity, FAI, consistent with other findings, shifting poleward in the last decades of the southern hemisphere. 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.

What Controls Recent Changes in the Circulation of the Southern Hemisphere: Polar Stratospheric or Equatorial Surface Temperatures?: Recent research suggests that both tropical ocean warming and stratospheric temperature anomalies due to ozone depletion have led to a poleward displacement of the mid- and high-latitude circulation of the Southern Hemisphere over the past century. In this study, we attempt to distinguish the influences of ocean warming and stratospheric cooling trends on seasonal

changes of both the zonally symmetric and asymmetric components of the southern hemisphere circulation. Our analysis makes use of three data sets-the ERA40 reanalysis and results from two different runs of the GFDL global atmosphere and land model (AM2.1) for the period 1870 to 2004. A regression analysis was applied to two variables in each of the three data sets-the zonal component of the surface wind U(10 m) and the height at 300 hPa—to determine their correlation with zonally averaged polar stratospheric temperatures (T_polar—at 150 hPa, averaged over a band from 70S - 80S) and low-level equatorial temperatures (T_equator—at 850 hPa averaged over a band at 5S - 5N).

Our analysis shows that the zonally *symmetric* surface winds have a considerably enhanced intensity in high latitudes of the southern hemisphere over the summer period, and that the stratospheric temperature trend, and thus ozone depletion, is the dominant contributor to that change. However, the climatic change of the *asymmetric* component of zonal wind component at z = 10 m (U10) as well as of 300hPa heights has been found to be large for both summer and winter periods. Our regression results show that correlation with T_equator (our proxy for global warming) explains most of the climatic changes for the asymmetric component of U10 and 300 hPa heights for summer and winter periods, suggesting the influence of warming of the global oceans on anticyclones south of the Indian Ocean and south-eastern Pacific Ocean.

Publications:

Silvina A. Solman and Isidoro Orlanski. 2014: Poleward Shift and Change of Frontal Activity in the Southern Hemisphere over the Last 40 Years, Journal of the Atmospheric Sciences, 71(2) : 539-552, doi: 10.1175/JAS-D-13-0105.1.

Isidoro Orlanski. 2013: What Controls Recent Changes in the Circulation of the Southern Hemisphere: Polar Stratospheric or Equatorial Surface Temperatures? Atmospheric and Climate Sciences, 3, 497-509 http://dx.doi.org/10.4236/acs.2013.34052.

Progress Report Title: **Development of an Ice-Sheet Model**

Principal Investigator: Olga Sergienko (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Robert Hallberg (GFDL), Matthew Harrison (GFDL)

Other Participating Researchers: Yonggang Liu (Woodrow Wilson School, Princeton University), Richard Hindmarsh (British Antarctic Survey)

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 present-day ice sheets behavior and the processes controlling their ongoing changes and mechanisms through which they interact with other components of the climate system

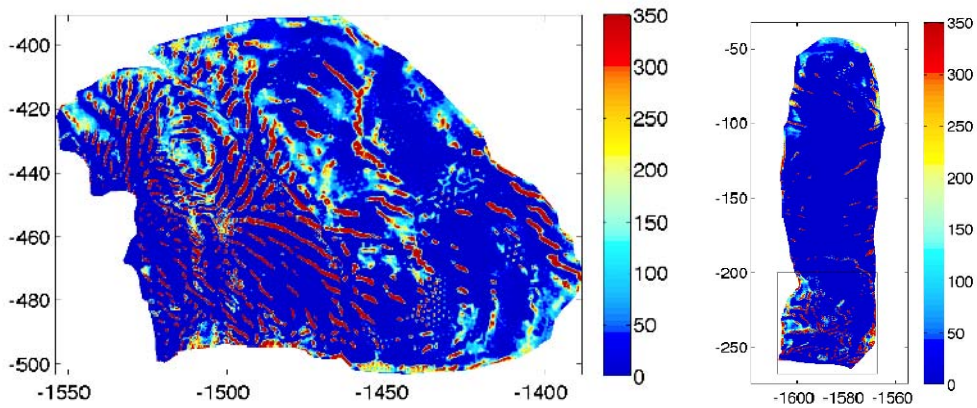
Methods and Results/Accomplishments:

Observations show that the largest mass loss from both Greenland and Antarctic ice sheets takes place at their margins, where warm oceanic waters have direct access either to ice shelves in Antarctica or floating tongues or fronts of outlet glaciers in Greenland. In order to better understand processes and mechanisms operating at those locations, several aspects of the ice/ocean interactions have been investigated.

In situ and remote sensing observations show that ice shelves in Antarctica and the floating tongue of Peterman Glacier in Greenland interacting with very warm oceanic waters (ocean temperatures ~2-4 K warmer than in situ melting temperatures) have a complicated network of channels ~ 1-3 km wide and ~100-300 m deep incised upward into their bottoms. The presence of these channels has several important implications for their stability and for ocean-water masses in the ambient oceans. In order to understand mechanisms and processes leading to formation of these channels as well as their effects on ice-shelf stability, a fully coupled ice-shelf/sub-ice-shelf ocean model has been developed and applied for idealized geometries. The model simulations show that channels may form spontaneously in response to meltwater plume flow initiated at the grounding line if there are relatively high melt rates and if there is transverse to ice-flow variability in ice-shelf thickness. Melt rates and seawater transport in the channels are significantly higher than on the smooth flat ice bottom between the channels. Simulations suggest that both steady state and cyclic state solutions are possible depending on conditions along the lateral ice-shelf boundaries. Internal dynamics of this system thus controls the evolution of the channels in a manner that is unrelated to variations in the far-field ocean and grounded ice.

Conditions under ice sheets, at the ice-bedrock interface control the rate with which ice sheets flow and determines the rate at which ice is discharged from their interior to the ocean, hence determining the rate at which glaciers contribute to sea level. Using recently compiled high-resolution data sets and a standard inverse method, basal shear stress distributions have been computed beneath Pine Island and Thwaites Glaciers (Antarctica), which are currently losing mass at an accelerating rate. The inversions reveal the presence of riblike patterns of very high basal shear stress embedded within much larger areas with zero basal shear stress (Figure 1). Their co-location with highs in the gradient of hydraulic potential suggests that subglacial water may control the evolution of these high–shear-stress ribs, potentially

causing migration of the grounding line by changes in basal resistance in its vicinity. The presence of such rib-like spatial patterns in the basal shear of these fast flowing glaciers has implications for stability of their grounding lines. Both glaciers have inland-sloping over-deepened beds. The grounding lines in such geometric configurations are thought to be inherently unstable. There is a possibility of their temporal and spatial variability through, for instance, flooding of some of these ribs and reduction of their basal shear stress, that would lead to enhanced ice discharge into the ocean.



(a) Thwaites Glacier (b) Pine Island Glacier

Figure (1) Inferred basal shear stress (kPa) under (a) Thwaites Glacier and (b) Pine Island Glacier

Publications:

Refereed articles:

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

Principal Investigator: Elena Shevliakova (Princeton Senior Climate Modeler)

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

Other Participating Researchers: Steve Pacala (Princeton)

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

Methods and Results/Accomplishments:

During 2013, I participated in the analysis of the GFDL comprehensive Earth System Models ESM2M and ESM2G and the development of new capabilities for the next generation LM4 model. 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). Previous studies have demonstrated the importance of enhanced vegetation growth under future elevated atmospheric CO_2 for 21st-century climate warming. Surprisingly, no study has completed an analogous assessment for the historical period, during which emissions of greenhouse gases increased rapidly and land-use changes (LUC) dramatically altered terrestrial carbon (C) sources and sinks. Using the Geophysical Fluid Dynamics Laboratory (GFDL) comprehensive Earth System Model, ESM2G, and a new reconstruction of the LUC, we estimate that enhanced vegetation growth has lowered the historical atmospheric CO_2 concentration by 85 ppm avoiding an additional 0.31±0.06°C warming. We demonstrate that without enhanced vegetation growth the total residual terrestrial carbon flux (i.e. the net land flux minus LUC flux) would be a source of 65-82 GtC to atmosphere instead of the historical residual carbon sink of 186-192 GtC, a carbon saving of 251-274 GtC.

Additionally, I have contributed to the analysis of the interaction of land use change to historical carbon and nitrogen cycling (Gerber et al 2013), the analysis of the CMIP5 carbon cycle-climate models (Hoffman et al 2013), the 21st Century compatible emissions that were assessed using an ensemble of the CMIP5 ESMs (Jones et al 2013), and the soil carbon dynamics in the CMIP5 ESMs (Todd-Brown et al 2013). Additionally, I have worked on the revisions of the chapter on land-water-energy interactions for the National Climate assessment. (Hibbard et al, 2013).

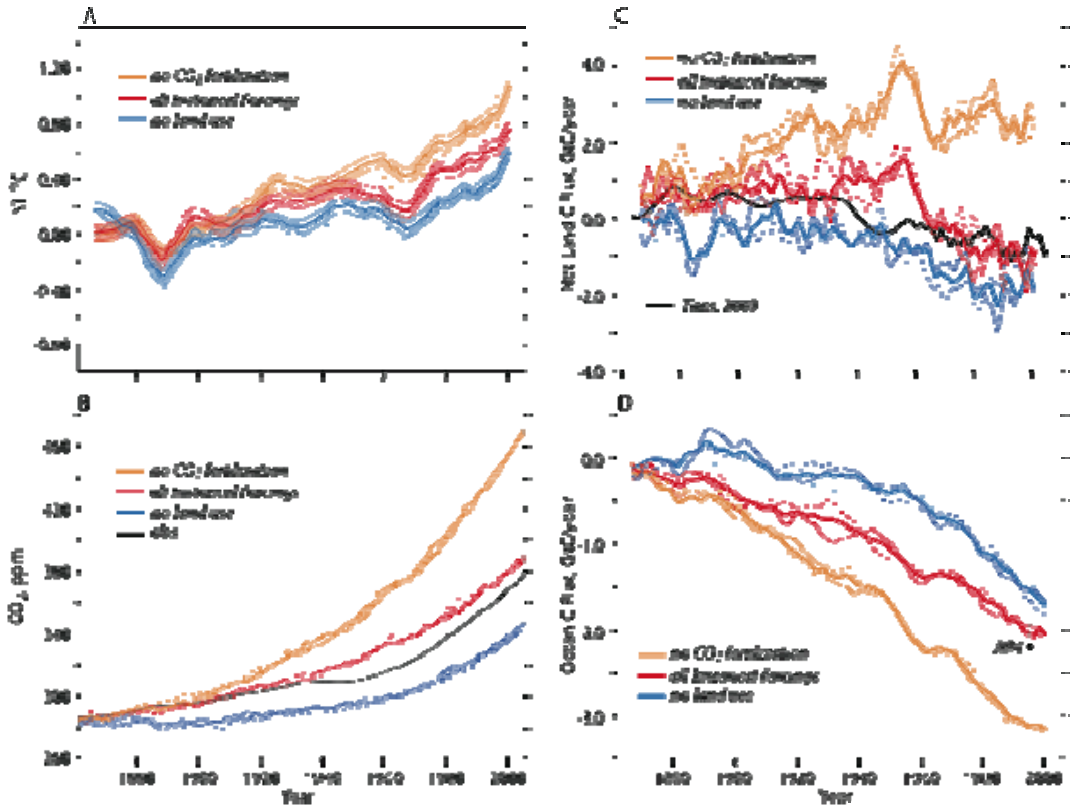

Figure. (A) Change in annual, globally averaged surface air temperature (10-year-smoothed, ensemble mean) simulated in the emission driven ESM2G experiments from preindustrial to current under all historical forcings (red), without land-use changes (blue), and without enhanced growth effect (orange). The shading represents decadal variability (2σ) computed from the 400-years of the control simulations. The thin and two dashed lines represent each ensemble; (B) Annual atmospheric globally averaged CO_2 concentrations simulated by 3 ensemble members of experiments. The black line is the observed atmospheric CO_2 concentration (www.esrl.noaa.gov/gmd/ccgg/trends); (C) The net land (c) and ocean (D) carbon fluxes (10-year smoothed) simulated by 3 ensemble members in the ESM2G experiments.

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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.

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Yin, Lei, R Fu, Elena Shevliakova, and R Dickinson, December 2013: How well can CMIP5 simulate precipitation and its controlling processes over tropical South America? Climate Dynamics, 41(11-12**)**, DOI:10.1007/s00382-012-1582-y.

Progress Report Title: **Mapping Antarctica's Mass Loss in Space and Time**

Principal Investigator: Frederik J. Simons (Princeton Professor)

CICS/GFDL Collaborator: Chris Harig (Princeton)

Task III: Individual Projects

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: While data from multiple sources confirm that Antarctica is losing ice at an accelerating rate, the details of its geographically highly variable mass balance remain incompletely measured, modeled, and understood. In this study we use time-variable gravimetry to determine the geographic pattern of mass change in Antarctica between January of 2003 and January of 2013.

Methods and Results/Accomplishments:

Using robust signal processing and statistical estimation methods applied to the latest, and longest, time series of data from the Gravity Recovery and Climate Experiment we precisely map Antarctica's mass loss in space and in time. Much of the apparent lack of precision in the all-Antarctica ice mass loss curves is due to geographical variations both between and within a number of broad regions in Antarctica. West Antarctica has experienced large acceleration of ice mass losses, doubling in the past 5 years, and is driven both by increased losses in the Pine Island and Thwaites glacier area and by increased losses along other areas of the Amundsen Sea coast. The Antarctic Peninsula shows slightly accelerating ice mass loss, with loss increases in the southern half of the Peninsula. Ice mass gains in Dronning Maud Land have continued to add about half the amount of West Antarctica's loss back into the system over the last decade. All areas show significant intraregional variability within which to frame future observations and comparison with other methods, data and models.

Overall our analysis shows that the lengthening time series from GRACE clearly resolves continued acceleration of ice mass losses from the Antarctic Ice Sheet, punctuated by strong accelerations of mass losses from West Antarctica. The Western Antarctic ice mass loss acceleration has doubled in the past 5 years and is driven both by increased losses in the Pine Island and Thwaites glacier area and by increased losses along other areas of the Amundsen Sea coast. The Antarctic Peninsula is slightly accelerating its mass losses, with increased losses occurring in the southern half of the Peninsula. While the largest source of uncertainty remains the correction for glacio-isostatic adjustment, our Slepian-function method separates Antarctica into several well-resolved regions and reduces the estimation error from geographic variability compared to the continent as a whole. Importantly, this allows us to resolve the acceleration of West Antarctica to a very high degree, independent of any GIA response. It is, of course, unclear whether the trends we observe will continue in the near future, but a long and continuous record of ice sheet mass balance remains key for informing our view of late century changes, and the estimation techniques that we developed will remain important for follow-on satellite gravimetry missions.

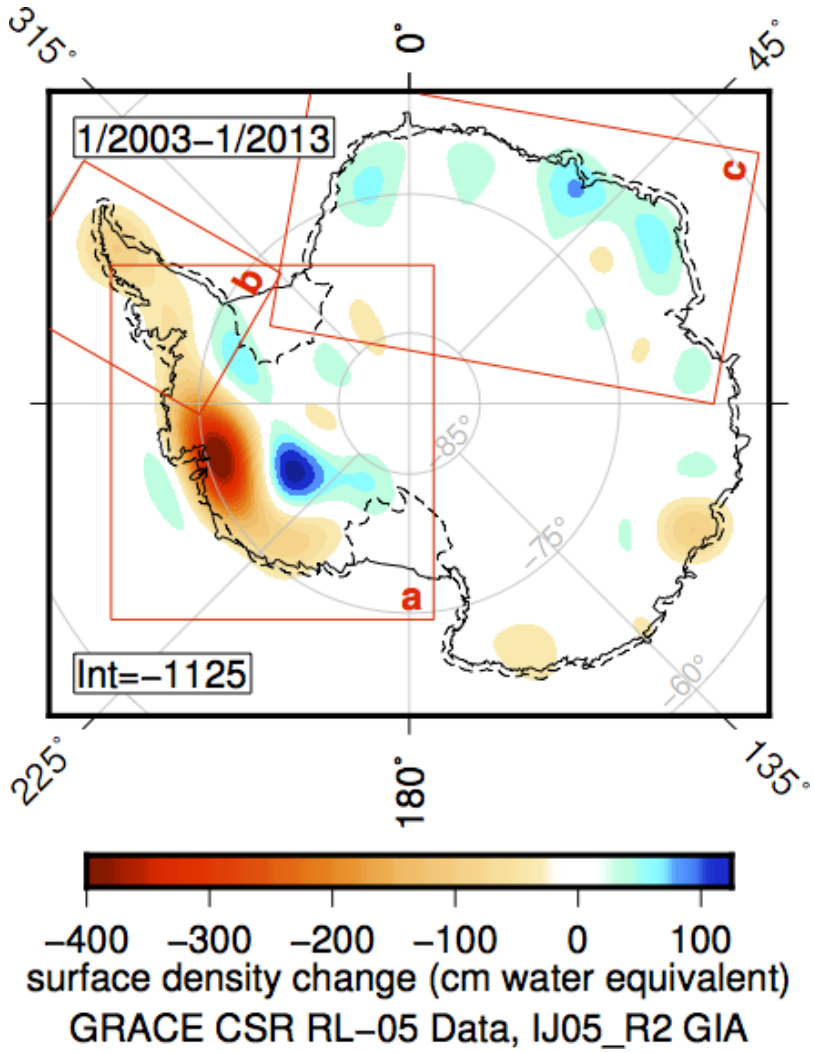

Figure 1: *Ice mass change (corrected for ongoing glacio-isostatic adjustment) over Antarctica for the combined period 1/2003 to 1/2013. This solution is from a localization over the whole of Antarctica.*

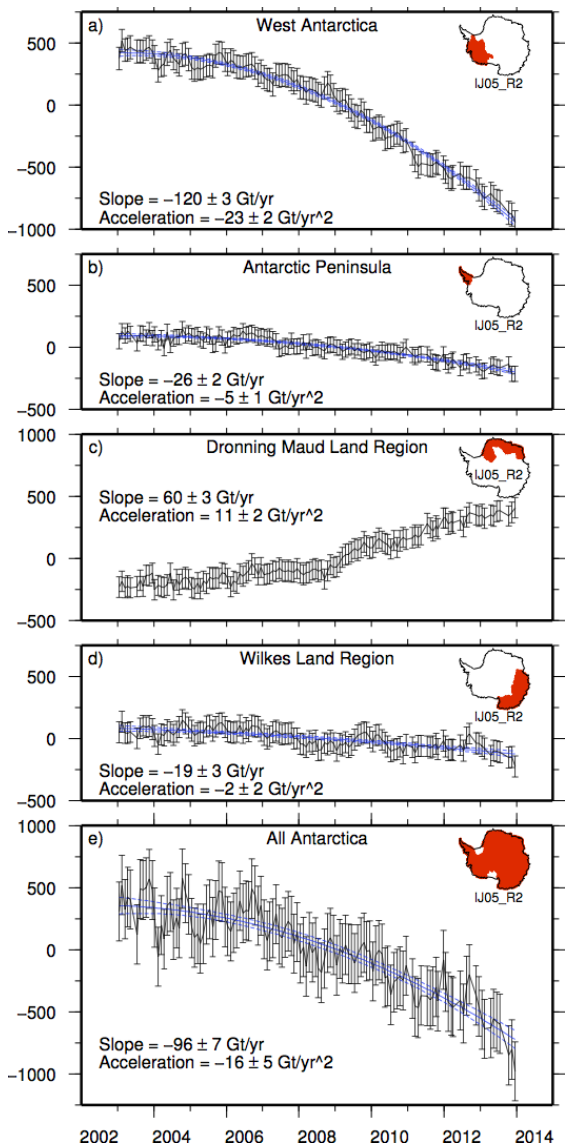

Figure 2: *Ice mass trends (corrected for ongoing glacio-isostatic adjustment) in gigatons for several regions of Antarctica including West Antarctica, the Antarctic Peninsula, Dronning Maud Land, Wilkes Land, and the whole of Antarctica. The regions covered by each localization are shown in red in the top right of each graph. The black lines are monthly GRACE observations with error bars determined from our analysis. The solid blue lines bounded by dashed blue lines are the best fit quadratic curves and their error envelopes.*

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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: Daniel Wright (Princeton), Tim Marchok (GFDL), Gabe Vecchi (GFDL), Tom Knutson (GFDL)

Other Participating Researchers: Brianne Smith (Princeton), Long Yang (Tsinghua), Maofeng Liu (Princeton), Ping Lu (Princeton), Mary Lynn Baeck (Princeton)

Task III: Individual Projects

NOAA Sponsor: Brian Gross

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:

We have have carried out climatological analyses of urban modification of rainfall in Charlotte (Wright et al. 2014b, c and d), New York (Yeung et al. 2014) and Milwaukee (Yang et al. 2013a) based on long (10 year) high-resolution radar rainfall data sets developed from volume scan reflectivity observations using the Hydro-NEXRAD system. Analyses highlight pronounced spatial heterogeneities in warm season rainfall over the urban areas and suggest possible physical mechanisms at play. Numerical modeling studies using WRF have been used to test the relative importance of specific mechanisms controlling urban modification of rainfall (Li et al. 2013, Yang et al. 2013b). Urban canopy effects, combined with urban heat island circulation, play a central role in determining the "downwind" maximum of warm season rainfall in Baltimore (Smith et al. 2012). The interaction of urban heat island circulation and land - lake breeze circulation results in a maximum in warm season rainfall in the central portion of the main urban watershed in Milwaukee (Yang et al. 2013 a and b).

