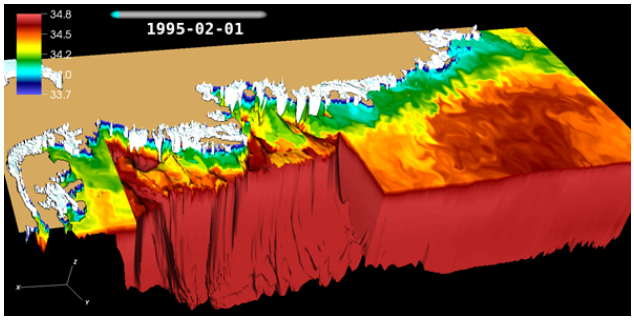

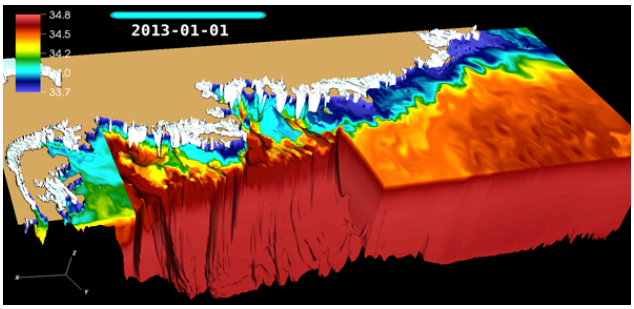

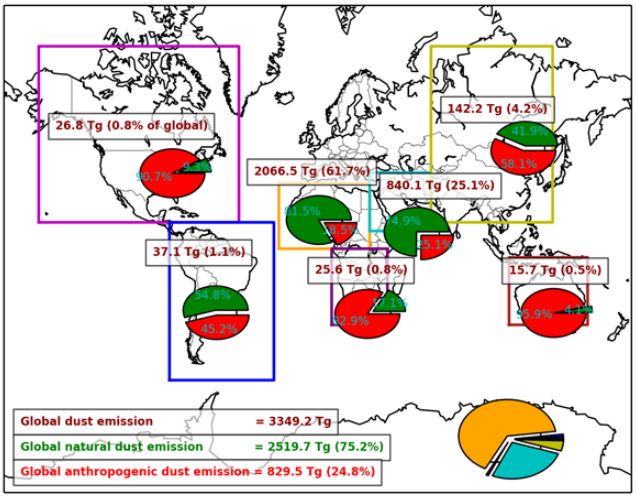

Annual Progress Report
April 1, 2015 – March 31, 2016

Cooperative Institute for Climate Science
at Princeton University
NOAA Cooperative Agreement
NA14OAR4320106

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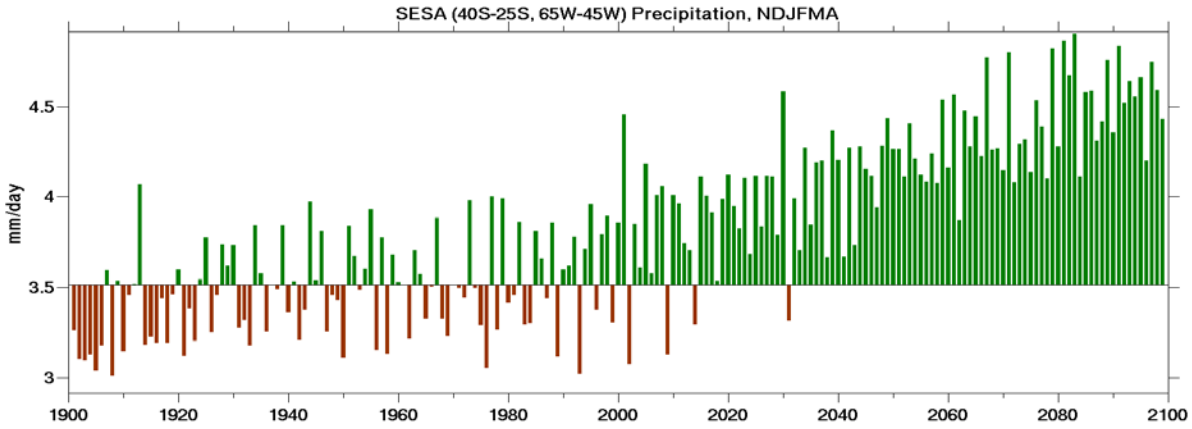

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Cooperative Institute for Climate Science
Princeton University

Annual Progress Report under cooperative agreement NA14OAR4320106

For the period April 1, 2015 – March 31, 2016

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 two research themes both 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 primarily 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.

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

Many CICS-funded scientists, students and postdocs take the initiative to participate in outreach and education activities, as described in the individual reports. Here we describe principal outreach activities sponsored by CICS/AOS.

Application of Seasonal to Decadal Climate Predictions for Marine Resource Management Workshop

More than sixty fisheries and climate scientists converged on Princeton University's Main Campus from June 3-5, 2015 to assess the utility of present seasonal to decadal climate predictions for marine resource management, and to develop new and innovative applications of these prediction systems. The CICS-sponsored workshop was titled "Application of Seasonal to Decadal Climate Predictions for Marine Resource Management" and was intended to gather experts from the fisheries and climate sciences to discuss the utility and challenges of including seasonal to decadal climate forecasts into the management of living marine resources.

Talks and discussions provided an overview of climate effects on fisheries and the fisheries management framework. The talks also focused on communicating the capabilities of present seasonal to decadal prediction systems, and presenting a synthesis of the predictive skill of seasonal to decadal climate predictions for ecosystem-relevant physical climate variables. CICS researchers presented examples of successful implementation of seasonal forecasts in marine management and identifying further proof of concept applications to assess the utility of seasonal climate predictions for marine resource management. CICS Scientist Barbara Muhling, an AOS associate research scholar, discussed the spatial management of bluefin tuna in the Gulf of Mexico and CICS Scientist Desiree Tommasi presented a talk on incorporating seasonal climate forecasts into a harvest guideline control rule for Pacific sardine.

Workshop participants presented some of the future challenges facing the use of seasonal climate predictions for marine resource management. Among the discussions, GFDL's Keith Dixon described the challenge of scale: downscaling techniques to help refine seasonal predictions and Tom Delworth, an AOS lecturer, reported on decadal climate prediction: physical underpinnings and future prospects. Tommasi facilitated the workshop's final discussion session which explored the benefits and limitations of downscaled projections with regard to fisheries environmental data needs, discussed the kinds of information decadal forecasts can provide fisheries managers, and considered the best practices to apply seasonal climate forecast information into the marine resource management framework. In addition to daily discussion sessions, a poster session and reception was held on the first day of the workshop which provided a focus for informal discussion.

The workshop brought together a diverse group of scientists with a common interest in applying short-term climate predictions toward sustainable marine resource management. The pioneering applications presented gave reason for considerable optimism, according to workshop organizers, and the workshop identified concrete steps for addressing remaining challenges.

CICS Summer Internship

During the summer of 2015, CICS supported summer intern Shaun Howe, an undergraduate from Cornell University. The internship provided Shaun a unique opportunity to complement his academic interests with hands-on research. Shaun worked with GFDL Scientist Vaishali Naik on processing surface station-based horizontal visibility data from the Global Surface Summary of the Day (GSOD) database to convert into a user-friendly format. Additionally, Shaun analyzed spatio-temporal patterns in visibility and its relationship with atmospheric stagnation. CICS funding covered his summer stipend.

Ocean Fun Days 2015

CICS, AOS, and GFDL scientists joined forces with fellow scientists and environmentalists from around the state to promote the wise use of New Jersey's marine and coastal resources during the twelfth annual celebration of Ocean Fun Days at the Jersey Shore. The 2015 event was held on Saturday, May 16th, and Sunday, May 17th in Island Beach State Park and Sandy Hook, and provided interactive activities for school-aged children and their families. This popular pre-summer event featured eco-friendly hands-on programs and interactive activities designed to promote the wise use of New Jersey's marine and coastal resources. The event included dozens of exhibitors, displays, and demonstrations by marine scientists, researchers, and environmentalists that promote natural resources and energy conservation. CICS Associate Director Sonya Legg and CICS researchers Ben Mater (currently at Alden Research Laboratories), Rob Nazarian, and Hannah Zanowski were among the nearly 50 exhibitors participating in the event. They conducted three hands-on experiments as a vehicle for introducing the children and their families to scientific processes: "ocean acidification in a cup," "iceberg melting," and "taste the difference between the bay and the ocean."

CICS Associate Director Sonya Legg, an AOS faculty member, and Ivy Frenger (former AOS postdoctoral research fellow)

CICS Scientist Rob Nazarian, an AOS graduate student, and Stuart Evans (PEI, Princeton)

Ocean Fun Days is presented by New Jersey Natural Gas through its Conserve to Preserve Foundation, in partnership with the New Jersey Sea Grant Consortium (NJSGC), the Asbury Park Press, the New Jersey Department of Environmental Protection, the New Jersey Division of Parks and Forestry and the National Oceanic and Atmospheric Administration (NOAA).

2016 Young Women's Conference in Science, Mathematics, Technology, and Engineering

On Friday, March 18, 2016, CICS Scientist Hannah Zanowski, an AOS graduate student, took part in the Princeton Plasma Physics Laboratory's (PPPL) annual Young Women's Conference along with colleagues from the AOS Program. The conference is aimed at inspiring young women's interest in the STEM fields and sparking their interest in STEM careers. Celebrating its 15th anniversary this year, the

event attracted a record number of participants – 575 seventh through tenth grade girls from New Jersey, Pennsylvania, and Maryland – as a means of cultivating girls' interest in STEM subjects and career paths through a myriad of hands-on activities, demonstrations, and talks by female scientists.

L to R: CICS Scientist Hannah Zanowski and AOS colleagues

Among the more than 30 exhibits and activities, CICS interactive displays included "Taste and Sea," in which the participants learned about the different processes that affect ocean salinity in a fun game that involves tasting and ranking water with different salinities, "The Ocean's Acid Test," an experiment exploring ocean acidification by demonstrating the relationship between CO_2 and ocean acidification, and "Ice, Ice Baby," a hands-on display demonstrating how both temperature and salinity determine the density of seawater based on the behavior of the meltwater from dyed ice cubes. Staffing the exhibit with Zanowski were AOS colleagues Rebecca Asch, Alison Gray, Natasha Henschke, Anna Trugman, and Ping Zhai. The conference demonstrated to the young participants how fun, fulfilling, and accessible science can be, while creating a connection between young aspiring female scientists and the women who forge their way in a field where women are often underrepresented.

Structure of the Joint Institute

Princeton University and NOAA's Geophysical Fluid Dynamics Laboratory have a successful 49-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:

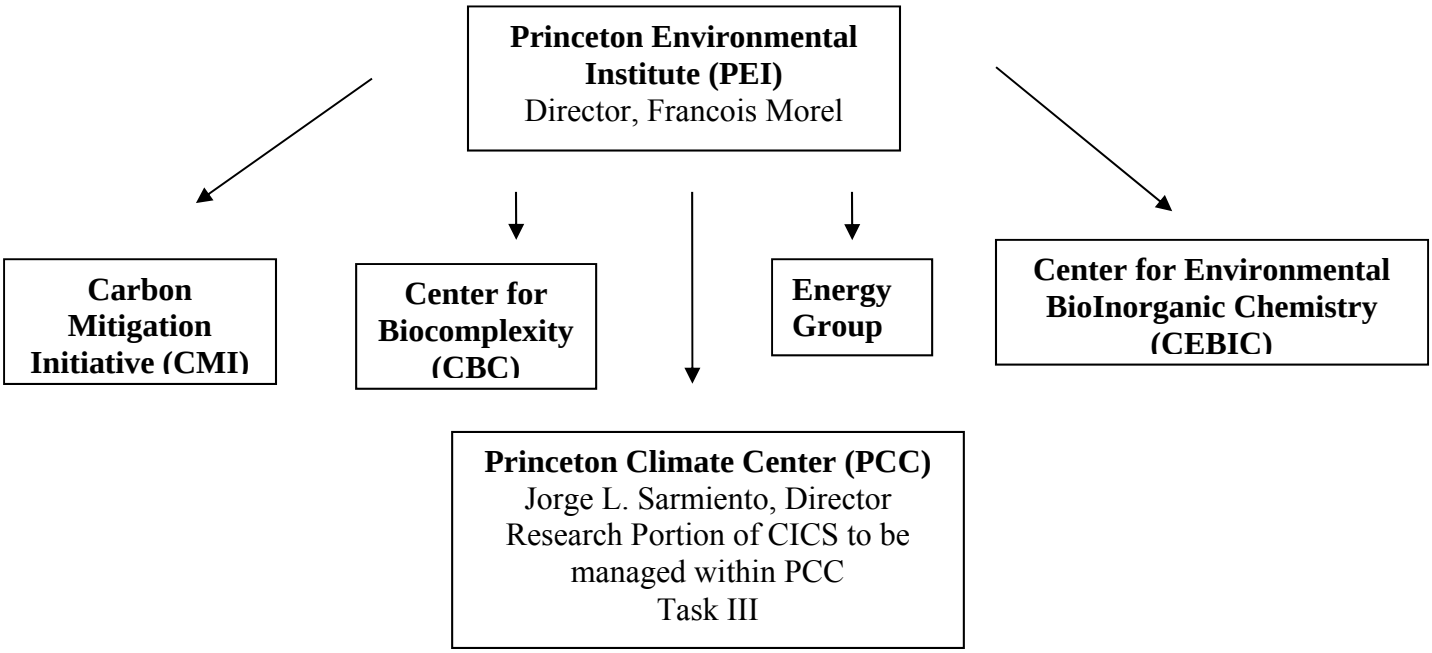
I. Administrative Activities including outreach efforts are carried out jointly by the AOS Program and Princeton Environmental Institute (PEI).

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 postdoctoral 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.

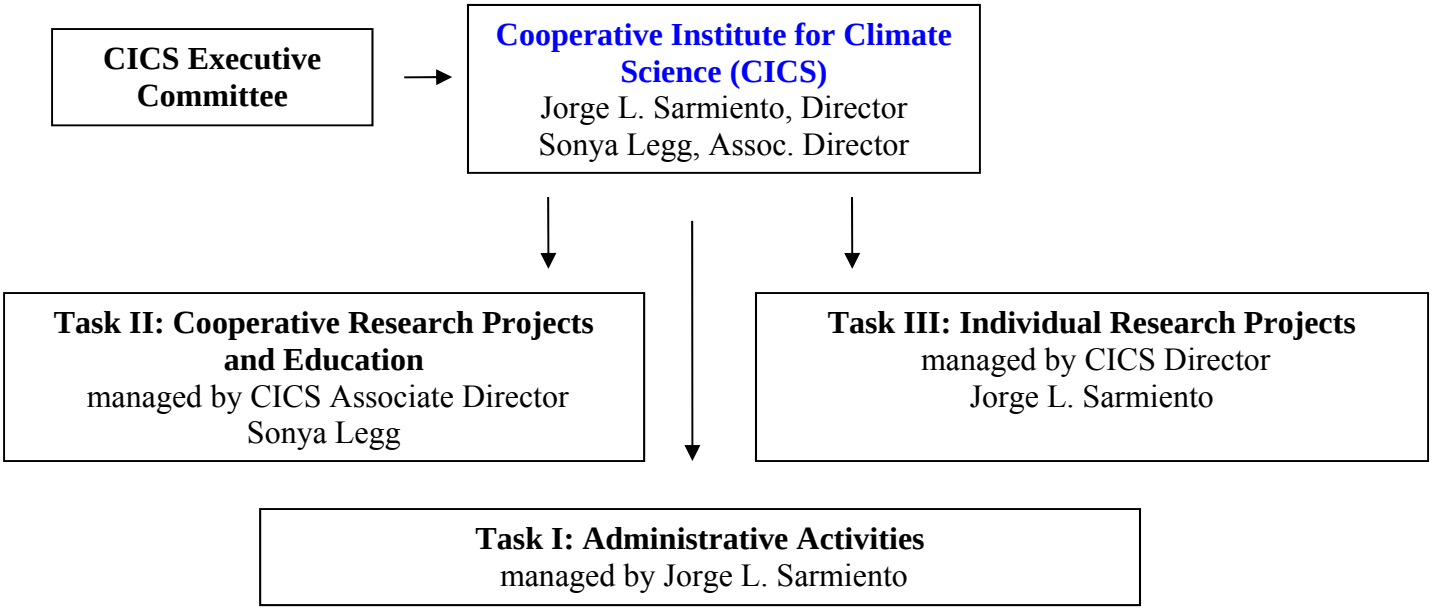
III. Principal Investigator led research projects supported by grants from NOAA that comply with the themes of CICS. These all occur within AOS and the Princeton Environmental Institute (PEI), and may also include subcontracts to research groups at other institutions on an as needed basis.

The Director is the principal investigator for the CICS proposal. The Director is advised by an Executive Committee consisting of 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 – Professor of Ecology and Evolutionary Biology
Michael Oppenheimer – Professor Geosciences and Public and International Affairs, WWS
Denise Mauzerall – Professor of Civil and Environmental Engineering and Public and International Affairs, WWS

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

Executive Summary of Important Research Activities

The following selection highlights a few of the many exciting 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.

Development of the Land Component of the Earth System Model

The land surface plays an important role in the climate system, determining the albedo, the surface heat, water and momentum fluxes, as well providing sources and sinks of dust and chemical components such as carbon and nitrogen. The feedbacks between the atmosphere and the terrestrial biosphere are therefore essential components of a complete earth system model, as is representation of land-use such as cropland and urban areas. The past year has seen significant developments in the next generation of the GFDL land surface model, LM4, led by CICS researchers **Elena Shevliakova** and **Sergey Malyshev**, in collaboration with Chris Milly (USGS) and Steve Pacala (Princeton) and other CICS postdocs and faculty. Particular new components include representation of soil nitrogen deposition (**Fabien Paulot** and **Benjamin Sulman**), a coupled land-river nitrogen cycling module (**Minjin Lee**), a scheme for coupling fire emissions with atmospheric aerosols and chemistry (**Daniel Ward**), an urban climate module (**Dan Li**), a new high-resolution land model initialization of the continental USA for use in GFDL's seasonal prediction models (**Nathaniel Chaney**), and development of a cropland parameterization (**Denise Mauzerall**). Together these developments will contribute to GFDL's next generation earth system model, providing a model able to simulate carbon and nitrogen cycles and predict the role of vegetation and land use in future climate changes.