Analyses of tropical cyclones have continued in collaboration with the Hurricane Research Group at GFDL. We have examined the spatial distribution of tropical cyclone floods for the US east of the Rocky Mountains (Villarini et al. 2014). These analyses point to a surprisingly large contribution of tropical cyclones to regional flood frequency in the central US and to anomalous spatial gradients in tropical cyclone flooding (that will be examined in subsequent research. We have also examined rainfall distribution from landfalling tropical cyclones, using Hurricane Irene as a case study (Liu et al. 2014). Analyses of Hurricane Irene focused on the role of extratropical transition in determining the spatial and temporal evolution of rainfall. We have initiated analyses of major flood-producing hurricanes in the mid-Atlantic and northeastern US based on downscaling simulations with WRF using 20th century reanalysis fields. Case studies of Hurricanes Connie and Diane (1955) have been completed. A sample of 25 hurricanes (1900 - 2013) will be used for climatological analyses of rainfall distribution in the

northeastern US. The role of extratropical transition in controlling rainfall distribution will be a central focus of these analyses.

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Yang, L., J. A. Smith, M. L. Baeck, E. Bou-Zeid, S. M. Jessup, F. Tian, and H. Hu,, Impact of Urbanization on Heavy Convective Precipitation under Strong Large-Scale Forcing: A Case Study over the Milwaukee-Lake Michigan Region, J. of Hydrometeorology, 15, 261-278, 2014.

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, 2014.

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

Principal Investigator: Katherine Allison Smith (Princeton Associate Research Scholar)

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

Other Participating Researchers: Daniele Bianchi (McGill University)

Task III: Individual Projects

NOAA Sponsor: Brian Gross (GFDL)

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: One objective has been to develop a biologically mechanistic model of particles sinking in the water column to understand and predict the processes of particle decomposition and remineralization in the global ocean. A second objective has been to identify organismally-relevant thresholds of hypoxia stress that account for the effect of temperature in the pelagic ocean environment. These two objectives are linked because oxygen is depleted by bacterial respiration as bacteria consume particles in the mesopelagic zone potentially affecting the vertical zonation of species in the pelagic marine ecosystem.

Methods and Results/Accomplishments:

Particles in the mesopelagic zone: The microbial remineralization model is based on a 1-dimensional Eulerian framework. The depth range of the model is from the base of the euphotic zone to the ocean bottom in 10 m depth intervals. The time step is 30 s. Carbon in mg m^{-3} seawater is traced through 9 biological compartments including particulate organic carbon (POM), particle-attached bacteria (BP), free-living bacteria (BD), active exoenzyme in the particle (EP), inactive exoenzyme in the particle (XP), hydrolysate in the particle (HP), hydrolysate in the dissolved environment (HD), active exoenzyme in the dissolved environment (ED), and inactive exoenzyme in the dissolved environment (XD) (Figure 1). Remineralized inorganic carbon (CO_2) is not modeled explicitly. We assume that CO_2 produced by bacterial respiration is eventually transported by mixing and large-scale circulation to the ocean surface where phytoplankton uptake and convert it to organic carbon during photosynthesis. Some of the organic carbon then becomes new sinking particles.

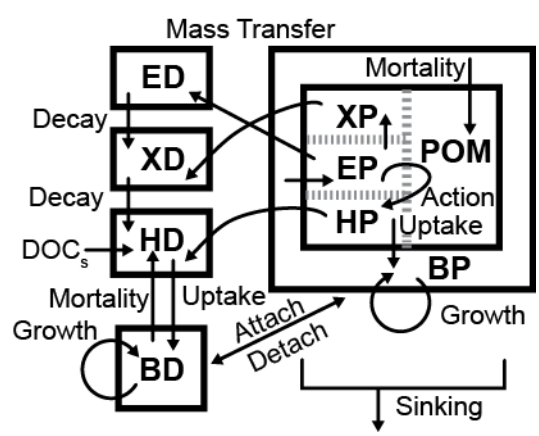

Figure 1: Diagram of the 1D microbial remineralization model. The units for all the state variables are mg C m^{-3} seawater.

We investigated strategies used by bacteria to counteract diffusive losses of exoenzymes and hydrolysate in the microbial remineralization model. We find that production of exoenzymes by bacteria is only energetically worthwhile at high bacterial abundances. Quorum sensing provides the means to determine local abundances, and thus the model results demonstrate the need for quorum sensing on sinking particles. Bacterial production is sensitive to the

arrangement of bacteria either within or around a particle, and the ability of bacteria to slow diffusion of exoenzymes and hydrolysate from particles enhances bacterial production as much as 15×. Bacterial colonization rates and activities on particles in both the euphotic and mesopelagic zones impact remineralization length scales. Shoaling or deepening of the remineralization depth has been shown to exert significant influence on the residence time and concentration of CO_2 in the atmosphere and ocean. By linking variability in remineralization depths to bacterial colonization of particles and group coordination of exoenzyme production, we connect microscale bacteria-particle interactions to the carbon cycle and provide new insights for future observations.

Hypoxia thresholds in the mesopelagic zone: We base thresholds for oxygen stress on characteristics of respiratory transport proteins, hemoglobin and hemocyanin, which are used to transport oxygen from respiratory surface areas such as gills to tissues in the bodies of multicellular organisms. The relationship between oxygen pressure and percent of oxygenated respiratory proteins is sigmoidal. The P_{50} is the oxygen pressure at which the respiratory proteins are 50% oxygenated, and is used to determine the oxygen affinity of respiratory proteins. The reaction of oxygen with respiratory proteins can be either exergonic or endergonic, energy released or needed respectively as the reaction occurs, and varies among marine species. The energy of the reaction is referred to as the apparent heat of oxygenation, ΔH. ΔH is negative when the reaction is exergonic and positive when the reaction is endergonic. Using the van't Hoff integration, the ΔH is used to determine the sensitivity of P_{50} to temperature (Clark et al. 2008). By making the assumption that environmental oxygen pressure is equal to internal oxygen pressure at the respiratory surface, we are able to determine the depths at which P_{50} is reached in the pelagic ocean environment, hereafter referred to as the P_{50} depth. In a global analysis, we used oxygen and temperature data from the World Ocean Atlas 2009 to determine the geography of P_{50} depths (Bianchi et al. 2012, Garcia et al. 2009, Locarnini et al. 2009). The analysis assumed that organisms were acclimated to water temperatures near the surface and were migrating/diving down to deeper depths. We also did a comprehensive search of the literature for measurements of P_{50} and ΔH in marine species.

In marine species, we found that P_{50} ranged from 0.27 to 9.50 kPa and ΔH ranged from -77 to 30 kJ mol^{-1}. We calculated the percent of ocean area with a P_{50} depth for these ranges and found that the area varied from 0 to 80% of the global ocean. P_{50} depths in a single grid cell differed depending on P_{50} and ΔH characteristics. Species with $\Delta H>0$ and high P_{50} values have the shallowest P_{50} depths. We hypothesize that P_{50} depth is related to the vertical zonation of species habitat utilization in the ocean water column. Therefore, species such as southern bluefin tuna which has $\Delta H>0$ (Clark et al. 2008) and giant squid which has the highest P_{50} value (Brix et al. 1989) will be more vertically restricted than other species in the ocean water column.

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Publications: (*I publish as K.A.S. Mislan.)

Bianchi, D., Galbraith, E. D., Carozza, D. A., Mislan, K. A. S., and Stock, C. (2013). Intensification of open-ocean oxygen depletion by vertically migrating animals. Nature Geoscience, 6:545-548, doi:10.1038/ngeo1837.

Submitted Manuscripts:

Mislan, K. A. S., Stock, C. A., Dunne, J. P., and Sarmiento, J. L. Group behavior among model bacteria influences particulate carbon remineralization depths. Submitted.

Conference Presentations:

Smith, K. A., Stock, C. A., Dunne, J. P., and Sarmiento, J. L. (Aug. 2013) A role for bacterial group behavior in particle remineralization. Poster Presentation, Trait-based approaches to Ocean Life Workshop, Copenhagen, Denmark.

Smith, K. A., Stock, C. A., Dunne, J. P., and Sarmiento, J. L. (Feb. 2014) Group behavior among model bacteria influences particulate carbon remineralization depths. Poster Presentation, Ocean Sciences Meeting, Honolulu, Hawaii.

Progress Report Title: **The Response of a Turbulent Boundary Layer to a Step Change in Stabilizing Surface Heat Flux**

Principal Investigator: Alexander Smits (Princeton Professor), Elie Bou-Zeid (Princeton Assistant Professor)

CICS/GFDL Collaborator: Chris Golaz (GFDL), Dan Li (Princeton), Elena Shevliakova (Princeton)

Other Participating Researchers: Tristen Hohman, Mostafa Momen, Stimit Shah, Tyler Van Buren, and Owen Williams (Princeton)

Task III: Individual Projects

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: The project aims to understand the impacts of a step change in surface/boundary temperature on air or water flow; such abrupt changes are common for example in polar regions over leads and polynyas. Both the implications on the flow and turbulence, and the repercussions on heat, momentum, and mass fluxes in geophysical media are investigated.

Methods and Results/Accomplishments:

In our experimental work, we have completed the studies of thermally stratified turbulent boundary layers with homogeneous boundary conditions. We have studied smooth wall and rough wall flows, with constant temperature and constant heat flux conditions. For the rough wall, we used a woven mesh, with a geometric maximum height of k = 4.1 mm, corresponding to k^+ = 11 to 50, and □/k=30 to 31. The experiments were conducted at nine velocities for each of eight wall temperatures, including the neutrally stable case. The corresponding Richardson number and Reynolds number ranges for the smooth wall were:

$0<Ri_\delta<0.52$ and $400<Re_\theta<1650$, and for the rough wall they were $0<Ri_\delta<0.7$ and $900<Re_\theta<2500$.

The collapse in the turbulent stresses with increasing Richardson number is evident from Figure 1. The main difference observed between the smooth and rough cases was the Richardson number at which the turbulent shear stress levels collapses, and effectively where turbulent production ceases. For the smooth case, this occurred at a bulk Richardson number of 0.1 while in the rough case it was 0.15. The experiments on step changes in roughness and wall temperature are now in progress. We will investigate all eight permutations: smooth to rough, rough to smooth, neutral, stabilizing, neutral to stabilizing, and stabilizing to neutral.

Concomitantly, we are conducting large eddy simulations of such transitions going from stable to more stable and from stable to unstable and vice-versa. In figure 2, we show an averaged temperature field from one simulation that illustrates the development of a cold air plume over the cold patch and a hot air plume over the hot patch. The figure is for a temperature jump of ΔT = 12K (the air is at the intermediate temperature, 6K colder than the hot patch and 6K warmer than the cold patch). We also conducted similar simulations with jumps of 8K and 4K. Figure 3 depicts the domain averaged friction

velocity and heat fluxes for all 3 cases. Note that in all cases the domain averaged mean temperature difference between the air and surface is 0 (the averaged surface temperature is equal to the air temperature). While the friction velocity is quite insensitive to the temperature change, as shown in figure 3, there is a robust upward net heat flux that increases linearly with ΔT. For ΔT = 12K, this flux is equivalent to a dynamic flux of about 200W/m^2, a very significant value. This illustrates the asymmetry between the unstable and stable patches and underlines the need to study the problem. In the coming year, we will focus on developing these results into useable models that account for surface temperature heterogeneity when computing surface-atmosphere coupling and fluxes.

Publications:

Momen M. and Bou-Zeid E. "Large eddy simulations and reduced models of the Unsteady Atmospheric Boundary Layer". AGU Fall Meeting 2012, San Francisco, CA, Abstract A43A-0199.

Shah S. and Bou-Zeid E. "Direct and large-eddy simulations of the stable atmospheric boundary layer: the effect of unsteadiness and surface variability". AGU Fall Meeting 2012, San Francisco, CA, Abstract A43A-0195.

Williams, O. and Smits, A. J., "Measurement in a hypersonic turbulent boundary layer using PIV." Bulletin of the American Physical Society, 65th Annual Meeting of the APS Division of Fluid Dynamics, San Diego, CA, November 18-20, 2012.

Shah S. and Bou-Zeid E. "Large-eddy simulations of the Ekman boundary layer over walls with variable temperatures: the complex implications of spatially-varying static stability", Bulletin of the American Physical Society, 66th Annual Meeting of the APS Division of Fluid Dynamics, Pittsburgh, PA, November 24-26, 2013.

Smits, A. J., Williams, O., Hohman, T. and Van Buren, T., "Experimental investigation of thermally stable turbulent boundary layers." Bulletin of the American Physical Society, 66th Annual Meeting of the APS Division of Fluid Dynamics, Pittsburgh, PA, November 24-26, 2013.

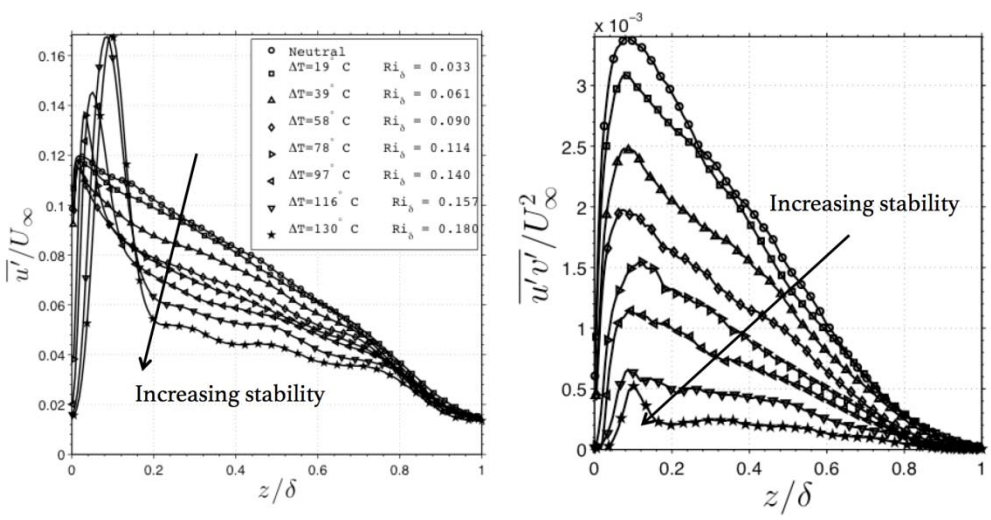

Figure 1. Rough wall. Effect of increasing Richardson number on instantaneous velocity fields, for Re_θ=990 to 1550, and Ri_δ=0 to 0.18.

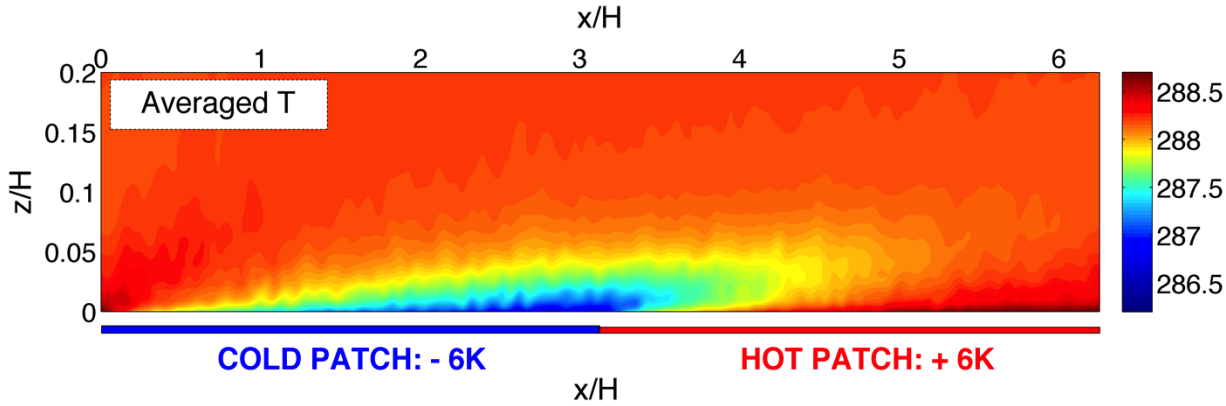

Figure 2. Mean temperature fields from a periodic simulation (the flow that exits at the right side boundary is recirculated as inflow at the left side boundary).