Ice-Ocean Interactions

Another new component of the earth system model which has seen important developments this year is the representation of interactions between the ocean and the cryosphere. CICS researcher **Olga Sergienko** has led the development of a model of the floating ice shelves together with GFDL scientists Robert Hallberg and Matthew Harrison, allowing the ocean circulation in the ice-cavities and the thermodynamic effects of the ice shelves on the ocean to be simulated within the context of a global ocean circulation model for the first time. Such two-way interaction between ice and ocean needs to be represented if the impact of ocean warming on ice-sheet melting and hence sea-level rise is to be understood. Using this new model, **Gustavo Marques** is examining the impact of the under-ice thermodynamics and circulation on the formation of Antarctic bottom waters. Ice-shelves further impact the ocean circulation by calving of ice-bergs which modify the ocean salinity stratification when they melt. **Olga Sergienko** and **Alistair Adcroft** are developing new methods of representing the iceberg calving process in the GFDL climate models. **Marianne Haselhoff** is exploring parameterizations to connect the ice-shelf model with the grounded continental ice sheets. Together these developments are contributing to the formulation of a dynamical model of land ice and its outflow into the ocean, as a component of a fully coupled physical

climate model. Another important interaction between ocean and cryosphere occurs in the Arctic, where sea-ice and its response to global warming is highly sensitive to interactions with the ocean below. **Dawei Li**, with GFDL scientists Rong Zhang and Tom Knutson, has examined and quantified the important role of the inflow of warm Atlantic water in determining interannual variability in summer sea-ice extent.

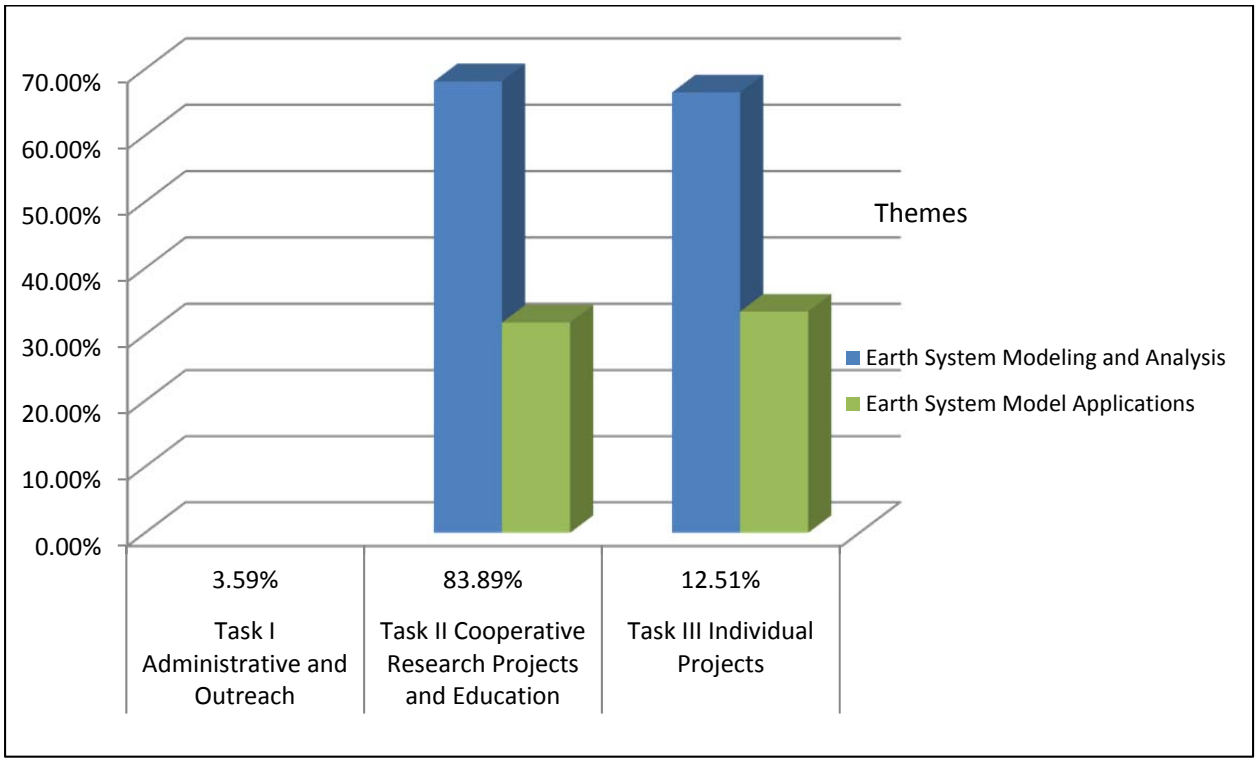
EARTH SYSTEM MODELING: APPLICATIONS

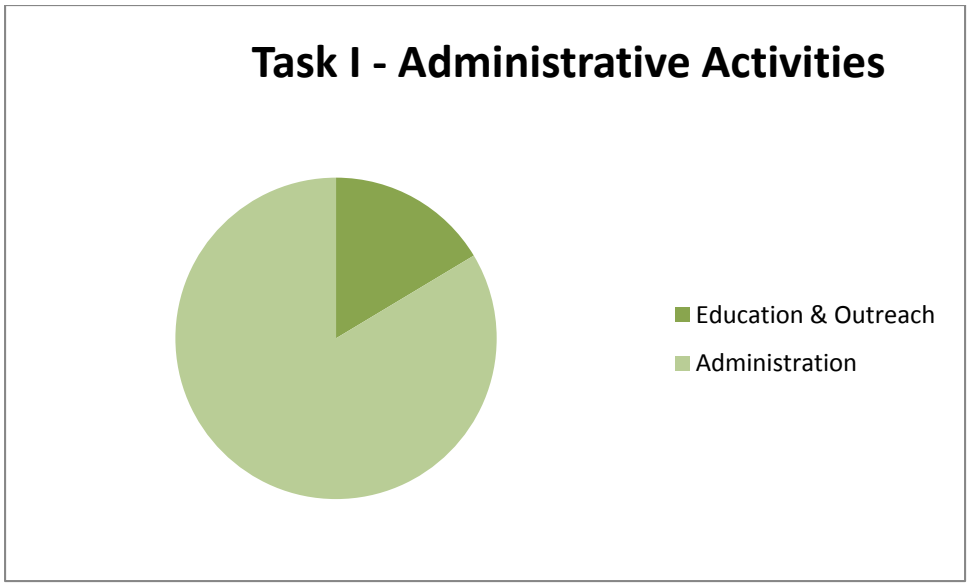
The earth system models developed by CICS and GFDL researchers are applied to examine a variety of societally relevant problems. Here we highlight some of the most interesting and exciting applications made over the past year.

Prediction and Predictability

GFDL models are increasingly being used for prediction on timescales from sub-seasonal to decadal. Several CICS researchers have been examining the predictive skill of the GFDL models, and the predictability of specific phenomena. At subseasonal timescales, **Nathaniel Johnson** has examined the impact of El Nino/Southern Oscillation and Madden-Julien Oscillation and North Pacific and North Atlantic sea surface temperatures on drought prediction on 3-4 week timescales, while **Usama Anber** is exploring the impact of mesh refinement and convection parameterization in the GFDL HiRAM model on tropical cyclone prediction. At seasonal timescales, **Mitch Bushuk** has identified the importance of sea-ice thickness initialization for seasonal predictions of Arctic sea-ice using the GFDL FLOR model. At longer timescales, **Honghai Zhang** has examined the relative roles of radiative forcing and internal climate variability such as Pacific Decadal Oscillation and Atlantic Multidecadal Oscillation in determining decadal trends in South American rainfall, and the implications for future projections. **Liping Zhang** has examined the impact of global warming on the Pacific Decadal Oscillation in the GFDL coupled models, showing that global warming reduces the amplitude and shortens the timescale of the PDO.

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 and outreach activities. Administrative funding included minimal support of the CICS Director, Associate Director and Administrator. Educational outreach activities included funding for a summer intern and a workshop.

Budget Amount and Milestones

During the past CICS-Princeton reporting year, April 1, 2015 – March 31, 2016, Princeton received funds in the amount of $5,495,548 for Task II and Task III research projects (see details in ***CICS FY'16 List of Awards***). Except for Task III and any subaward for Task II or Task III, no dollar amount has been specified for a project, nor is spending tracked by CICS-Princeton on a project not given specific funding. Any milestone/project progress has been reported under ***Methods and Results/Accomplishments*** as we do not list specific milestones to be met in our proposal.

Project Titles

Cooperative Institute for Climate Science (CICS)
NOAA Cooperative Award NA14OAR4320106

Education/Outreach Projects

- Application of Seasonal to Decadal Climate Predictions for Marine Resource Management Workshop
- CICS Summer Internship
- Ocean Fun Days 2015
- 2016 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)
- Turbulent Diffusion and Jet Formation on β-plane (Junyi Chai)
- Development of a Field-Scale Resolving GFDL Land Model (Nathaniel Chaney)
- Entropy Budget of a Dry Idealized General Circulation Model (Chiung-Yin Chang)
- Development of GFDL Cubed-Sphere Dynamical Core and Dynamical Core Selection in the NGGPS Project (Xi Chen)
- Role of the Mean State Climate in Simulating ENSO (Kityan Choi)
- Implementation and Testing of Regional and Global Dust Forecasting (Adrien Deroubaix)
- Process Level Investigations of the Connections between Tropical Pacific Biases and Parameterizations of Convection and Clouds in GFDL Next Generation Global Climate Models (Stephan Fueglistaler)
- The Dynamics of Ice Shelves and Ice Streams (Marianne Haseloff)
- Understanding the Transient Climate Sensitivity and Ocean Heat Uptake (Jie He)
- Constraining Future Rainfall Change in the Sahel Using the Moist Static Energy Budget (Spencer Hill)
- The Influence of the Hypohydrostatic Scaling on Convection and Baroclinicity in the Mid-Latitude Atmosphere (Tsung-Lin Hsieh)
- Climate Prediction and Predictability on Seasonal and Sub-Seasonal Time Scales using a Suite of GFDL Climate Models (Liwei Jia)
- Predicting and Explaining Extreme Events: Comparing Models and Observations to Assess Model Fidelity and Anthropogenic Influence (Jonghun Kam)
- A Next Generation Data Product for Model Initialization, Comparison and/or Assimilation (Robert Key)
- The Role of Temperature and Oxygen for the Remineralization of Sinking Organic Matter (Charlotte Laufkotter)
- Global River Nutrient Loading Responses to Land Use and Climate Changes (Minjin Lee)
- Ocean Mixing Processes and Parameterization (Sonya Legg)
- Urban Model Development and Surface-Atmosphere Interaction (Dan Li)
- Understanding the Decline of Summer Arctic Sea Ice Extent (Dawei Li)
- Statistical Modeling of Tropical Cyclones in a Changing Climate (Ning Lin)