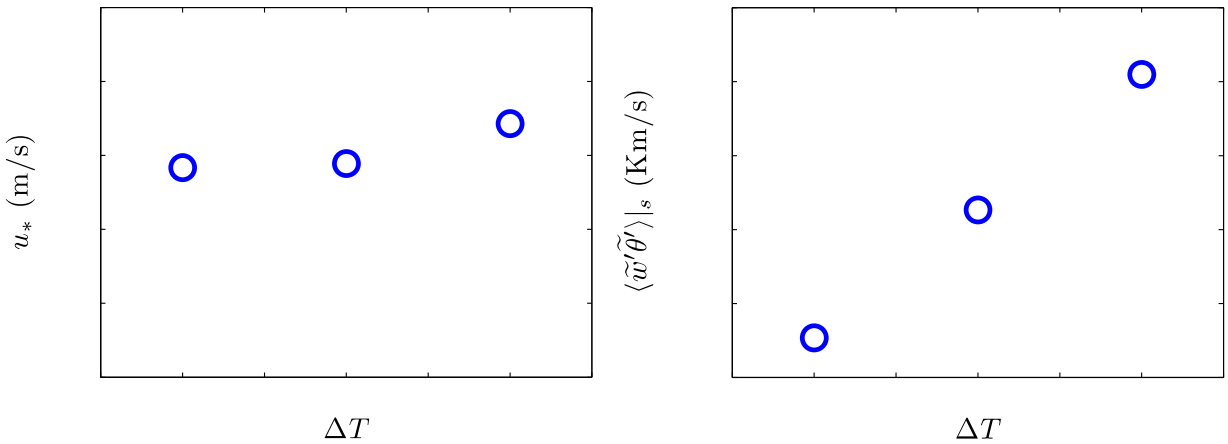

Figure 3. Friction velocity (left) and kinematic heat/buoyancy flux (right) for increasing ΔT.

Progress Report Title: **Improving Microphysical Parameterization in Numerical Models**

Principal Investigator: Kara J. Sulia (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Chris Golaz (GFDL)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: To improve microphysical representation within the GFDL Atmospheric Model (AM3), and to understand these impacts on the larger scale

Methods and Results/Accomplishments:

There is a looming need for the accurate representation of cloud microphysics in multi-scale models. While the parameterization of microphysics is on the order microns to millimeters and seconds to minutes, the effect microphysical evolution can have on the water phase budget, and subsequently radiative and energy budgets, can trickle into larger-scale processes. This fact has become all the more clear as a variety of microphysical methods (e.g. Morrison-Gettelman) produce an array of results on a global scale.

Within the enumerable processes that occur on the micro scale, the growth of ice crystals can play an important role in the prediction and evolution of the water phase. A new method of ice crystal growth has been developed in which the particle shape history is tracked in an accurate sense in order to glean a better representation of depositional growth. This effect directly impacts the liquid and ice phase, and indirectly effects cloud lifetime and the radiative budget. The method was developed and refined within a large-eddy simulation, and has since been implemented into AM3.

Initial three-year results containing the new adaptive habit microphysics scheme reveals a strong sensitivity to ice-snow auto conversion threshold and also indicates the need for prognostic snow. Figure 1 indicates the improvement to the predicted ice water path using the new microphysics scheme, reducing the root-mean-squared error by almost 10 points as compared to the Morrison-Gettleman scheme. Likewise, Figure 2 suggests improvements to the predicted LWP by approximately 12 points using the new scheme. Further tests are to be completed to indicate radiative sensitivities and climate effects on a longer time-scale.

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Morrison, Hugh, Andrew Gettelman, 2008: A New Two-Moment Bulk Stratiform Cloud Microphysics Scheme in the Community Atmosphere Model, Version 3 (CAM3). Part I: Description and Numerical Tests. J. Climate, 21, 3642–3659, doi: 10.1175/2008JCLI2105.1.

Harrington, J. Y., K. Sulia, and H. Morrison, 2012: A method for adaptive habit prediction in bulk microphysical models. Part I: Theoretical development. J. Atmos Sci., 70 (2), 349-364, doi: 10.1175/JAS-D-12-040.1.

Sulia, K., H. Morrison, and J. Y. Harrington, 2013: Dynamic and microphysical evolution during mixed-phase cloud glaciation. To be submitted, J. Atmos. Sci.

Donner, L. J., et al., 2011: The dynamical core, physical parameterizations, and basic simulation characteristics of the atmospheric component AM3 of the GFDL Global Coupled Model CM3. J. Climate, 24, 3484–3519, doi:10.1175/2011JCLI3955.1.

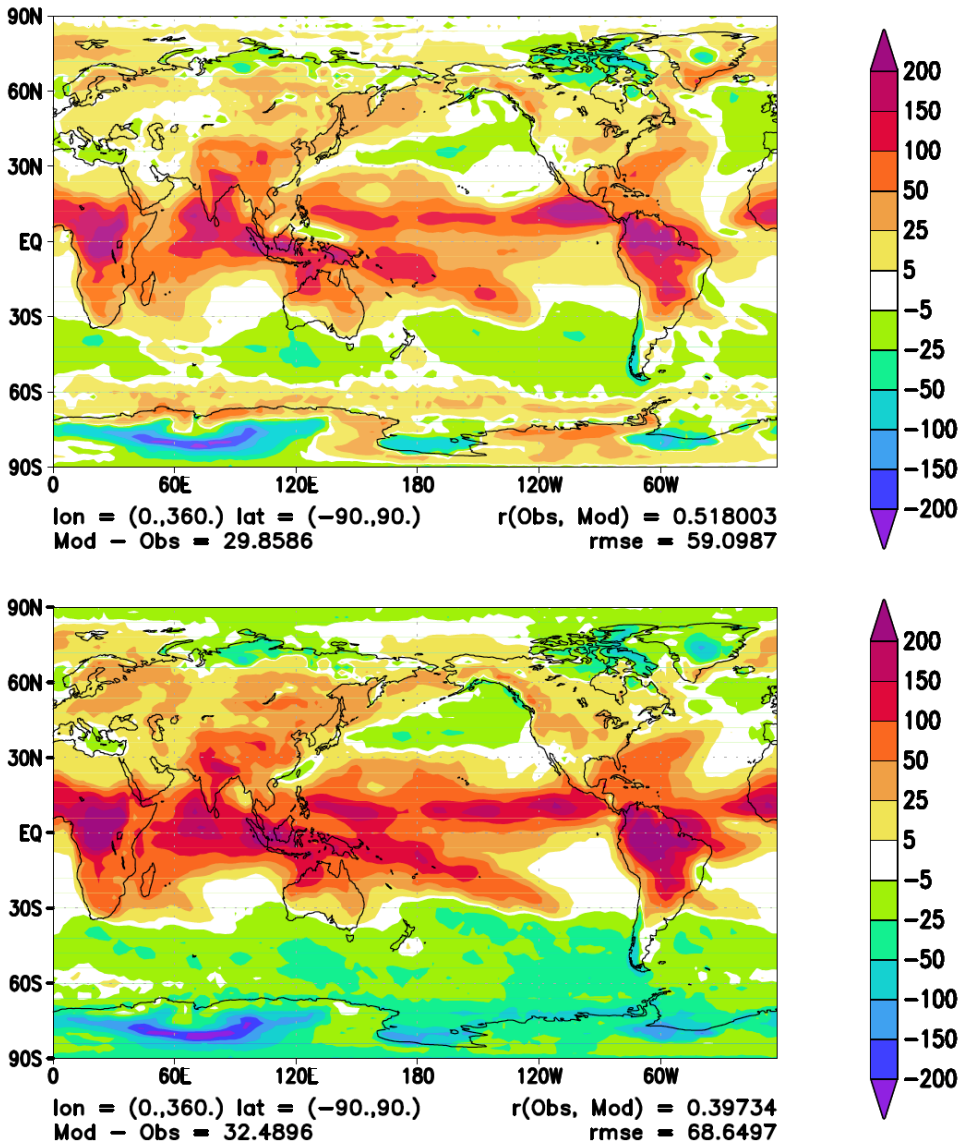

Figure 1. The difference in model-simulated IWP in g/m^2 for the adaptive habit microphysics scheme (top) and the Morrison-Gettelman microphysics scheme (bottom) to observations retrieved using the NASA JPL A-Train Aqua MODIS satellite.

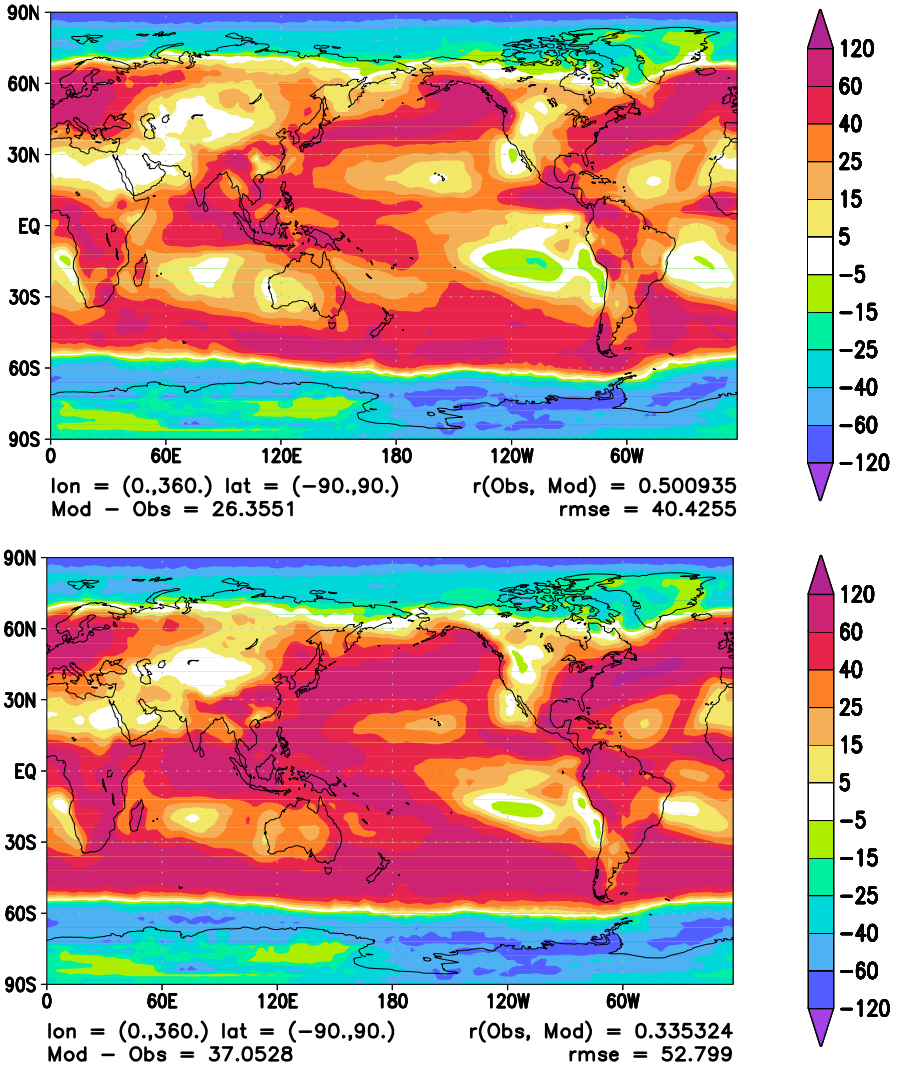

Figure 2. The difference in model-simulated LWP in g/m^2 for the adaptive habit microphysics scheme (top) and the Morrison-Gettelman microphysics scheme (bottom) to observations retrieved using the NASA JPL A-Train Aqua MODIS satellite.

Progress Report Title: **Processes of Dense Water Formation and Transport in the North Atlantic and their Influences on the 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: Using climate models to understand the impacts on the AMOC and climate of the processes in the North Atlantic dense water formation regions, including overflows, freshwater transport and shear-driven diapycnal mixing

Methods and Results/Accomplishments:

Marginal seas including the Nordic Seas and the Labrador Sea in the northern part of the North Atlantic Ocean are key regions of the dense water formation. The dense waters formed there are the major components of the lower limb of the Atlantic Meridional Overturning Circulation (AMOC)'s upper cell, and contribute to 18 Sv of the transport. Therefore, the variability and stability of the formation rate and southward transport of these dense waters have potential influences on the strength of the AMOC and climate. Here we focus on three processes in the North Atlantic related to the dense water formation in the North Atlantic, including the Nordic Seas dense water overflows, freshwater transport into the Labrador Sea and shear-driven diapycnal mixing.

In the first project, we study how the representation of the overflows in coupled models influences the AMOC and climate. The Nordic Seas overflows combined with their entrainment contributes to 2/3 of the southward dense water transport in the AMOC. Comparing the two sets of GFDL's climate models used in IPCC's AR5 report (CM2G and CM2M), we find two major differences in the overflow representation: the horizontal pathway and the vertical diapycnal mixing. Two perturbation experiments are conducted in CM2G targeting these two differences. It is found that by shutting off the eastern outlet of the overflow, the gyre circulation in the North Atlantic is altered and the climate is therefore modified; and by adding diffusivity in the overflow downstream region, the upper cell of the AMOC is lifted. These findings indicate potential model errors and possible improvements of the simulated climate by changing the representations of the overflows. This work is to be submitted to Ocean Modeling.

In the second project, the importance of the freshwater pathway through the Canadian Arctic Archipelago (CAA) is studied. Freshwater transport into the Labrador Sea impacts the stratification and dense water formation rate there. Along with the surface current along the coast of Greenland via East/West Greenland Current, the channels among the CAA act as a gateway of freshwater entering the Labrador Sea. We study the relative roles of these two pathways in CM2G by closing the CAA channels. In response to the closure of the channels, the convection and therefore dense water formation in the Labrador Sea is shut off and the AMOC volume transport is decreased by 3 Sv. As the freshwater transport via the Greenland coast circulates around the entire Labrador Sea, it has a larger impact on the open ocean convection than the freshwater coming through CAA channels which flows mainly along the western boundary. The changes in freshwater pathway also impact the sea surface temperature and

salinity. By opening wider channels and closing the pathway through Fram Strait to the east of Greenland, an opposite surface property change is observed. Further, similar changes can also be found in perturbation experiments in CM2M. This work is in preparation for publication.

In the currently ongoing third project, we will study the role that shear-driven mixing plays in setting the AMOC. Shear-driven mixing act as an important process in the entrainment and mixing of the overflow water, and is potentially important in setting the strength and structure of the AMOC. The main tool of this work will be CM2G, in which some key parameters in the shear-driven mixing parameterization will be changed.

Publications:

Wang, H., S. Legg and R. Hallberg, 2014: Representations of the Nordic Seas Overflows and their Large Scale Climate Impact in Coupled Models. under internal review.

Progress Report Title: **Implementation of Ice Nucleation Scheme in Mixed-Phase Clouds**

Principal Investigator: Yuxing Yun (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Yi Ming (GFDL)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: To improve the understanding of aerosol indirect effect in mixed-phase clouds

Methods and Results/Accomplishments:

Mixed-phase clouds are clouds that typically occur between 0 and -40 degree C and contain both liquid and ice phase condensate. Understanding the effects of aerosols in these clouds in global models is a challenge. One reason is the coexistence of liquid and ice phase microphysics and the interactions between them. Another is the coarse space and time resolution of global models, which requires the usage of parameterizations. The GFDL AM3+ model is an updated version of the AM3 model, which includes a double moment cloud microphysics scheme. Therefore, in addition to droplet number/mass, ice number/mass is also included as prognostic variables. Detailed ice/liquid microphysical processes such as nucleation, autoconversion, accretion, and sedimentation are included.

In this study, we aim to improve the simulation of aerosol indirect effects in mixed-phase clouds in the GFDL AM3+ model by introducing an ice nucleation parameterization for black carbon and dust aerosol (Phillips et al., 2013). It was found that after implementing the new parameterization, the grid-averaged ice number concentration and ice water mixing ratio decreased significantly. Based on the Bergeron effect, and decreased ice water content will lead to less "burn-out" of liquid water, therefore an increased liquid water content, as the investigator has seen with the CAM3 model (Yun and Penner, 2012). However, in the AM3+ model, the ice water decrease is accompanied by a significant liquid water decrease. From a budget analysis of the liquid and ice water change, it is found that the reason for this reduction of liquid water is as follows: the decrease of ice water in mixed-phase clouds with the new parameterization leads to decrease in ice sedimentation, therefore less ice melting in the warm clouds, which reduces the source for liquid water in these clouds. This effect has outweighed the increase of liquid water from Bergeron effect, leading to a net reduction of liquid water. This result points to the importance of ice sedimentation and melting process, which has been previously neglected in studies of the mixed-phase clouds.

References:

Phillips, V. T. J., Demott, P. J., Andronache, C., Pratt, K. A., Prather, K. A., Subramanian, R., and Twohy, C.: Improvements to an Empirical Parameterization of Heterogeneous Ice Nucleation and Its Comparison with Observations, J. Atmos. Sci., 70, 378-409, doi:10.1175/jas-d-12-0801.1, 2013.

Yun, Y., and J. E. Penner (2012), Global model comparison of heterogeneous ice nucleation parameterizations in mixed phase clouds, J. Geophys. Res., 117, D07203, doi:10.1029/2011JD016506.

Publications:

Yun, Y., J. E. Penner, and O. Popovicheva (2013), The effects of hygroscopicity on ice nucleation of fossil fuel combustion aerosols in mixed-phase clouds, Atmos. Chem. Phys., 13, 4339-4348, doi:10.5194/acp-13-4339-2013.

Yun, Y., and J. E. Penner (2013), An evaluation of the potential radiative forcing and climatic impact of marine organic aerosols as heterogeneous ice nuclei, Geophys. Res. Lett., 40, 4121-4126, doi: 10.1002/grl.50794.

Jiao, C., M. Flanner, S. Bauer, N. Bellouin, T. Bernsten, H. Bian, K. S., Carslaw, M. Chin, N. De Luca, T. Diehl, S. Ghan, T. Iversen, A. Kirkevåg, D. Koch, X. Liu, G. W. Mann, J. E. Penner, G. Pitari, M. Schulz, Ø. Seland, R. B., Skeie, S. D. Steenrod, P. Stier, T. Takemura, K. Tsigaridis, T. van Noije, Y. Yun, and K. Zhang (2013), An Aerocom assessment of black carbon in Arctic snow and sea ice, Atmos. Chem. Phys., 14, 2399-2417, doi:10.5194/acp-14-2399-2014.

Komurcu, M., T. Storelvmo, I. Tan, U. Lohmann, Y. Yun, J. E. Penner, Y. Wang, X. Liu, and T. Takemura (2013), Inter-comparison of the cloud water phase among global climate models, J. Geophys. Res., in press, doi: 10.1002/2013JD021119.

Progress Report Title: **Decadal Variability and Prediction**

Principal Investigator: Liping Zhang (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Tom Delworth (GFDL)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: To understand the physical mechanisms of Pacific decadal oscillation and its potential impact on North American precipitation; to examine the Pacific decadal oscillation predictability

Methods and Results/Accomplishments:

North Pacific decadal oceanic and atmospheric variability is examined from different versions of the Geophysical Fluid Dynamics Laboratory (GFDL) model (Delworth et al. 2006; Delworth et al. 2012). The dominant pattern of annual mean sea surface temperature (SST) variability is similar to the observed Pacific decadal oscillation (PDO) (Mantua et al. 1997), with maximum amplitude along the western midlatitude. SST anomalies in this region exhibit significant spectral peaks at approximately 20 yr. The mechanisms of this decadal peak includes wind-driven adjustments from both subpolar and subtropical North Pacific gyres. The decadal temperature anomalies may originate from the subsurface subpolar and subtropical North Pacific Ocean because of the wave and gyre adjustments to the preceding basin-scale wind stress curl forcing. The subpolar anomalies then ascend to the surface and further travel to the Kuroshio Oyashio Extension (KOE) region by the southward Oyashio, which can be further intensified through local temperature-salinity convective feedback. Similarly, the subsurface subtropical temperature anomalies can be uplifted to the surface and then spread to the KOE region by the Kuroshio current. The SST anomaly around the KOE region is able to feed back to the large scale atmospheric circulation inducing a wind stress anomaly which can amplify the SST by the anomalous Ekman transport on one hand, and also a wind stress curl anomaly over the North Pacific Ocean which in turn generates anomalous temperature anomalies in the subsurface subpolar and subtropical Oceans several years later on the other hand.

Fig. 1a shows that the PDO is nearly in its mature positive phase at lag 0, which is characterized by a classical horseshoe pattern, with a cooling in the midlatitude North Pacific region surrounded by a warming along the west coast of North America. The cold water in the midlatitude then decays, while the warm subpolar water gradually moves southwest (Fig. 1b-e). Later, the warm subpolar surface water extends into the midlatitude KOE region, switching the sign of the PDO (Fig. 1f and g). On the other hand, a weak warming appears in the western subtropics at Lag 2 as a result of negative wind stress curl in the preceding years (Fig. 1b and h). This subtropical warming grows, gradually advects to the northeast, and then expands to the KOE region, and eventually induces a reverse of PDO (Fig. 1c-g). The PDO cycle is also accompanied with the ocean gyre boundary shifts (Fig. 2u-o), which is largely due to the shift of the zero contour of the total wind stress curl (Fig. 1h-n). The vertical temperature profiles show that the decadal signal appears to emerge first in the subsurface subpolar/subtropical gyres, then ascends to the surface, and eventually travels southward/northward to the KOE region by the oyashio/Kuroshio (Fig. 2a-n). Moreover, the subpolar temperature and salinity anomalies tend to vary in phase in the upper ocean (Fig. 2a-n), suggesting the important role of local convective instability.

References:

Delworth, T. L. et al., 2006: GFDL's CM2 Global Coupled Climate Models. Part I: Formulation and Simulation Characteristics. J. Climate., 19(5), 643-674.

Delworth, T. L. et al., 2012: Simulated climate and climate change in the GFDL CM2.5 high-resolution coupled climate model. J. Climate., 25(8), 2755-2781.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis, 1997: A Pacific interdecadal climate oscillation with impacts on salmon production. Bull. Amer. Meteor. Soc., 78, 1069-1079.

Publications:

A manuscript describing this study is now in preparation.

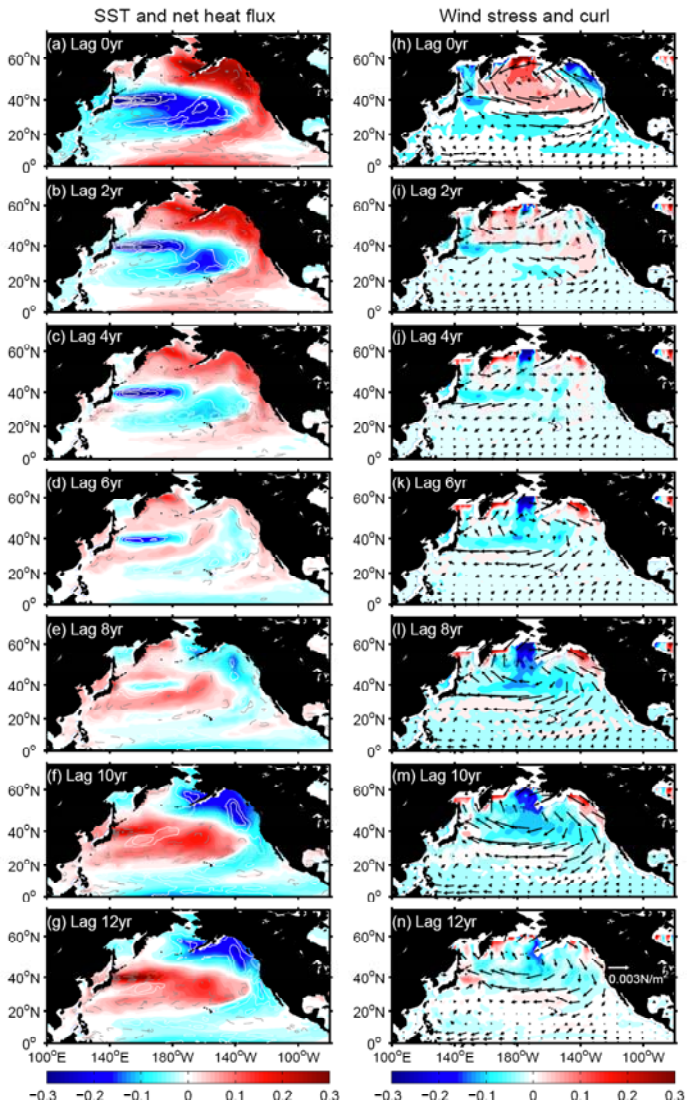

Figure 1: Lagged regression of SST (shading in the left panel, Unit: ^{o}C), surface net heat flux (contours in the left panel, Unit: W/m^2, white (gray) contours imply heating (cooling) the ocean), surface wind stress (vector in the right panel, Unit: N/m^2) and wind stress curl (shading in the right panel, Unit: 10^{-9} N/m^3) against the normalized principal component of EOF1. All data are 10-30-yr band filtered before regression.

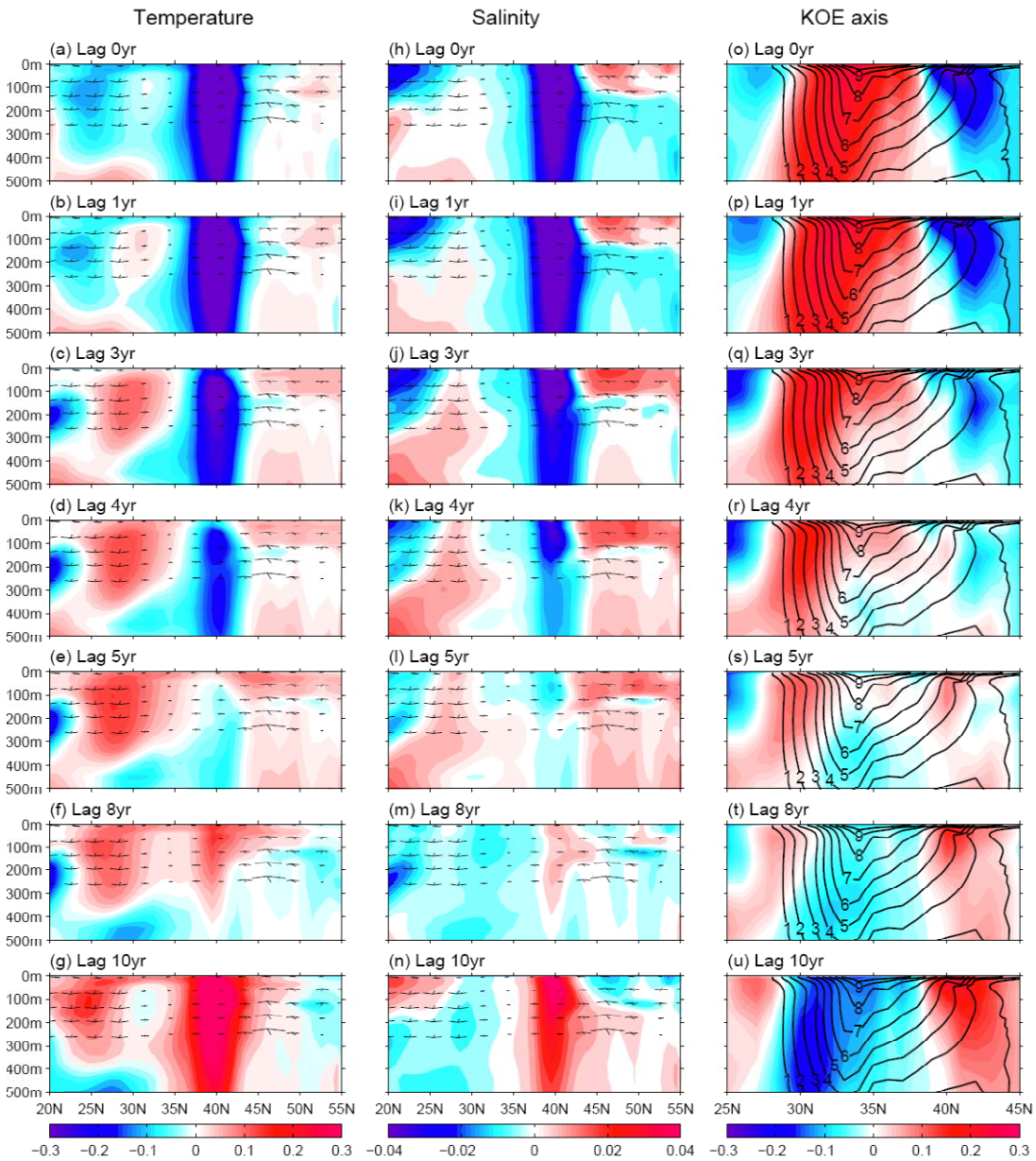

Figure 2: Same as Figure 1 but for the zonal mean (140-170°E) temperature (left panel, Unit: °C), salinity (middle panel, Unit: psu) and zonal velocity (right panel, Unit: cm/s).

Progress Reports:

Data Assimilation

Progress Report Title: **Creation of GLODAPv2: A Next Generation Data Product for Model Initialization, Comparison and/or Assimilation**

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

Task III: Individual Projects

NOAA Sponsor: Brian Gross (GFDL)

Theme: Data Assimilation

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

Objectives: Creation of GLODAPv2: A next generation data product for model initialization, comparison and/or assimilation

Methods and Results/Accomplishments:

During the initial year of this grant the remainder on new cruises that are to be included in GLODAPv2 were assembled and subjected, where necessary, to primary quality control, formatting and documentation. The "new" cruise totals were 17 for the Arctic, 60 for the Atlantic, 8 for the Indian, 19 for the Pacific and 27 for the Southern Ocean for a total of 131. This number is a bit misleading since some of the individual cruises are in fact entire collections of cruises. An example is the IOS collection that here is counted as 1 cruise but actually includes data from 35 separate cruises. In the final analysis these counts aren't particularly important, but it is significant that these new cruises contain more data than version one of GLODAP. Alternately stated, the addition amounts to more samples than were collected for the WOCE one-time survey.

Relative to GLODAPv1, probably the most valuable addition has been for the Arctic Ocean. GLODAPv1 had only a very few GEOSECS stations from the mid 1970 and a few TTONAS stations from the early 1980s in the far southern end of the Greenland-Norwegian Sea and no data from the Arctic itself. GLODAPv2 will include >7700 stations from the Arctic and surrounding marginal seas. The distribution of these stations is indicated in Figure 1. In addition to being a huge improvement over the existing situation, the glaringly empty regions in the Kara/Barents Seas and north of Canada provide strong arguments for those interested in acquiring funds to sample in the Arctic. As a matter of interest, the U.S. CLIVAR (or GO-SHIPS) program has proposed a trans Arctic cruise for the next project interval. v2 will include additional stations in the Bering Sea, but these are grouped into the Pacific and most are not shown in Figure 1. The Arctic collection in GLODAPv2 will be approximately 75% the size of the global GLODAPv1 sample set. Similarly the Mediterranean Sea was not covered in v1 except for 2 GEOSECS stations and it is now reasonably well covered with very high quality data. The Indonesian Throughflow region, completely devoid of data in v1, now has 6 cruises – still far too few to adequately describe the chemistry of this critical region, but a start.

The one region where v2 gains have been disappointing is the Indian Ocean. The reasons are twofold. There has been no work in recent years in the northwestern Indian due to the pirate/terrorist activities extending out from northeastern Africa. Cruises planned for this region were replaced with other fieldwork. Second, no country in that region has the resources to sample adequately. The French do routinely sample in the Indian, but only between South Africa and their Antarctic research station. Australian efforts are focused almost entirely to the south and southeast.

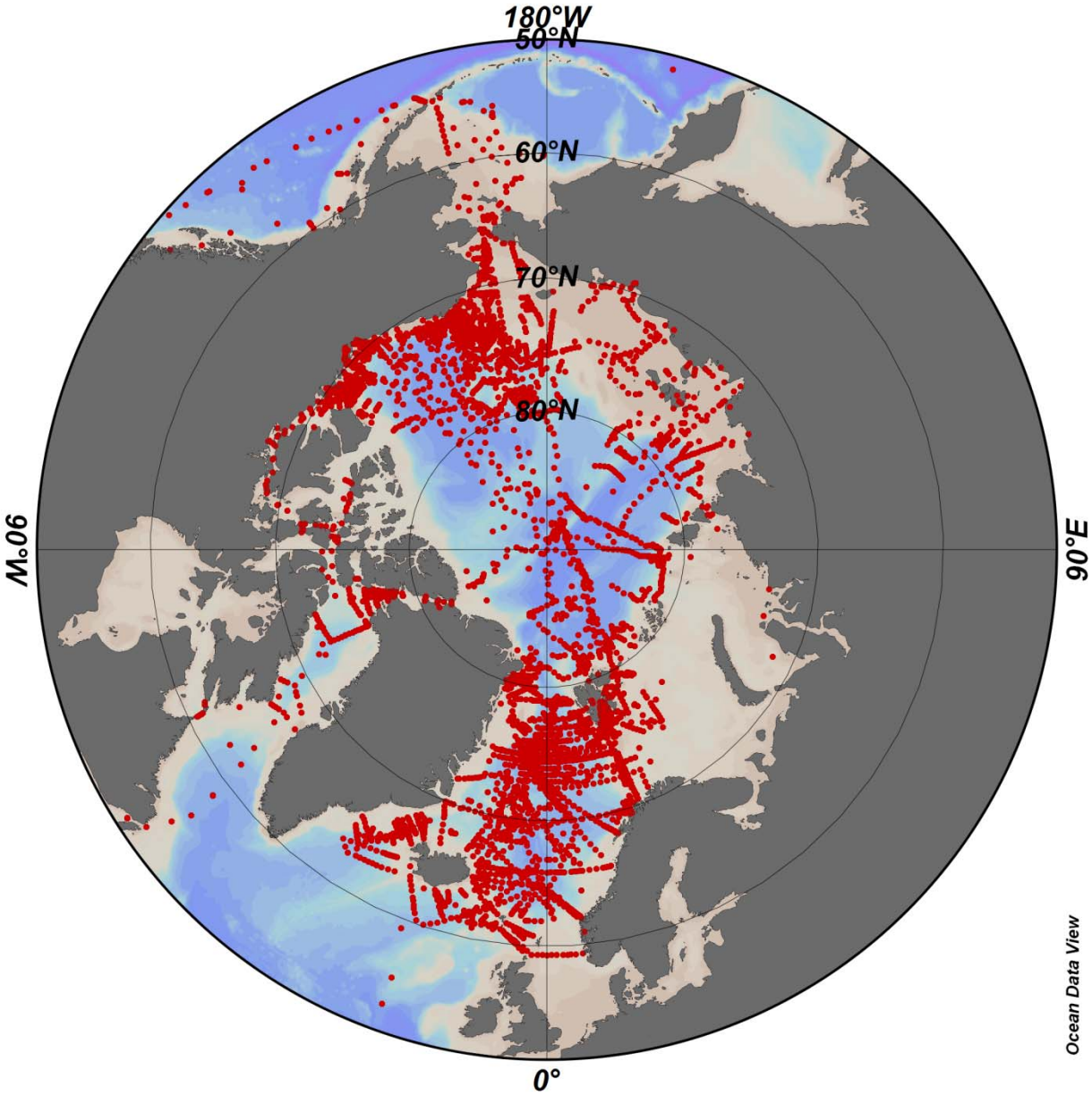

Figure 1. Distribution of more than 7700 Arctic stations that will be included in GLODAPv2.

In the original proposal v2 was estimated to be approximately 4 times the size of v1. Now that all the data are actually collected the truth is that it will be about 7 times larger and include a total of almost 800 cruises. The exact size is yet to be determined since the data product has thus far only been assembled in parts and a minor bit of duplication is yet to be eliminated. Initial statistical analysis of the v2 data indicates that the data collection for the 2000-2010 decade will be approximately the same size as that for the previous decade. This is a bit surprising since the official global CLIVAR effort is significantly less that that for the WOCE project during the 1990s. One possible interpretation is that our international effort to get individual ocean researchers to submit their data for public use has had some success.

The original proposal also mentioned the production of GOCS12, a much smaller data set composed only of high quality CLIVAR era cruises. This product was compiled and distributed to those for whom it was designed. These data are currently being used to make the global decadal change of

anthropogenic CO2 calculations using accepted techniques (delta C* and EMLR). This effort is being led by N. Gruber at ETH in Zurich.

In addition to the data collection a very significant effort has been dedicated to secondary quality control of the data. Secondary quality control consists of a series of tests developed over the past 12 years to quantify data measurement bias. Figure 2 shows a "crossover summary plot" for phosphate data that graphically compares data from 2 cruises in the far North Atlantic. Many thousands of these plots have been produced and examined in order to help quantify various parameter measurement biases. In addition to these crossover investigations, the v2 team also carries out large scale inversion calculations to help quantify bias for ambiguous cases. The total collection amounts to about 0.5Tb of required storage that will be made public along with the final v2 data products. We make this information public so that anyone who is curious about a particular parameter adjustment that we assign can investigate the supporting evidence with just a few "mouse clicks".