Earth System Modeling and Analysis Projects continued

- Stratospheric Climate Change and its Influence on the Troposphere and Surface (Pu Lin)
- The Response of an Idealized Atmosphere to Orographic Forcing: Zonal vs. Meridional Propagation (Nicholas Lutsko)
- Exploring Historical and Future Urban Climate in the Earth System Modeling Framework (Sergey Malyshev)
- Ozone and Secondary Organic Aerosols over Southeast U.S. (Jingqiu Mao)
- Changes in Bottom Water Formation in the Western Ross Sea Due to the Melting of Ice Shelves in West Antarctica (Gustavo Marques)
- Parameterization of Internal Wave-Driven Mixing in GFDL's Global Climate Model (Benjamin D. Mater)
- Improving the Cropland Parameterization in the GFDL Land Model LM3 (Denise L. Mauzerall)
- Critical Processes and Parameters Governing the Spring Bloom in Antarctica (François Morel)
- Internal Wave Mixing in Continental Slope Canyons (Robert Nazarian)
- Processes that Control Climate Change over the Southern Hemisphere (Isidoro Orlanski)
- Impact of Land-Use on Surface Particulate Matter and Nitrogen Deposition (Fabien Paulot)
- Implementation and Testing of Regional and Global Dust Forecasting (Carlos Perez Garcia-Pando)
- Detection and Attribution of Dust Sources to Understand Dust Effects on Climate and Air Quality (Bing Pu)
- Understanding Tropical Pacific Biases in Climate Simulations and Initialized Predictions (Sulagna Ray)
  Development of an Ice-Sheet Model, its Iceberg Component, and Coupling with Other Climate-Model Components (Olga Sergienko)
- Towards Development of the New Land Model LM4 for Use with CM4 and ESM4 (Elena Shevliakova)
- Probing Interactions between Clouds and the Large-Scale Circulation (Levi G. Silvers)
- Terrestrial Ice Mass Loss and the Sea-Level Budget (Frederik J. Simons)
- Next-Generation Carbon and Nitrogen Cycling in the GFDL Land Model (Benjamin N. Sulman)
- The Impact of Large Phytoplankton on Biogeochemical Modeling of Primary Production and Response to Climate-Induced Ecosystem Changes (Bess B. Ward)
- Emissions from Fires: Interactions and Impacts in the Coupled Land-Atmosphere (Daniel Ward)
- Assessing the Seasonal Predictive Skill of FLOW over AFRICA (Eric Wood)
- Implementation and Evaluation of the NCEP GFS Physics with the FMS Prototype NGGPS Model (Linjiong Zhou)

Earth System Model Applications Projects

- Subseasonal Hurricanes Forecast in the GFDL Nested Grid Prediction System (Usama Anber)
- Diverse Impacts of Orography on Asian Climate (Jane Baldwin)
- Plankton Community Dynamics in a Changing Climate (Andrew Barton)
- Regional Predictability of Arctic Sea Ice (Mitch Bushuk)
- The Role of Water Vapor and Moist Convection in the Intertropical Convergence Zone (ITCZ) Response to Hemispherically Asymmetric Forcings (Spencer Clark)
- Southern Ocean Surface Buoyancy Fluxes and Circulation: The Role of Sea Ice and Icebergs (Anna FitzMaurice)

Earth System Model Applications Projects continued

- Understanding Cloud Processes with an Idealized Model (Michelle Frazer)
- Long Term Variability of Planktonic Ecosystems in Earth System Models (Fernando González Taboada)
- Subseasonal-to-Seasonal Climate Prediction with a Focus on Drought (Nathaniel Johnson)
- Exploring Emission versus Climate Drivers of Tropospheric Ozone Variability and Trends over Northern Mid-Latitudes from Space (Meiyun Lin)
- Dynamics of Transient Baroclinic Eddies in the Atmosphere of Mars (Todd Mooring)
- Projecting Anadromous Fish Habitat in the Northeastern United States Using Downscaled Climate Models (Barbara Muhling)
- Impact of ENSO on East Asian Precipitation (Ching Ho Justin Ng)
- Preparation GFDL Curator Infrastructure for CMIP6 (Serguei Nikonov)
- Climate Implications of the Heterogeneity of Anthropogenic Aerosol Forcing (Geeta Persad)
- Interactions between Cloud-Radiative Effects and the Large-Scale Circulation (Max Popp)
- Using Models to Improve our Ability to Monitor Ocean Uptake of Anthropogenic Carbon (Keith Rodgers)
- Climate Impacts of the Atlantic Multidecadal Variability (Yohan Ruprich-Robert)
- On the Seasonal Cycle of Arctic Haze (Zhaoyi Shen)
- Climate Response to Saharan Dust Perturbations (Jeffrey Strong)
- Application of Seasonal to Decadal Climate Predictions for Marine Resource Management (Desiree Tommasi)
- Extreme Weather in High-Resolution Global Coupled Models (Karin van der Wiel)
- Examining Climate Impacts of Antarctic Open-Ocean Polynyas (Hannah Zanowski)
- Detection, Attribution and Projection of Regional Rainfall Changes on (Multi-) Decadal Time Scales (Honghai Zhang)
- Decadal Variability and Predictability (Liping Zhang)

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), Matthew Harrison (GFDL), Stephen Griffies (GFDL), John Dunne (GFDL), Olga Sergienko (Princeton), Alon Stern (Princeton)

Other Participating Researchers: Malte Jansen (U. Chicago), Gokhan Danabasoglu (NCAR), Todd Ringler (LANL)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Weather-Ready Nation Goal: Society is Prepared for and Responds to Weather-Related Events (10%)
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts (80%)
Resilient Coastal Communities and Economies Goal: Coastal and Great Lakes Communities are Environmentally and Economically Sustainable (10%)

Objectives: Contribute to the development of GFDL's next generation ocean circulation, sea-ice and iceberg models

Methods and Results/Accomplishments:

My attention has been devoted development of i) the OM4 ¼° ice-ocean model (with input from OWG), and ii) the CM4 physical coupled model using the ¼° ocean model (under the auspices of CWG). John Dunne has been mirroring the ¼° development with a ½° counterpart which will form a more affordable basis of ESM development. Code development focused on the MOM6 ocean model (with extensive contributions from Hallberg, Harrison, Griffies and Krasting) with some related refinements to the SIS2 sea-ice model (led by Hallberg). Particular model developments include further refinement of the sub-mesoscale mixed-layer eddy parameterization and implementation of neutral diffusion (stirring by mesoscale eddies). Development of CVmix (collaboration with Griffies, Danabasoglu, Ringler) reach a stable point and we have been able to evaluate KPP alongside alternative PBL parameterizations in OM4/CM4.