During the WOCE era measurement bias in carbon system measurements was almost eliminated by the introduction of Certified Reference Materials. Since then, as was noted in the production of GLODAPv1, the primary remaining data bias is with macro nutrient measurements (silicate, nitrate and phosphate) and to a much lesser degree with oxygen measurements. Over much of this time interval the Japanese have led an effort to develop Reference Material Nutrient Solutions. While RMNS has been used a fair bit by the Japanese and the Scripps lab, the usage is yet insufficient to carry out a global calibration/unification of existing data. Indications to date are that the entire global nutrient data collection may be biased by as much as 1-2% relative to the RMNS values. It will probably require another decade of data collection to verify these early results.

During production of GLODAPv2 all of the WOCE CTD oxygen and salinity data were very well calibrated to shipboard chemical analyses at the same time. Now that the various project components have collected data from a far wider source, we have found that much of the available CTD data are not calibrated to the shipboard measurements. Often this calibration is not done purely due to lack of funding. Regardless, we have assumed this responsibility of necessity. It is certainly true that we cannot, after the fact, calibrate the CTD salinity and oxygen data as well as the original investigators, we almost always can render these data "usable for all common chemical purposes" using available data. Subsequent to this internal calibration, the bottle and CTD salinity and oxygen data are then, together, subjected to secondary QC comparison to data from other cruises. The final GLODAPv2 data product will contain only 1 salt and 1 oxygen value for each sample in the collection.

Publications:

A number of oral presentations and posters have been generated by this project. We will be writing the major initial papers for submission this summer. All of the products from this project will be distributed through CDIAC at Oak Ridge, TN (http://cdiac.ornl.gov/oceans/index.html).

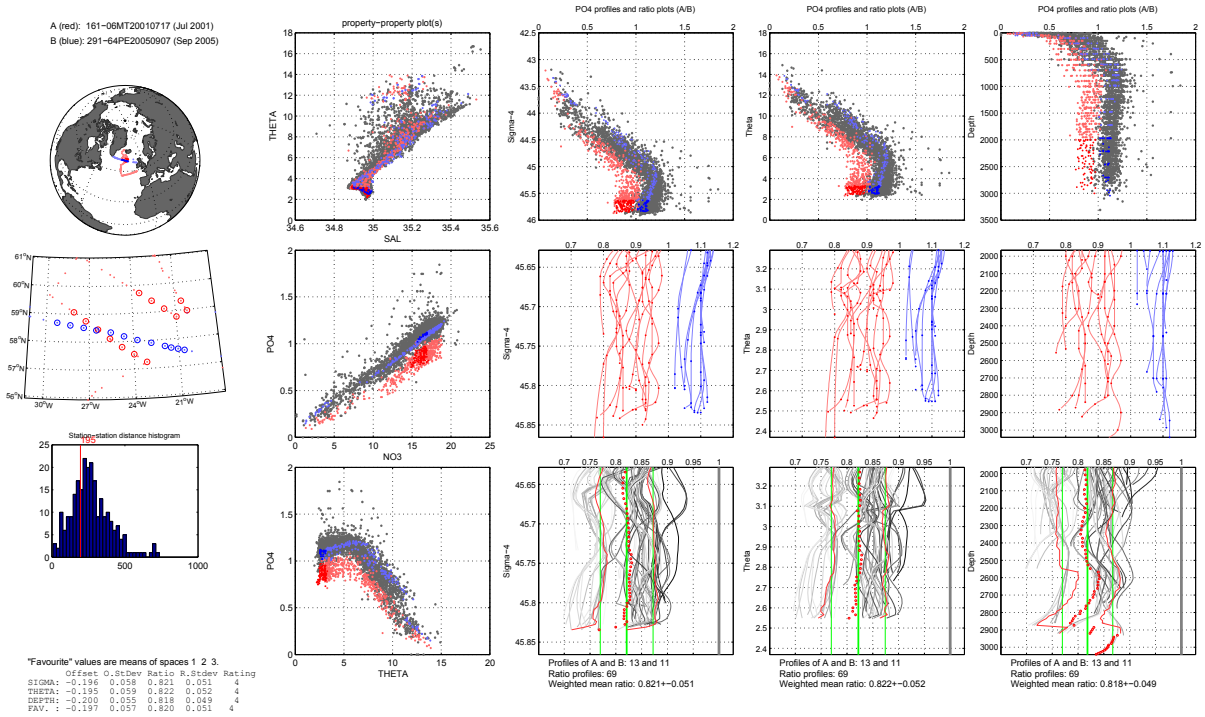

Figure 2. Example of a single crossover summary plot for phosphate measurements between two cruises in the far North Atlantic. Similar plots are prepared for each parameter undergoing secondary QC for each possible crossover between every cruise pair globally.

Progress Reports:

Earth System Model Applications

Progress Report Title: **Central Asian Climate: Aridity and Orography**

Principal Investigator: Jane Baldwin (Princeton Graduate Student)

CICS/GFDL Collaborator: Gabriel Vecchi (GFDL), Tom Delworth (GFDL), Isaac Held (GFDL)

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

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

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

Objectives: Use a hierarchy of observations and models, including state-of-the-art high resolution GFDL GCMs, to understand the mechanisms controlling the position and structure of arid regions in Asia and build a basis for predicting their likely future evolution

Methods and Results/Accomplishments:

Most deserts, including the Sahara, are found in the subtropics where dry air from the Hadley Cell subsides. However, the extratropical deserts that stretch across Asia are too far north to be explained by this mechanism. Prior studies have hypothesized three possible causes for the location of arid central Asia: drying of the westerlies as they move from oceanic moisture sources over the vast extent of the Asian continent, orographic stationary wave or rainshadow effects from the Himalayas and Tibetan Plateau, or remote Indian monsoon influences. These mechanisms are not exclusive of each other, and the monsoon likely depends on orography. Coupled with drying vegetation feedbacks, any combination of these mechanisms could generate the arid regions in Asia.

Work this year was divided into observational analysis, development of model experiments, and analysis of model results. Observational analysis using both station and satellite-based precipitation products indicated that this arid region consists of two distinct hydroclimatic regimes: a western desert dominated by a winter peak in precipitation, and an eastern desert with a summer peak in precipitation. The two regions are divided by the wetter Tianshan Mountains, an orographic offshoot of the Tibetan Plateau. To explore the mechanisms controlling precipitation in this region, the Tianshan Mountains were flattened in an experiment with the high-resolution GCM CM2.5 FLOR. This recently developed model, which has a high-resolution (50 km) land and a low-resolution (200 km) ocean, simulates the details of continental climates more rapidly than other high-resolution GCMs, making it uniquely suited to exploring the climate of central Asia. Results of the model experiments indicate that while the Tianshan Mountains affect the distribution of precipitation in central Asia, they are not fundamental to the climatological divide in the desert or its overall extent, suggesting larger-scale circulation drivers. Somewhat unexpectedly, the simulated Tianshan Mountains also significantly increase precipitation in eastern China, likely reflecting a portion of the role the entire Tibetan Plateau plays in remotely driving the East Asian monsoon.

Future work will pursue two directions: 1) examination of larger-scale climatic drivers of deserts using GCMs with idealized orographic and continental configurations , and 2) perturbation experiments with CM2.5 FLOR exploring the relative influences of land-use and radiative forcing/global warming in driving environmental change in this region.

References:

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Charney, J. G. (1975). Dynamics of deserts and drought in the sahel. Quarterly Journal of the Royal Meteorological Society, 101(428):193–202.

Progress Report Title: **Dynamical Responses of the Tropical Atmosphere to Anthropogenic Forcing**

Principal Investigator: Spencer Hill (Princeton Graduate Student)

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

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

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

Objectives: Improve predictions of changes in tropical precipitation and other circulation characteristics due to human-induced climate change in the 21st century

Methods and Results/Accomplishments:

We use experiments in several of GFDL's climate models to examine how the tropical atmosphere (and to a lesser extent the ocean) respond to human activity, focusing particularly on how aerosol emissions alter rainfall patterns. Our focus is on idealized perturbation experiments that isolate a particular facet of anthropogenic forcing, which enables understanding of the precise physical mechanisms involved and ultimately to improvements to and/or development of new theories. Repeating our experiments on several models of different complexities and resolution clarifies what features are robust and thus likely tractable from a theoretical perspective.

Work to date has focused on experiments in three GFDL atmospheric GCMs -- AM2, AM3, and HiRAM -- in which sea surface temperatures (SSTs) are perturbed as to represent the effect of historical aerosol or greenhouse gas emissions. In companion experiments, these SST anomalies are decomposed into spatially uniform and spatial pattern components, which enables direct testing of their respective roles. Hill et al 2014 describe how, in these experiments, the gross moist stability of the Hadley cells -- essentially how efficiently the cells transport energy poleward as they overturn -- responds to both components of the SST field and introduces simple theoretical arguments to explain the behavior. This theory additionally suggests that changes to the energy transport efficiency effective near the cell centers are ineffective near the cells equatorward border, thereby providing a physical basis for the tight correlation between movements of the Intertropical Convergence Zone and anomalous energy transports near the equator presented by previous authors.

References:

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Publications:

Hill, S. A., Y. Ming, and I. M. Held, February 2014: Forced tropical meridional energy flux change. Submitted to J. Climate.

Hill, S. A., Y. Ming, and I. M. Held, December 2013: Forced tropical meridional energy flux change. Oral presentation, AGU Fall Meeting, San Francisco, CA.

Hill, S. A., Y. Ming, and I. M. Held, November 2013: Forced tropical meridional energy flux change. Oral presentation, Graduate Climate Conference, Woods Hole, MA.

Hill, S. A., Y. Ming, and I. M. Held, June 2013: Forced tropical meridional energy flux change.

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Hill, S. A. and Y. Ming: Tropical precipitation responses to anthropogenically forced sea surface temperature changes in three atmospheric general circulation models: Zonal mean and Sahel. Manuscript in preparation for submission to Geophysical Research Letters.

Hill, S. A. and Y. Ming, February 2014: Tropical precipitation responses to anthropogenically forced sea surface temperature changes in three atmospheric general circulation models: Zonal mean and Sahel. Oral presentation, AMS Annual Meeting, Atlanta, GA.

Hill, S. A., Y. Ming, and I. M. Held: East Asian aerosols, the Pacific Walker circulation, and the global warming hiatus. Manuscript in preparation.

Hill, S. A. and Y. Ming: Tropical precipitation distribution changes, from dry-spells to extreme rainfall events. Manuscript in preparation.

Progress Report Title: **Assessing the Hydroclimate in High-Resolution GCMs**

Principal Investigator: Sarah Bancroft Kapnick (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Tom Delworth (GFDL), Sergey Malyshev (Princeton), Rich Gudgel (GFDL), Tony Rosati (GFDL), Fanrong Zeng (GFDL), Whit Anderson (GFDL), V. Balaji (Princeton), H.S. Kim (GFDL), Bill Stern (GFDL), Seth Underwood (GFDL), Andrew Wittenberg (GFDL), Shaoqing Zhang (GFDL), Keith Dixon (GFDL)

Other Participating Researchers: P.C.D Milly (USGS), Moetasim Ashfaq (Oak Ridge National Laboratory, Department of Energy), Leiwei Jia (UCAR), Laksmi Krishnamurthy (UCAR), Rym Msadek (UCAR), Gabrielle Villarini (University of Iowa), Xiaosong Yang (UCAR), Melissa Wrzesien (Ohio State), Michael Durand (Ohio State), Tamlin Pavelsky (UNC-Chapel Hill), Thomas Painter (NASA/JPL)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

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

Objectives: The main objectives of my research are to understand variability and changes to the climate system relating to the hydroclimate. In addition to wanting to understand the climate, I am also involved in researching which questions can be answered by models and model-development.

Methods and Results/Accomplishments:

Papers Submitted/Published: In my six-months as a CICS funded researcher I worked on various projects relating to high-resolution modeling of snow, storms, and precipitation. I submitted a paper to Nature Geoscience (in review, Kapnick et al. 2014) on variability of snowfall over the greater Himalaya region. The high-resolution model allows me to explore precipitation variability over this complex terrain in ways previously unheard of in coarser-resolution models, which are more widely available. The idea to look at this region was developed in my first published paper as a CICS fellow (Kapnick and Delworth 2013). Two separate projects relating to the new CM2.5FLOR model were also submitted on seasonal hurricane predictions (Vecchi et al. 2014) and the seasonal prediction of temperature and precipitation (Jia et al. 2014). I also helped advise the research of an undergraduate senior thesis at UNC-Chapel Hill, which will be submitted for publication this spring (Wrzesien et al. 2014).

Research under Development: As a CICS postdoc, I began to develop an understanding of storm identification and predictability in high-resolution climate models. My analysis helped me write a successful NSF Postdoctoral Fellowship (that is my current source of funding) and a proposal to look at extratropical cyclones recently submitted to the Department of Energy with Dr. Tony Broccoli (Rutgers) and Ning Lin (Princeton). I also have a paper still under development relating to North American Winter Hydroclimate (Kapnick and Delworth 2014) and Himalayan Hydrology (Kapnick et al. 2014) and an impacts paper on estimating damages from climate change (Lemoine and Kapnick 2014).

Publications:

Jia, L., Yang, Z., Vecchi, G.A., Gudgel, R., Delworth, T., Rosati, A., Stern, B., Wittenberg, A.T., Krishnamurthy, L., Zhang, S., Msadek, R., Kapnick, S., Underwood, S., Zeng, F., Anderson, W., Balaji,

V., Dixon, K., 2014: Improved Seasonal Prediction of Temperature and Precipitation over Land in a High-Resolution GFDL Climate Model. Submitted to Journal of Climate.

Kapnick, S., Ashfaq, M., Milly, P.C.D., Malyshev, S., Delworth, T., 2014: Himalayan Hydrology. In preparation.

Kapnick, S., Delworth, T., Ashfaq, M., Malyshev, S., Milly, P.C.D., 2014: Why Karakoram Glaciers Have Not Been Receding Despite Warming. In Review at Nature Geoscience.

Kapnick, S. and T. Delworth 2013: Controls of Global Snow under a Changed Climate. Journal of Climate, 26 (15), 5537-5562.

Kapnick, S., and T. Delworth, 2014: Variability of North American Winter Hydroclimate. In preparation.

Kapnick, S. and Delworth, T., 2013: Himalayan Hydroclimate, AGU Fall Meeting, San Francisco, CA, 2013.

Kapnick, 2013: Himalayan Snowfall Variability, Department of Environmental Sciences, Rutgers University, New Brunswick, NJ, 2013.

Kapnick and Delworth, 2013: High-Resolution Modeling of Snow, NOAA MAPP Webinar, NOAA Climate Program Office, Virtual Meeting, 2013.

Kapnick, 2013: Complexities of understanding snow, Department of Geological Sciences, UNC-Chapel Hill, Chapel Hill, NC, 2013.

Kapnick and Delworth, 2013: Controls of Global Snow, NOAA Library Webinar, NOAA Headquarters, Silver Spring, MD, 2013.

Lemoine, D. and S. Kapnick, 2014: Estimating Damages from Climate Change. In preparation.

Vecchi, G.A., Delworth, T., Gudgel, R., Kapnick, S., Rosati, A., Zeng, F., Anderson, W., Balaji, V., Jia, L., Kim, H.-S., Krishnamurthy, L., Msadek, R., Stern, W.F., Underwood, S.D., Villarini, G., Wittenberg, A.T., Yang, X., Zhang S., 2014: On the Seasonal Prediction of Regional Tropical Cyclone Frequency. Submitted to Journal of Climate.

Wrzesien, M., Pavelsky, T., Kapnick, S., Durand, M., and Painter, T., Validation of Snow Cover Fraction for Regional Climate Simulations in the Sierra Nevada. To be Submitted in April to International Journal of Climatology or Environmental Research Letters.

Progress Report Title: **Climate Versus Emission Drivers of Tropospheric Ozone Variability and Trends**

Principal Investigator: Meiyun Lin (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Larry Horowitz (GFDL)

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

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications
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 project seeks to advance knowledge on the role of dynamics on tropospheric ozone, which has key implications for interpreting observed trends in tropospheric ozone levels as well as for developing seasonal forecast capability to aid regional air quality planning.

Methods and Results/Accomplishments:

Tropospheric ozone is a potent greenhouse gas, biological irritant, and the primary source of highly reactive hydroxyl radicals. Over the past four decades, shifts in atmospheric circulation have played a key role in the autumnal ozone increase and the absence of spring ozone change over Hawaii by modulating pollution transport from Asia, reports Lin et al. (2014a) published in Nature Geoscience. This finding implies a need to consider decade-long variability in climate when detecting and attributing trends in tropospheric ozone levels to changes in precursor emissions. Lin et al (2014a) examined the link between decadal variability in climate and Hawaiian ozone levels over the past half century. They find that the flow of ozone-rich air from Eurasia towards Hawaii during spring weakened in the 2000s as a result of La-Niña-like decadal cooling in the eastern equatorial Pacific Ocean. During autumn, in contrast, the flow of ozone-rich air from Eurasia to Hawaii strengthened in the mid-1990s onwards, coincident with the positive phase of the Pacific-North American pattern. The authors suggest that these shifts in atmospheric circulation patterns can reconcile observed trends in tropospheric ozone levels at Mauna Loa and the northern mid-latitudes in recent decades. These findings were highlighted in Nature Geoscience's Press Release and News & Views. The paper also received broad media attention.

A second manuscript currently under review for possible publication in Nature Geoscience finds that year-to-year variability in springtime high-ozone events in western U.S. surface air is tied to stratospheric influence and variability in meandering polar jet (Lin et al. 2014b). There is mounting evidence that ozone transported from the stratosphere can episodically push ground-level ozone to exceed the health-based limit over high-altitude western U.S. regions during spring. Understanding year-to-year variability in the frequency of these deep stratospheric intrusion events is crucial to developing a predictive capability to aid Western U.S. air quality planning. Lin et al. (2014b) use observations and chemistry-climate model simulations for 1980-2012 to demonstrate a linkage to modes of climate variability. They show more frequent late spring deep stratospheric intrusions when the polar jet stream meanders towards the southwestern United States, as occurs following strong La Niña conditions. Fewer and weaker intrusion events followed the pronounced positive phase of the Arctic Oscillation in response

to volcanic aerosols from the 1991 eruption of Mt. Pinatubo. A higher background ozone season associated with more frequent stratospheric intrusions implies a need for tighter U.S. emission controls to achieve a targeted level of air quality. The linkage between stratospheric intrusion frequency and known modes of climate variability can potentially be exploited to develop seasonal predictions with a few months of lead time to aid Western U.S. air quality planning for a high-ozone spring.

References:

Lin M., L.W. Horowitz, S. J. Oltmans, A. M. Fiore, Songmiao Fan (2014a): Tropospheric ozone trends at Manna Loa Observatory tied to decadal climate variability, Nature Geoscience, 7, 136–143 (2014) | doi:10.1038/ngeo2066.