A significant achievement this year is the development of a positive-definite implementation of the neutral diffusion operator. Mesoscale processes are thought to preferentially stir properties (heat, salinity, bio-geo-chemical markers) along neutral directions (local directions of neutral density gradient). In traditional ocean models, neutral diffusion has been implemented via a rotation acting of the gradient operator, commonly referred to as the Redi tensor. It has been established previously that such an implementation cannot be positive definite, thus violating the physical property of diffusion which is to be extrema diminishing (extrema cannot amplify). In short, this parameterization of diffusion has been known to create false new values (e.g. negative salinities) and has frustrated model developers and users for decades, for all model classes except isopycnal coordinate models. I am quite pleased that, in collaboration with Hallberg and Griffies, we have found a solution to this problem that we have been able to implement and is now in regular use within the OM4/CM4 experiments. The algorithm was presented as Ocean Sciences, 2016, and will be documented this year.

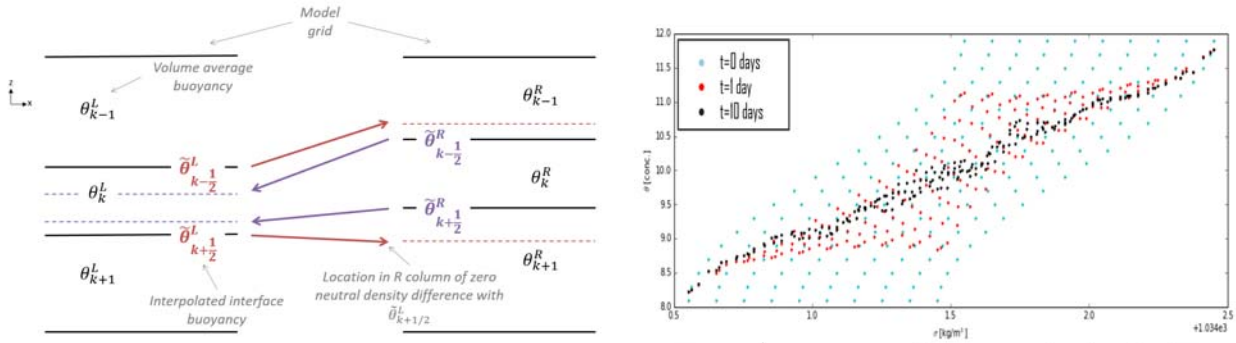


Fig 1: a) A schematic of the positive-definite neutral diffusion algorithm, indicating the vertically non-local nature of the method. b) Results from an idealized calculation illustrating the convergence of a diffused scalar approaching a monotonic function of buoyancy due to neutral diffusion of the scalar.

Publications:

Energy budget-based backscatter in an eddy permitting primitive equation model. Jansen, M., Held. I., Adcroft, A., and Hallberg, R.W., 2015: Ocean Model., 94, p. 15-26. http://dx.doi.org/10.1016/j.ocemod.2015.07.015.

Parameterization of eddy fluxes based on a mesoscale energy budget. Jansen, M., Adcroft, A., Hallberg, R.W., and Held. I., 2015: Ocean Model., 92, p. 28-41. http://dx.doi.org/10.1016/j.ocemod.2015.05.007.

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), Stephan Fueglistaler (Princeton), Sergey Nikonov (Princeton)

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

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme**:** Earth System Modeling and Analysis

NOAA Goals:
Weather-Ready Nation Goal: Society is Prepared for and Responds to Weather-Related Events (50%)
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts (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); GFDL Lead on NOAA Project SENA: Software Engineering for Novel Architectures; continued delivery of quasi-operational forecast starting March 2014; continued to serve as Head of Modeling Services at GFDL, including membership of the Science Board, Research Council, and Model Development Team.

Under my oversight, Modeling Services continued to maintain and deliver improvements to the Flexible Modeling System FMS, its runtime environment FRE, and the GFDL Curator model development database and data publication system. Team met 3 NOAA milestones in 2014 and 4 in 2015. Serving as co-chair of WGCM Infrastructure Panel (WIP), I am providing input to the WGCM, to modeling groups around the world, and the Earth System Grid Federation (ESGF) on the infrastructural implications of CMIP6 design. I gave several invited talks during 2014-2015, including keynote talks at symposia in ICTP, ECMWF, talks at Cambridge University, CERFACS, IPSL. I served on several major review boards, including on the Science Advisory Board for the Max Planck Institute for Meteorology, Hamburg; DOE ACME Project, NASA GMAO and GISS 5-year center renewal, NCAR-Wyoming Supercomputing Center renewal, NWSC2.

References:

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

Publications:

Williams, D. N., V. Balaji, L. Cinquini, S. Denvil, D. Duffy, B. Evans, R. Ferraro, R. Hansen, M. Lautenschlager, and C. Trenham, 2015a: A global repository for planet-sized experiments and observations. Bulletin of the American Meteorological Society, doi:10.1175/BAMS-D-15-00132.1.

Williams, D. N., M. Lautenschlager, V. Balaji, L. Cinquini, C. DeLuca, S. Denvil, D. Duffy, B. Evans, R. Ferraro, M. Juckes, and C. Trenham, 2015b: Strategic Roadmap for the Earth System Grid Federation. Big Data (Big Data), 2015 IEEE International Conference on, 2182-2190.

V. Balaji, 2015: Climate Computing: The State of Play. Computing in Science & Engineering, 17, 9--13.

Juckes, M., V. Eyring, K. Taylor, V. Balaji, and R. Stouffer, 2015: The CMIP6 data request: the next generation climate archive. EGU General Assembly Conference Abstracts, volume 17, 13112.

Yang, X., et al., 2015: Seasonal predictability of extratropical storm tracks in GFDL's high-resolution climate prediction model. Journal of Climate, 28, 3592--3611.

Progress Report Title: **Turbulent Diffusion and Jet Formation on *β*-plane**

Principal Investigator: Junyi Chai (Princeton Graduate Student)

CICS/GFDL Collaborator: Isaac Held (GFDL)

Other Participating Researchers: Malte Jansen (University of Chicago)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: One layer barotropic model on *β*-plane is arguably the simplest idealization of the midlatitude atmospheric dynamics. We focus on how the forcing scale influences eddy diffusivity and jet formation in this model, which eventually helps us understand the dynamics in more complicated global climate models.