Nature Geoscience Press Release on Lin et al (2014a): Atmospheric-induced shifts in surface ozone levels over Hawaii http://www.nature.com/ngeo/press_releases/ngeo0114.html.

Nature Geoscience News & Views on Lin et al (2014a): Atmospheric science: Blown with the wind by Guang Zeng http://www.nature.com/ngeo/journal/v7/n2/full/ngeo2077.html.

Summary of media attention and news on Lin et al (2014a): http://www.nature.com/ngeo/journal/v7/n2/ngeo2066/metrics.

Lin M., A.M. Fiore, L.W. Horowitz, A.O. Langford, S. J. Oltmans, D. Tarasick (2014b): Climate variability modulates western U.S. ozone air quality in spring via deep stratospheric intrusions, Nature Geoscience, Submitted on 17 January 2014, Out for review on 28 January 2014.

Publications:

Articles published in peer-reviewed journals:

Lin M., L.W. Horowitz, S. J. Oltmans, A. M. Fiore, Songmiao Fan (2014): Tropospheric ozone trends at Manna Loa Observatory tied to decadal climate variability, Nature Geoscience, 7, doi:10.1038/NGEO2066.

Fiore, A.M., R. B. Pierce, R. Dickerson, M. Lin. Detecting and attributing episodic high background ozone events. Environmental Management, 23, February 2014.

Lapina K., D. K. Henze, J. B. Milford, M. Huang, M. Lin, A. Fiore, G. Carmichael, G. G. Pfister and K. Bowman. Assessment of source contributions to seasonal vegetative exposure to ozone in the U.S., J. Geophys. Res., DOI: 10.1002/2013JD020905, 2013.

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, 755–760, doi:10.1002/grl.50162.

Naik, V., Voulgarakis, A., Fiore, A. M., Horowitz, L. W., Lamarque, J.-F., Lin, M., Prather, M. J. + 25 coauthors: 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., 13, 5277-5298, doi:10.5194/acp-13-5277-2013, 2013.

Articles submitted to peer-reviewed journals:

Lin M., A.M. Fiore, L.W. Horowitz, A.O. Langford, S. J. Oltmans, D. Tarasick (2013): Climate variability modulates western U.S. ozone air quality in spring via deep stratospheric intrusions, Nature Geoscience, Submitted on 17 January 2014, out for review on 28 January 2014.

A.M. Fiore, J.T. Oberman, M. Lin, L. Zhang, O.E. Clifton, D.J. Jacob, V. Naik, L.W. Horowitz, J.P. Pinto: Estimating North American background ozone in U.S. surface air with two independent global models: Variability, uncertainties, and recommendations, Submitted to Atmos. Environ.

Zoogman, P., Jacob, D.J., Chance, K., Liu, X., Fiore, A., Lin, M., Travis, K. Monitoring high-ozone events in the US Intermountain West using TEMPO geostationary satellite observations, Atmos. Chem. Phys. Discussion, 13, 33463-33490, doi:10.5194/acpd-13-33463-2013.

Invited Talks, Selected Oral Presentations & Abstracts:

Dec 2013, UN Task Force on Hemispheric Transport of Air Pollution (HTAP), San Francisco. Meiyun Lin: Influence of decadal climate variability on hemispheric pollution transport.

Dec 2013, American Geophysical Union Fall Meeting, San Francisco. Meiyun Lin: Tropospheric ozone trends at Mauna Loa Observatory tied to decadal climate variability (Poster).

Aug 2013, Hiram "Chip" Levy Symposium, Princeton. Meiyun Lin: Footprints of decadal climate variability in ozone at Manna Loa Observatory.

July 2013, Western Regional Air Partnership (WRAP)-Western Air Quality Modeling Workshop, Boulder. Meiyun Lin: Asian and stratospheric influences on Western U.S. ozone variability and trends (Invited).

May 2013, Chemistry-Climate Model Initiative Workshop, Boulder. Meiyun Lin: Climate versus emission drivers of U.S. ozone variability and trends (Poster).

Progress Report Title: **Stratospheric Circulation Changes in Response to Natural and Anthropogenic Forcings**

Principal Investigator: Pu Lin (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Yi Ming (GFDL), V. Ramaswamy (GFDL)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

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

Objectives: To understand stratospheric circulation changes in response to natural and anthropogenic forcings

Methods and Results/Accomplishments:

The Brewer-Dobson circulation is the slow overturning circulation in the stratosphere that serves as a major pathway of the stratosphere-troposphere exchange and governs the transport of stratospheric species (Holton et al. 1995). By altering the concentration and spatial distribution of water vapor, ozone, aerosols and other radiatively active species, changes of the Brewer-Dobson circulation would affect the radiative balance of the climate system. Previous studies have predicted a stronger Brewer-Dobson circulation as greenhouse gases (GHGs) concentrations increase (Butchart et al. 2006, 2010) and during El Nino events (Calvo et al. 2010). In this project, we investigate changes of the Brewer-Dobson circulation in the unforced control simulation as well as in the historical simulations under different forcing with GFDL CM2.1 and CM3.

We diagnose the strength of the Brewer-Dobson circulation from the monthly model output of the diabatic heating rates. Compared to the conventional method to diagnose the Brewer-Dobson circulation that requires archiving meteorological fields of high frequency (daily or higher), this new diagnostics is much more efficient and as accurate.

We find that the variations of the shallow branch of the Brewer-Dobson circulation can be explained largely by those of the tropical-mean surface temperature. This bottom-up control of the lower stratospheric circulation operates on a range of timescales (from interannual to multi-decadal), and holds for natural and forced variations alike. The circulation change caused by an external forcing is relatively insensitive to its spatial structure. We suggest that this robust stratospheric circulation response arises from the tropical upper tropospheric amplification of the variations of surface temperature, and the resulting changes in the meridional temperature gradient and subtropical zonal wind structures. This result has been summarized in a paper that is currently under internal review and will be submitted to Nature Geoscience.

References:

Holton, J. R., P. H. Haynes, M. E. McIntyre, A. R. Douglass, R. B. Rood, and L. Pfister, 1995: Stratosphere-troposphere exchange, Rev. Geophys., 33, 403-439.

Butchart, N., and coauthors, 2006: Simulations of anthropogenic change in the strength of the Brewer-Dobson circulation, Clim. Dyn., 27, 727-741.

Butchart, N. and coauthors, 2010: Chemistry-climate model simulations of twenty-first century stratospheric climate and circulation changes, J. Clim., 23, 5349-5374.

Calvo, N., R. R. Garcia, W. J. Randel, and D. R. Marsh, 2010: Dynamical mechanism for the increase in tropical upwelling in the lowermost tropical stratosphere during warm ENSO events, J. Atmos. Sci., 67, 2331-2340.

Publications:

Lin, P., Y. Ming and V. Ramaswamy, 2014: A robust tropical bottom-up control of the lower stratopsheric circulation. (internal review).

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

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

CICS/GFDL Collaborator: John Dunne (GFDL)

Other Participating Researchers: Simon Donner (UBC), Mark Eakin (NOAA-Coral Reef Watch)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

NOAA Goals:
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 climate warming and ocean acidification

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., 2014). 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 (Logan et al. 2014).

Our next step is expand upon our projections of coral reef bleaching frequency based on output from GFDL's Earth System Models. We will move from empirically-derived algorithms of coral bleaching to more mechanistic prediction methods that will allow us to incorporate genetic diversity of algal symbionts to modulate coral adaptation to changing thermal stress after the work of Baskett et al. (2009). We also plan to include the effects of ocean acidification in the model by decreasing calcification rates as aragonite saturation state decreases. This will allow us to additionally assess trajectories of coral cover within reefs and estimate the frequency of thermal stress to coral reefs, the rate of recovery from bleaching events, the combined effects of temperature and ocean acidification, and the resulting trajectories of coral cover. The results will represent a range of possible futures for each local coral reef "grid cell", subject to uncertainty in the factors governing reef resistance and resilience and in future climate projections.

References:

M.L. Baskett, S.D. Gaines, and R.M. Nisbet. 2009. Symbiont diversity may help coral reefs survive moderate climate change. Ecological Applications 19(1):3-17.

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, 2014: Incorporating adaptive responses into future projections of coral bleaching. Global Change Biology. Doi: 10.1111/gcb.12390

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, 2014: Incorporating adaptive responses into future projections of coral bleaching. Global Change Biology. doi: 10.1111/gcb.12390.

Progress Report Title: **Diurnal Land/Atmosphere Coupling Experiment (DICE)**

Principal Investigator: Sergey Malyshev (Princeton Professional Specialist)

CICS/GFDL Collaborator: Kirsten Findell (GFDL)

Other Participating Researchers: Martin Best (UK Met Office), Adrian Lock (UK Met Office)

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 better understand land-atmosphere coupling processes on sub-diurnal time scale, and in comparison with observations

Methods and Results/Accomplishments:

The GLACE experiment (Koster et al, 2006, Guo et al., 2006) identified regions of the where there is a high coupling strength between soil moisture and precipitation, i.e., between the land surface and the atmosphere. However, this community experiment also highlighted large differences in the coupling strength between the various models, even in the hot spot regions. If the coupling between the land and the atmosphere is not correctly modeled, then such seasonal predictions may not be correctly constrained, leading to a reduced quality for these valuable predictions. In addition, land atmosphere interactions play a critical role in determining the near surface atmospheric states of temperature and humidity throughout the diurnal cycle, but in particular during the stable nocturnal boundary layer.

To understand the coupling strength difference among models and their relationship with nature, Martin Best and Adrian Lock from UK Met Office spearheaded the Diurnal land/atmosphere Coupling Experiment (DICE), which aims at providing a comprehensive comparison between land-atmosphere coupling strength simulated by multiple models, and in-situ atmospheric observations. The experiment focuses on short-time-scale interaction in a specific location where extensive observations are available: site of CASES-99 campaign, 37.65°N, 263.265°E (Svensson et al., 2011). Participants are asked to run their land/atmosphere models for this location in different modes (1a) land model forced by the observed atmospheric forcing (1b) single-column atmospheric model driven by the observed fluxes surface fluxes (2) coupled land and single-column atmosphere driven by the tropospheric advective tendencies (3) land and atmosphere models driven by "surrogate observations" obtained in stage 1.

We created a version of the GFDL single-column atmospheric model that can be driven by common forcing data provided by the project coordinators, and can also that couple to the land model. The land model initial condition was obtained as result of multi-year spin-up driven by observed local meteorology provided by the project coordinators. The land model LM3 was not tuned in any way for this study; it used the same parameters as in GFDL Earth System Model runs. However, the obtained state of the vegetation matches the observed (grassland) pretty well. We then performed the simulations requested for the project and provided the data to the project coordinated for inter-comparison. Preliminary results of the model comparison were presented at DICE workshop (14th to 16th October 2013, Exeter, UK) by Martin Best and Adrian Lock.

Figure 1 shows the Stage 2 surface fluxes simulated by the model participating in DICE for three days in October of 1999, together with the observations. Most model produce sensible heat fluxes that

compare to observations reasonably well. However, most of the models overestimate latent heat flux. GFDL LM3 is one of the few that get the magnitude of the daytime latent heat reasonably well compared to observations. Given that both vegetation properties and soil state were emergent properties in this simulation, this result demonstrates model's ability to reproduce right behavior in local settings.

DICE is an ongoing project and will result in publication in the future.

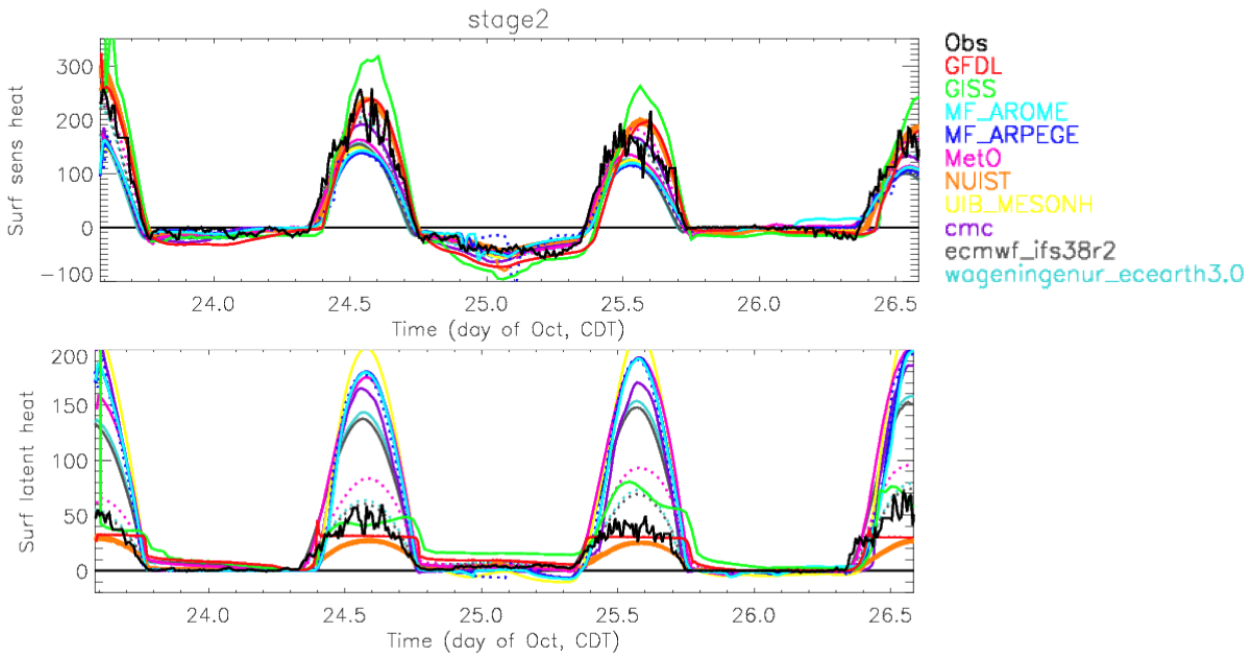

Figure 1. Sensible (top) and latent (bottom) heat fluxes produced by a number of models participating in DICE experiment. Presented by Adrian Lock and Martin Best at DICE workshop (14th to 16th October 2013, Exeter, UK).

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Progress Report Title: **Remote and Regional Impacts of East Asian Aerosol/Climate Interactions**

Principal Investigator: Geeta Persad (Princeton Graduate Student)

CICS/GFDL Collaborator: Yi Ming (GFDL), V. Ramaswamy (GFDL), Paul Ginoux (GFDL), Tom Delworth (GFDL), David Paynter (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: Our objective is to understand how increased aerosol-driven atmospheric absorption over East Asia since the 1960s has impacted regional circulation and climate and how those regional climate perturbations can be propagated downstream to remote locations, such as North America.

Methods and Results/Accomplishments:

My project seeks to shed light on the local and remote climate impacts of increased aerosol concentrations over East Asia, focusing on how their perturbation of the local surface and atmospheric radiative balance manifests in regional and remote climate impacts. In particular, I illuminate how increased atmospheric absorption from aerosol emissions over East Asia has impacted local dynamics and thermodynamics, with possible downstream effects. My working hypothesis is that increased loading of absorbing aerosols over East Asia since the 1960s has induced increased atmospheric absorption of solar radiation that can cause local tropospheric circulation changes, which may be propagated as a Rossby wave perturbation to North America.

The first stage of the project is currently under review for publication in *Journal of Geophysical Research [*Persad et al., 2014] and was awarded the American Geophysical Union's 2013 Outstanding Student Paper Award in the Atmospheric Sciences Section. Its main finding is that increased aerosol absorption contributes a large portion of the surface solar radiation decrease over East Asia. It uses a combination of atmospheric general circulation models (AGCMs), radiative transfer calculations, and observations to characterize the relative contribution of scattering versus absorbing aerosols to clear-sky surface solar radiation (SSR) trends since 1960 over East Asia.

I validate the Geophysical Fluid Dynamics Laboratory's AM2.1 and AM3 AGCM simulations of East Asian clear-sky SSR using an observational dataset derived from Global Energy Balance Archive pyranometer and International Satellite Cloud Climatology Project data. I also use attribution runs in AM2.1 and AM3 to establish that the SSR trends are indeed aerosol-driven. I then use standalone radiative transfer calculations to distinguish how various aerosol characteristics (such as mixing state, hygroscopic growth, and seasonality) affect the simulated values. AM2.1 and AM3 both produce trends in clear-sky SSR that are comparable to that observed, but via disparate mechanisms. Despite their different aerosol treatments, however, the models produce nearly identical increases in aerosol absorption since the 1960s, constituting as much as half of the modeled dimming (see Figures 1 and 2).

In the second stage, I investigate the surface and atmospheric response to the radiative perturbations described above, primarily using aerosol-only attribution runs in AM3. I have analyzed the trends in surface latent and sensible heat and longwave fluxes in response to the SSR trends on a seasonal basis. Preliminary results indicate that the surface energy balance responds as predicted by similar studies in other regions [e.g. Ramanathan et al, 2001], with primarily latent heat flux balancing the reduced SSR

during spring and summer and latent and sensible heat fluxes both balancing it during fall and winter.

I have also analyzed the atmospheric dynamical and thermodynamic response on a seasonal basis, looking at atmospheric heating rates and vertical motions. Preliminary results suggest that, particularly in summertime, the increased atmospheric absorption from local aerosols results in a spin-down of the climatological circulation (characterized by lower level convergence, rising motion through the atmospheric column, and divergence aloft). This may be driven largely by thermodynamical energy conservation, as the increased atmospheric heating replaces some of the lower-level convergence necessary to maintain the energy outflow from the climatological upper tropospheric divergence. These results will be further analyzed using AM3 experiments forced only with heating rates from an aerosol-only run to isolate the thermodynamical-dynamical linkage.

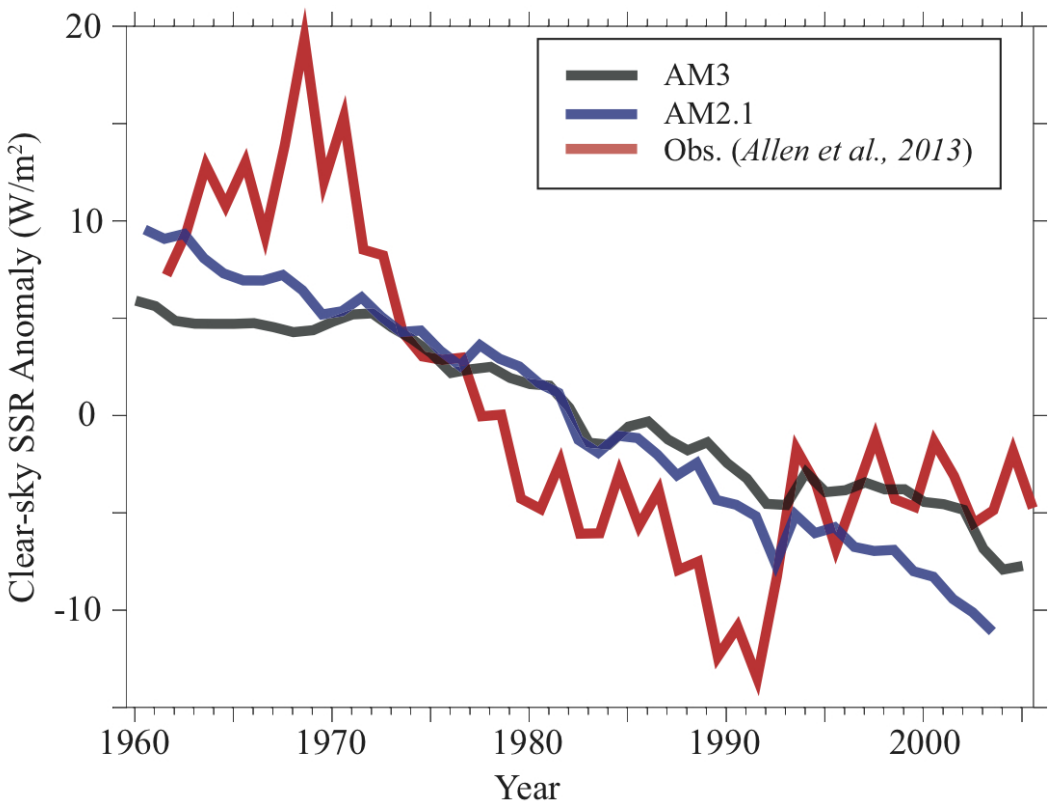

Figure 1. Clear-sky surface solar radiation anomaly over East Asia for AM3 (black) and AM2.1 (blue) models and an observational estimate (red) from Allen et al. (2013)

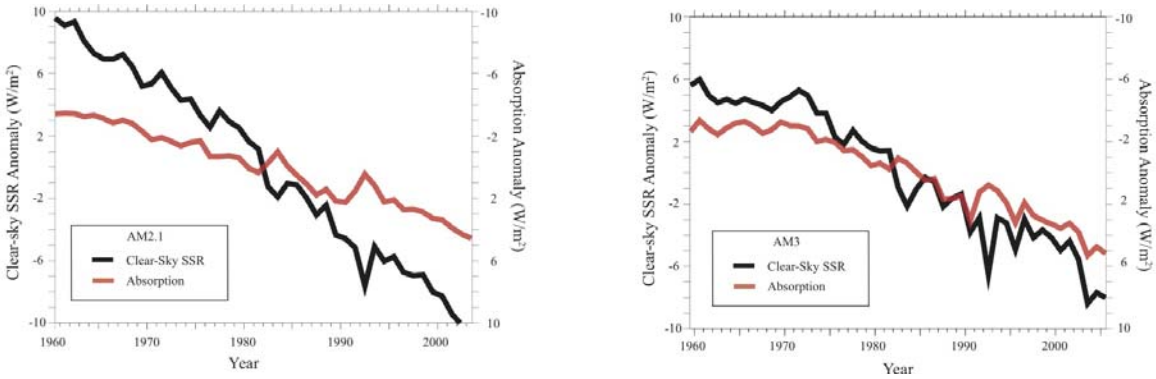

Figure 2. Atmospheric absorption anomaly (red; scale on right, increasing downward) versus clear-sky surface shortwave anomaly (black; scale on left, increasing upward) over East Asia for the AM2.1 model (left) and AM3 model (right).

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Publications:

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Persad, G., Y. Ming, and V. Ramaswamy, 2013: The Role of Aerosol Absorption in Solar Dimming over East Asia and Its Implications for Regional Climate. American Geophysical Union Fall Meeting, San Francisco, CA.

Persad, G., Y. Ming, and V. Ramaswamy, 2013: Aerosol Direct Radiative Effects through the Lens of East Asian Solar Dimming. Gordon Research Conference on Radiation & Climate. New London, NH.

Progress Report Title: **Using Models to Improve our Ability to Monitor Ocean Uptake of Anthropogenic Carbon**

Principal Investigator: Keith Rodgers (Princeton Research Scholar)

CICS/GFDL Collaborator: John Dunne (GFDL)

Other Participating Researchers: Thomas Frölicher (ETH, Switzerland)

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 use models to aid in the detection and quantification of carbon uptake by the ocean.

Methods and Results/Accomplishments:

Given the importance of CO_2 as a greenhouse gas and for climate change, it is important to understand how much of the CO_2 produced through human activity is being absorbed by the ocean, and how that quantity is changing in time. A number of recent studies have suggested that ocean uptake of anthropogenic carbon may be slowing, and if this were true it could imply that there is a positive feedback in the climate system associated with the ocean carbon cycle.

This last year saw the publication of the Plancherel et al. (2013) OSSE study, where it was argued in a modeling context that for the North Atlantic the Repeat Hydrography network is able to detect decadal changes in ocean carbon inventories to less than 10% uncertainty. Subsequent work in collaboration with Majkut et al. (2014a) evaluated the number of floats needed to constrain carbon uptake by the Southern Ocean through an OSSE, as well as through Majkut et al. (2014b) an interannually varying gridded pCO_2 product spanning 1980-2008.

Work this year will include collaboration with Gruber et al. (2014) in a synthesis of the global change in ocean carbon inventories between the 1990s and 2000s. This broad community effort will benefit from the methods first presented by Plancherel et al. (2013).

Work presented last year at the ICDC9 in Beijing on modulations of the seasonal cycle in the surface ocean carbon cycle will also be submitted for publication in 2014.

Further efforts are underway to apply a new suite of 30 ensemble calculations with GFDL's ESM2M over 1950-2100 to quantify the relative amplitudes of systematic and random uncertainty in projections of 21st century carbon uptake by the ocean. This work is intended to complement the detection and monitoring efforts described above, through quantifying the amplitude of natural variability against which the secular trend in CO2 uptake needs to be detected.

Publications:

Majkut, J.D., B.R. Carter, T.L. Frölicher, C.O. Dufour, K.B. Rodgers, and J.L. Sarmiento (2014a), An observing system simulation for Southern Ocean CO_2 uptake, accepted, Royal Society.

Majkut, J.D., J.L. Sarmiento, and K.B. Rodgers (2014b), A Growing Oceanic Carbon Uptake: Results from an inversion study of surface pCO_2 data, in press, Global Biogeochemical Cycles, DOI:10.1002/2013GB004585.

Plancherel, Y., K.B. Rodgers, R.M. Key, A.R. Jacobson, and J.L. Sarmiento (2013), Role of regression model selection and station distribution on the estimation of anthropogenic carbon change by eMLR, Biogeosciences, 10, 4801-4831.

Gruber, N., et al. (2014), The oceanic sink for anthropogenic CO_2 since the mid 1990s, in preparation.

Rodgers, K.B., T. Frölicher, J. Dunne, et al. (2014), Using Earth System Models to estimate the balance between random, systematic, and scenario uncertainty in future carbon projections, under preparation.

Rodgers, K.B., M. Ishii, J. Dunne, T. Frölicher, M. Kawamiya, L. Bopp, R. Wanninkhof, et al. (2013), Large changes in seasonality of the surface ocean carbon cycle under anthropogenic climate change, ICDC9 Conference, Beijing, June 2013.

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) and 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 continue to investigate the ability of standard coupled models and earth system models to provide insight regarding climatological variability in the California Current Large Marine Ecosystem (CCLME). This effort is proceeding with examination of output from standard AR5 model output and one-way model downscaling.

Methods and Results/Accomplishments:

Recent results have focused on models' representation of changes in upwelling-favorable winds in response to continued emissions of greenhouse gases. The four major eastern boundary currents have been the regions of focus. Analysis of AR5 models are inconsistent with the Bakun's (1990) hypothesis that upwelling-favorable winds would intensify with future climate warming. We find projected changes are consistent across models, but display meridional differences in the sign of the changes rather than uniform decreases in poleward wind stress as suggested by Bakun. For the CCLME, models generally show increased poleward winds (less upwelling) in the equatorward portion of the domain and decreasing poleward winds (more upwelling) in the poleward portion of the domain (Fig. 1). Results in the South Pacific (Fig. 1) and South Atlantic (Fig 2) display similar meridional dependency, while poleward wind changes in the North Atlantic (Fig. 2) display weakening (more upwelling) throughout the domain. Mechanisms driving these changes continue to be explored. Presentations emerging from this research were recently presented at the Ocean Sciences Meeting in Honolulu (February 2014), at the College of Charleston (November 2013), at the North Pacific Marine Science Organization Annual Meeting in Nanaimo (October 2013), at the University of Cape Town (July 2013), and at the University of British Columbia (March 2013). Rykaczewski also chaired an annual, international meeting regarding the biological, chemical, and physical dynamics of the Eastern Pacific Ocean in fall of 2013. See the list of presentations listed below.

In addition to these efforts specific to the CCLME, broader contributions to understanding of climate impacts on marine ecosystems include collaborative work with the Northwest Fisheries Science Center to assess the risk of future climate changes on forage fish populations (led by Jameal Samhouri, PU '00), work with SWFSC to assess changes in habitats of protected sea turtles (Willis-Norton et al., in press), and continuing work concerning the relationships among primary productivity and fisheries productivity (led by Charlie Stock).

Figure 1 – Multi-model projections of projected changes in v (poleward wind stress) from the historical period (1861-1890) to the end of the 21st century (2071-2100) for summer months in the Eastern Pacific (June-August in the Northern Hemisphere and January-March in the Southern Hemisphere) following RCP 8.5. Numbers above each coastal projection refer to an IPCC model index.

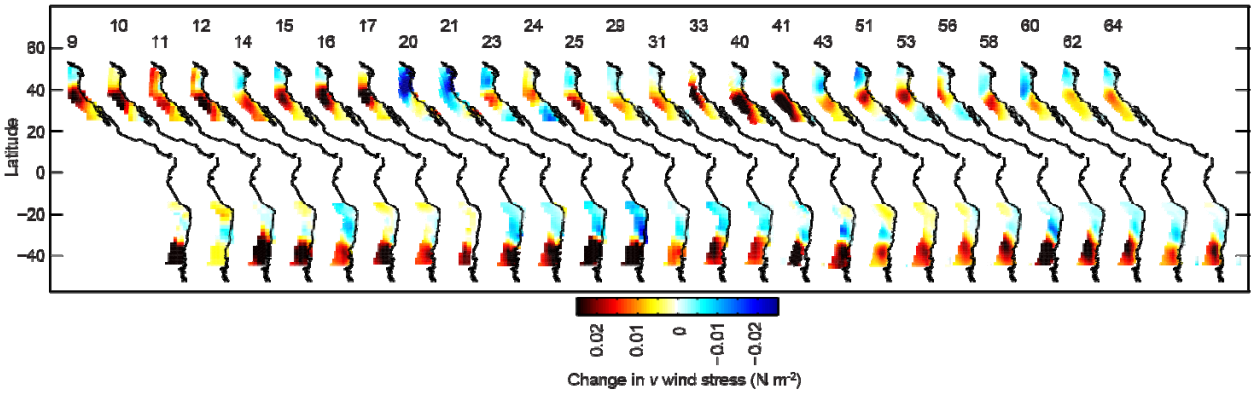
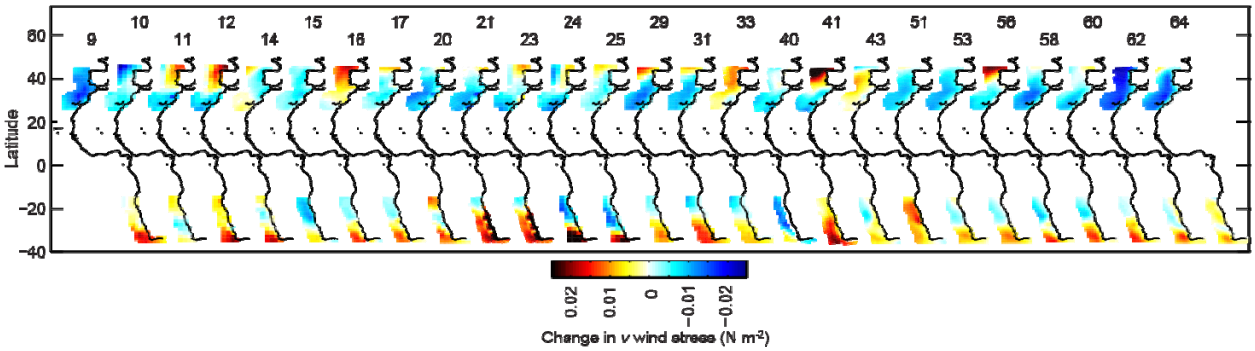


Figure 2 – Multi-model projections of projected changes in v (poleward wind stress) from the historical period (1861-1890) to the end of the 21st century (2071-2100) for summer months in the Eastern Atlantic (June-August in the Northern Hemisphere and January-March in the Southern Hemisphere) following RCP 8.5. Numbers above each coastal projection refer to an IPCC model index.



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Willis-Norton, E, EL Hazen, S Fossette, G Shillinger, RR Rykaczewski, DG Foley, JP Dunne, and SJ Bograd. 2014. Climate change impacts on leatherback turtle pelagic habitat in the southeast Pacific. Deep-Sea Res Part II Top Stud Oceanogr. In press, doi:10.1016/j.dsr2.2013.12.019.

Publications:

Beaulieu, C, SA Henson, JL Sarmiento, JP Dunne, SC Doney, RR Rykaczewski, and L Bopp. 2013. Factors challenging our ability to detect long-term trends in ocean chlorophyll. Biogeosciences 10(4):2711-2724. doi:10.5194/bg-10-2711-2013.

Conference presentations:

February 2013. *Brady, RX and RR Rykaczewski. Consequences of shifting high pressure zones on future coastal upwelling. AGU/ASLO/TOS Ocean Sciences Meeting, Honolulu, HI, USA. Poster presentation. *Student presenter

November 2013. Rykaczewski, RR. The influence of anthropogenic climate change on the hydrography and biogeochemistry of pelagic North Pacific ecosystems. Second JIMAR/PIFSC Symposium: Climate and Change. Joint Institute for Marine and Atmospheric Research, Honolulu, HI, USA. Invited Presentation.

November 2013. Rykaczewski, RR. Responses of subtropical North Pacific ecosystems to future climate change. Fort Johnson Marine Science Seminar Series. Grice Marine Lab, Charleston, SC, USA. Invited presentation.

October 2013. Rykaczewski, RR, JP Dunne, CA Stock, WJ Sydeman, M García-Reyes, BA Black, and SJ Bograd. Investigating the upwelling intensification hypothesis using climate-change simulations. PICES 2013 Annual Meeting: Communicating forecasts, uncertainty and consequences of ecosystem change. Nanaimo, Canada.

July 2013. Rykaczewski, RR. The potential influence of wind-stress curl on ecosystem structure in the California Current upwelling system. Marine Research Institute; University of Cape Town. Cape Town, South Africa. Invited presentation.

July 2013. Rykaczewski, RR. Consequences of large-scale climate change on the nutrients supplied to upwelling ecosystems. Marine Research Institute, University of Cape Town. Cape Town, South Africa.

March 2013. Rykaczewski, RR. Responses of the California Current Ecosystem to basin-scale increases in upper-ocean stratification. Department of Earth, Ocean and Atmospheric Sciences; University of British Columbia. Vancouver, BC, Canada. Invited presentation.

Other related professional activities:

Co-chairman of Session Co-Chair at AGU/ASLO/TOS Ocean Sciences Meeting: Mesoscale ocean processes and their representation in earth system models.

Meeting co-chair and organizer of 60th Annual Eastern Pacific Ocean Conference. September 2013. Fallen Leaf, CA, USA.

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

Principal Investigator: Jeffrey D. O. Strong (Princeton Graduate Student)

CICS/GFDL Collaborator: Gabriel Vecchi (GFDL), Thomas Delworth (GFDL), Paul Ginoux (GFDL), 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 with particular emphasis on the effects to tropical cyclone genesis and development

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 (Boucher et al., 2013). Strong winds over these areas loft the dust aerosols into the troposphere (Knippertz and Todd 2012), sometimes through the entire vertical extent, and can carry them thousands of miles from their source regions (Adams et al. 2012). 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 (Ansmann et al., 2011).

Using the GFDL's CM2.1 model, we have investigated how these variations in atmospheric loading and optical properties of North African mineral dust affect the climate system, with particular emphasis on West Africa and the tropical North Atlantic Ocean. A series of six experiments were conducted: Two 1000-year and one 200-year free-running controls with constant insolation, atmospheric gases, and land cover values representative of 1990 conditions alongside two 50-year, 21-member ensemble perturbations from their respective control run, initialized at 5-year intervals, and one 100-year perturbation. The forcing consisted of reducing atmospheric dust loading to simulate an 80% decrease in dust emissions over North Africa. Each set of experiments used different optical properties: One where the dust had the older CM2.1 standard, predominantly absorbing optical properties, one where the dust had a newer, predominantly scattering optical regime, and one with newer, but more moderate optical properties.

The results show considerable sensitivity to various optical properties. In the predominantly absorbing case, we observe that the dust induces a marked strengthening of the Sahel monsoon. This is explained via an enhancement of the Elevated Heat Pump (EHP) mechanism over North Africa (Lau et al., 2009) which leads to a moistening of the atmospheric column by anomalous Walker- and Hadley-like circulations (Fig. 1). In the predominantly scattering case, we note that the dust generates a significant decrease in the Sahel monsoon via a reversal of the EHP (Fig. 2). To capture the effect of dust on tropical cyclones we have performed a similar set of perturbation experiments with the GFDL's CM2.5-FLOR

model which has a similar ocean model to CM2.1, but an increased resolution in the atmosphere able to resolve tropical cyclones. We are currently working to compare these modeling results to those of CM2.1 and implement a tropical cyclone tracking scheme to examine the effect of dust on tropical cyclones.

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Ansmann, A., et al., 2011: Saharan mineral dust experiments SAMUM-1 and SAMUM-2: What have we learned? Tellus, 63B (4), 403–429, doi:10.1111/j.1600-0889.2011.00555.x.

Boucher, O., et al., 2013: Clouds and aerosols. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, T. F. Stocker, et al., Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 571–657.

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 (RG3005), 36 pp., doi:10.1029/2012RG000388.

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Lau, K. M., K. M. Kim, Y. C. Sud, and G. K. Walker, 2009: A GCM study of the response of the atmospheric water cycle of West Africa and the Atlantic to Saharan dust radiative forcing. Ann. Geophys., 27, 4023–4037, doi:10.5194/angeo-27-4023-2009.

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.

Publications:

Strong, J. D. O., G. A. Vecchi, and P. Ginoux, 2014: The response of the Tropical Atlantic and West African climate to Saharan dust in a fully coupled GCM. Proceedings, 31st Conf. on Hurricanes and Tropical Meteorology, San Diego, CA, Amer. Meteor. Soc.

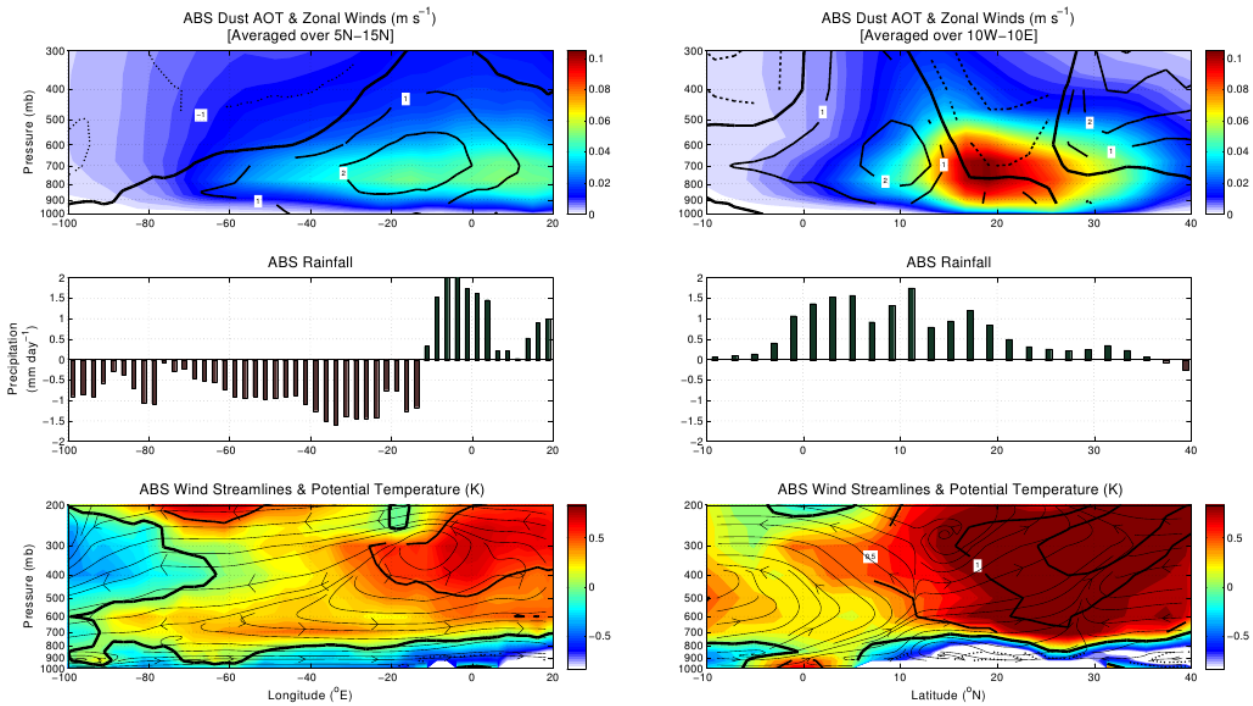

Figure 1

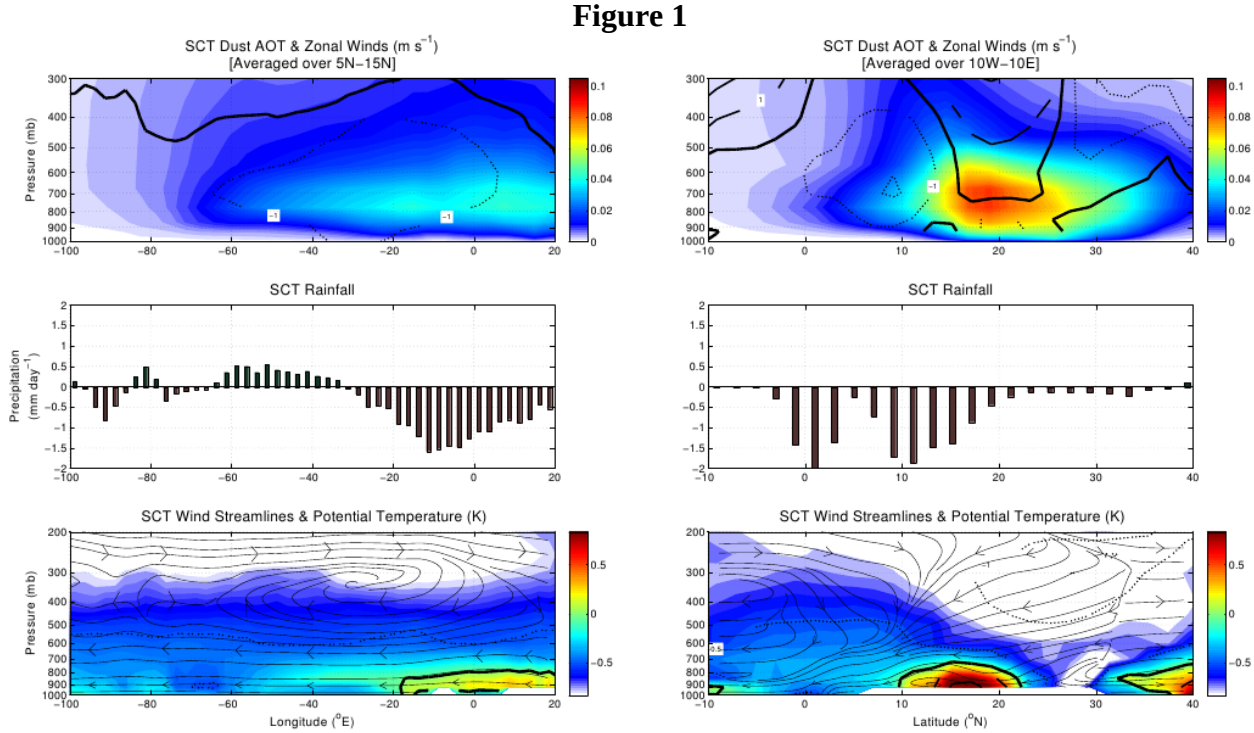

Figure 2

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 questions: 1) In what capacities (if any) are polynyas responsible for perturbing the climate system? 2) What are the temperature, salinity, and water mass changes associated with a typical polynya event, and are these anomalies adequate to explain recent abyssal ocean observations in context of the Weddell Sea polynya of the 1970s?

Methods and Results/Accomplishments:

In order to answer the above questions we analyze output from GFDL's coupled climate model, CM2G. Using the 2000-year time series of volume averaged Weddell Sea temperature, we have constructed a composite polynya by averaging over 40 individual polynyas occurring throughout this time series (figure 1). The composite polynya is used to gauge the typical magnitudes and timescales of changes associated with an average event.

We quantify the post-polynya temperature and salinity changes at various depths by differencing the temperature and salinity fields at the time of coldest temperature (yr 0013) from the temperature and salinity fields at the following time of warmest temperature (yr 0037) in the composite time series (figure 1). Figure 2 shows the post-polynya temperature and salinity changes at various depths.

Values of surface cooling and freshening for the composite typically range from -0.5°C to -0.05°C and -0.5 to -0.05 PSU, respectively, and are statistically significant at the 95% confidence level. A similar relaxation occurs at 1500m and 3200m. At these depths, the onset of a polynya causes an anomalous cooling and freshening. During the recovery period after cessation of a polynya, temperature and salinity tend to increase, and patterns of warming and salinification emerge. Between 1500m and 3200m, statistically significant warming between 0.02°C and 0.5°C occurs, which is roughly consistent with *Robertson et. al., 2002,* who find post-polynya warming by as much as a few tenths of a degree Celsius in the Weddell Sea at similar depths. The strongest temperature and salinity changes are amplified toward the south and confined to the Weddell Sea and the South Atlantic, which is consistent with *Johnson and Doney, 2006*, *Johnson et al., 2007* and *Purkey and Johnson, 2010*. Although much of the recent deep water changes in the Southern Ocean can be attributed to anthropogenic forcing, it is not unreasonable to conclude that a small part of these changes are a result of the rebound from the Weddell Sea polynya.

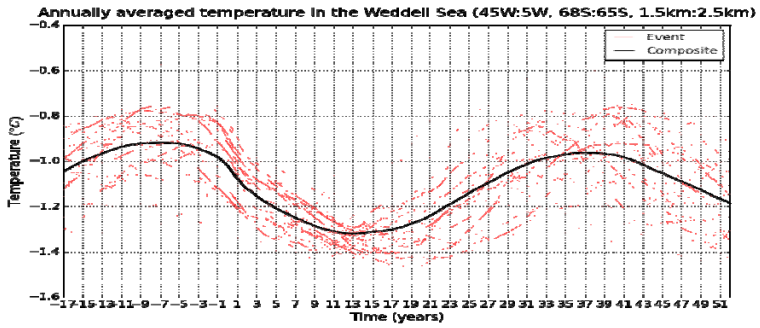

Figure 1. Time series of temperature for each of the 40 polynya events (red lines) and their composite (thick black line). Negative time values indicate time in years before the occurrence, or zero year, of the event, while positive values indicate time in years after the event.

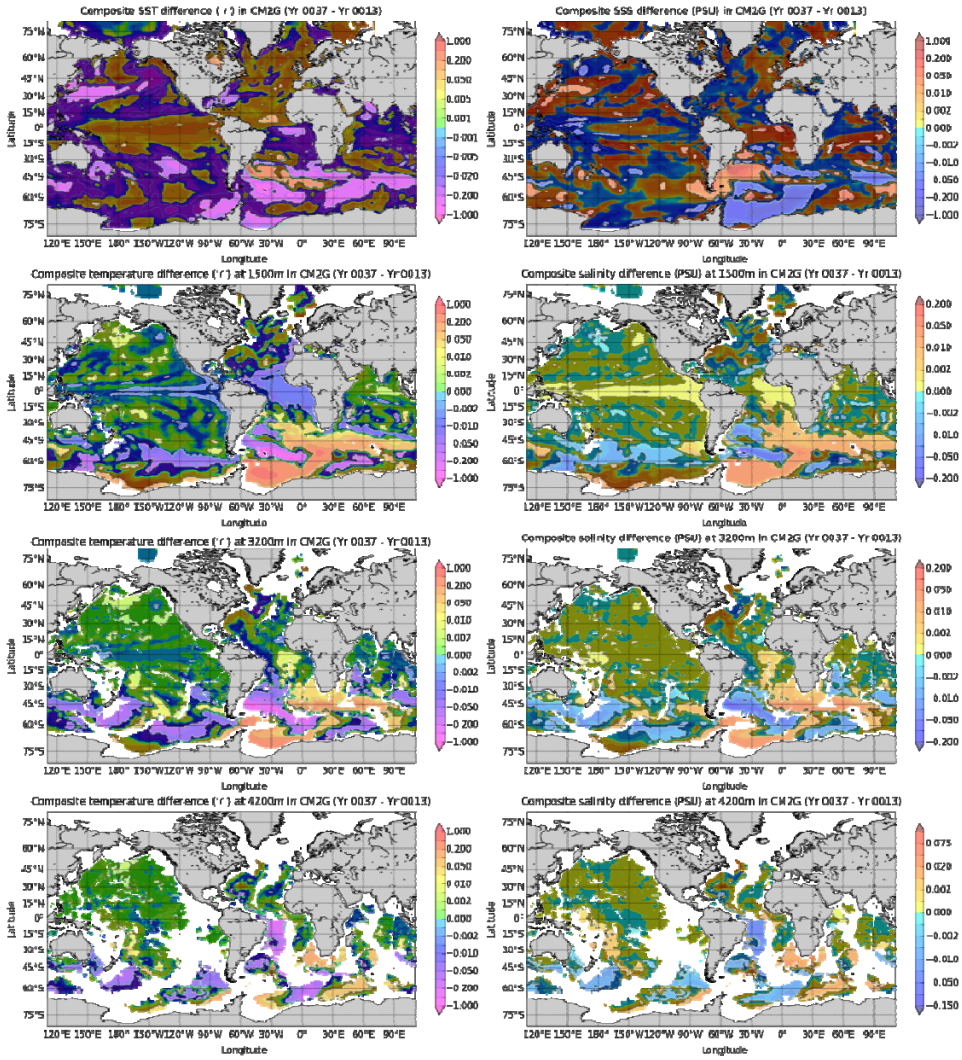

Figure 2. Composite temperature and salinity changes at the surface, 1500m, 3200m, and 4200m. Differences are calculated using the year of maximum temperature minus the year of minimum temperature after the zero year. Lightened regions are statistically significant at the 95% confidence level. Darkened regions are statistically insignificant.

References:

Johnson, G.C., and S.C. Doney, 2006: Recent western South Atlantic bottom water warming. Geophys. Res. Lett., 32, L14614.

Johnson, G. C., S. Mecking, B. M. Sloyan, and S. E. Wijffels., 2007: Recent bottom water warming in the Pacific Ocean. J. Climate, 20, 5365-5375.

Purkey, S. G., and G. C. Johnson, 2010: Warming of global abyssal and deep Southern Ocean waters between the1990s and 2000s: Contributions to global heat and sea level rise budgets. J. Climate, 23, 6336–6351.

Robertson, R., M. Visbeck, A. L. Gordon, and E. Fahrbach, 2002: Long-term temperature trends in the deep waters of the Weddell Sea, Deep Sea Res., Part II, 49, 4791– 4806.

Publications:

Zanowski, H.M., Hallberg, R.W., Sarmiento, J.L.: Evidence for long-term, large-scale climate impacts associated with the Weddell Sea polynya. Poster session presented at: The Southern Ocean and its role in the climate system: observations and modeling of physical and biogeochemical processes. 17th Biennial Ocean Sciences Conference, 2014 Feb 23-28; Honolulu, HI.

	JI Lead Author						NOAA Lead Author						Other Lead Author					
	FY 09	FY 10	FY 11	FY 12	FY 13	FY 14	FY 09	FY 10	FY 11	FY 12	FY 13	FY 14	FY 09	FY 10	FY 11	FY 12	FY 13	FY 14
Peer-reviewed	14	31	30	30	34	32	2	3	2	5	8	9	6	21	29	31	28	31
Non Peer-reviewed	14	13	3	41*	64*	64*	2	4	2	2*			2	7	2	2*	4*	8*
Chapters in books	1	1																
Ph.D. Thesis		2	3	2	1	2												

**Including Presentations*

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Task I: Administrative Activities and Outreach Supported Personnel

Name	**Rank**
Chen Chen	MPOWIR Summer Intern
Jinting Zhang	MPOWIR Summer Intern
Sarmiento, Jorge L.	CICS Director

Departures - Task II and Task III

Yalin Fan – July 2, 2013: Navy Research Laboratory at Stennis Space Center
Angelique Melet – December 13, 2013: LEGOS/CNES
Ryan Rykaczewski – September 30, 2013: University of South Carolina
Geoffrey K. Vallis – August 31, 2013: University of Exeter

Ph.D. Defenses

Student: Ilissa Ocko
Advisor: V. Ramaswamy – May 2013
Dissertation: Contrasting Features of Scattering and Absorbing Aerosol Direct Radiative Forcings and Climate Response
Current Affiliation: Environmental Defense Fund/Postdoctoral Fellow

Student: Daniel Wright
Advisor: James Smith – November 2013
Dissertation: Observation-Driven Understanding and Prediction of Urban Flood Hazard
Current Affiliation: Disaster Risk Management Analyst at The World Bank

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
Baldwin, Jane	Graduate Student	Vecchi
Chai, Junyi	Graduate Student	Held
Chen, Xi	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
Jansen, Malte	Visiting Postdoctoral Research Associate	Held/Hallberg
Legg, Sonya	Research Oceanographer	GFDL Director
Li, Dan	Postdoctoral Research Associate	Shevliakova/Milly
Lin, Meiyun	Associate Research Scholar	Horowitz
Lin, Pu	Postdoctoral Research Associate	Ming
Logan, Cheryl	Professor at CSUMB	Dunne
Lutsko, Nicholas	Graduate Student	Held
Malyshev, Sergey	Professional Specialist	Pacala
Mao, Jingqiu	Associate Research Scholar	Horowitz
Melet, Angelique	Postdoctoral Research Associate	Hallberg
Mooring, Todd	Graduate Student	Held
Nazarian, Robert	Graduate Student	Legg
Nikonov, Sergey	Professional Technical Specialist	Balaji
Orlanski, Isidoro	Sr. Research Meteorologist	GFDL Director
Persad, Geeta	Graduate Student	Ramaswamy
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
Sulia, Kara	Postdoctoral Research Associate	Golaz
Yun, Yuxing	Postdoctoral Research Associate	GFDL Director
Wang, He	Graduate Student	Legg
Zhang, Liping	Postdoctoral Research Associate	Delworth

Task III: Individual Research Projects Supported Personnel

Name	**Rank**	**Advisor**
Bonachela Fajardo, Juan	Postdoctoral Research Associate	Levin
Harig, Christopher	Postdoctoral Research Associate	Simons
Hervieux, Gaelle	Postdoctoral Associate	Curchitser
Hohman, Tristen	Graduate Student	Smits
Key, Robert M.	Research Scholar	Sarmiento
Momen, Mostafa	Graduate Student	Bou-Zied
Radley, Claire	Graduate Student	Fueglistaler
Rodgers, Keith	Research Scholar	Sarmiento
Smith, K. Allison	Associate Research Scholar	Sarmiento
Wright, Daniel	Graduate Student	Smith
Zanowski, Hannah	Graduate Student	Sarmiento

Personnel				
Category	Number	B.S.	M.S.	Ph.D.
Faculty	3	-	-	3
Research Scientist	5	-	-	5
Visiting Scientist	1	-	-	1
Postdoctoral Research Associate	11	-	-	11
Professional Technical Staff	4	-	-	4
Associate Research Scholar	5	-	-	5
Administrative	-	-	-	-
Total (≥ 50% support)	**21**			**21**
Undergraduates	-	-	-	-
Graduate Students	17	5	11	1
Employees that receive < 50% NOAA funding (not including graduate students)	8	-	-	8
Located at the Lab (include name of lab)	GFDL-26	3	4	19
Obtained NOAA employment within the last year	-	-	-	-

CICS FY'14 List of Awards for Institutional Award NA08OAR4320752

Amount	PI	Project Title
$ 38,600 [*20]	Keith Rodgers	Using Models to improve our ability to monitor ocean uptake of anthropogenic carbon (Task III) *COD-Joel Levy*

Amendment No./PI	Amount	Project Title
Amendment #20: PI: Keith Rodgers	$38,600	Using Models to Improve our Ability to Monitor Ocean Uptake of Anthropogenic Carbon