Methods and Results/Accomplishments:

Eddy diffusivity and jet formation in forced-dissipative, two-dimensional turbulent flow on the *β*-plane is investigated using high-resolution simulations, with particular focus on the forcing scale L_f. Traditionally, two natural length scales Rhines scale $L_{Rh} = \sqrt{U/\beta}$and cross-over scale $L_\epsilon = \epsilon^{1/5}\beta^{-3/5}$ are known to determine the properties of jet formation and turbulent diffusion; here U is the r.m.s velocity, β is the planetary potential vorticity gradient and ε is energy injection rate. Ignoring the dependency on the domain scale and (hyper-)viscosity, the flow is determined by two non-dimensional parameters: the zonostrophic index $Z = L_{Rh}/L_\epsilon$ and $\Pi = L_\epsilon/L_f$. The dependency on zonostrophic index has been well studied which shows that jet strength increases with Z, and within a range [2, 6] the eddy diffusivity D has little dependency on Z. In this study, we showed that the less known parameter $\prod$ also strongly influences the flow. For the same Z, jets are sharper when $\prod$ is smaller, especially when $\prod$<1. For large Z>5, potential vorticity staircase regime is only reached when $\prod$<1, whose kinetic energy spectrum is characterized by -4 slope; whereas the zonostrophic regime characterized by -5 spectral slope is reached when $\prod$ is much larger than 1. At regime $\prod$<1, eddy diffusivity shows a high dependency on $\prod$. A theoretical analysis based on Osborne-Cox diffusivity as well as Nakamura's effective diffusivity both suggest a new scaling of eddy diffusivity in the small $\prod$ regime as $D \sim \epsilon^{3/5}\beta^{-4/5}\Pi^2$, where $\epsilon^{3/5}\beta^{-4/5}$ is the traditional scaling for eddy diffusivity on *β*-plane. The dependency on $\prod$ should be lost when $\prod$>>1, which means there is a large range of isotropic inverse cascade. These results may have significant implications for fundamental theories for mixing by mesoscale eddies in the ocean.

References:

Smith, K. S., G. Boccaletti, C. C. Henning, I. N. Marinov, C. Y. Tam, I. M. Held and G. K. Vallis, 2002: Turbulent diffusion in the geostrophic inverse cascade. J. Fluid Mech., 469, 13–48.

Sukoriansky, S, N. Dikovskaya and B. Galperin, 2009: Transport of momentum and scalar in turbulent flows with anisotropic dispersive waves. Geophys. Res. Lett., 36 (14).

Scott, R. K. and D. G. Dritschel, 2012: The structure of zonal jets in geostrophic turbulence. J. Fluid Mech., 711, 576–598.

Nakamura, N., 2001: A new look at eddy diffusivity as a mixing diagnostic. J. Atmos. Sci., 58, 3685–3701.

Publications:

Chai, J., M. Jansen and I. M. Held, 2016: Turbulent diffusion and jet formation on β-plane. In preparation.

Chai, J., and M. Jansen, 2016: Equilibration of a baroclinic planetary atmosphere in the limit of zero bottom friction. In revision for J. Atmos. Sci.

Chai, J., M. Jansen and G. K. Vallis, 2015, Zonostrophic Turbulence in Two-layer Quasi-geotrophic Model. Presented at the American Geophysical Union Fall Annual Meeting.

Progress Report Title: **Development of a Field-Scale Resolving GFDL Land Model**

Principal Investigator: Nathaniel W. Chaney (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Elena Shevliakova (Princeton/GFDL), Sergey Malyshev (Princeton), Eric F. Wood (Princeton)

Other Participating Researchers: Chris Milly (USGS), Alexander McBratney (University of Sydney), Mike Ek (NCEP/EMC), Patrick Reed (Cornell University)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Weather-Ready Nation Goal: Society is Prepared for and Responds to Weather-Related Events

Objectives: Use existing very high-resolution land datasets to improve the representation of land surface spatial heterogeneity in the GFDL land model. This updated model will be used to understand the role of fine-scale spatial heterogeneity in the Earth system.

Methods and Results/Accomplishments:

The land surface plays a pivotal role in the Earth system through the exchange of carbon, water, and energy between the land and the atmosphere and ocean. Land models aim to account for these interactions through the representation of the physical processes that control these interactions over land. My research aims to use available very-high resolution land datasets to improve the representation of fine-scale land surface spatial heterogeneity in the GFDL land model. To accomplish this goal, over the past year I have undertaken the following goals: *Formalize tiling in the land model* – I have focused on recoding the input code of the GFDL land model to ensure that it can efficiently handle very high-resolution land datasets. This is leading to a much simpler code base and a much more flexible tiling scheme within the land model. This will allow to not only explicitly model the land processes at field-scales but also to provide very high-resolution simulations. *Download and process high resolution land datasets* – To take advantage of the updated tiling scheme in the GFDL land model, I have downloaded and processed a suite of data products that will assist in describing field-scale land surface heterogeneity over the globe (e.g., HydroSheds). These datasets will be pivotal towards the final implementation of the updated tiling scheme. *Preliminary simulations using the updated schemes* – I have applied the updated land model over the Little Washita watershed in Oklahoma. The databases that were downloaded were used to assemble the tiles for the watershed. The model was then run and the simulations for each tile were mapped out in space. The model results illustrate how adequately representing fine-scale processes plays an important role in simulating the entire catchment's behavior.

Outreach Activities: Monmouth County Science Fair; Boy Scouts of America***;*** Tutoring and mentoring of high school students

Publications:

Chaney, N., (2015), Field-scale land surface modeling over continental extents: Applications in satellite remote sensing of soil moisture, Abstract H43H-1622 presented at 2052 Fall Meeting, AGU, San Francisco, Calif., 14-18 Dec.

Progress Report Title: **Entropy Budget of a Dry Idealized General Circulation Model**

Principal Investigator: Chiung-Yin Chang (Princeton Graduate Student)

CICS/GFDL Collaborator: Isaac Held (GFDL)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: To analyze the entropy budget of a dry idealized general circulation model, test the hypothesis that planetary atmospheres may adjust to the state that maximizing entropy production, and provide a physical explanation for why atmospheres may deviate from the state of maximum entropy production.

Methods and Results/Accomplishments:

The hypothesis that planetary atmospheres at steady state maximize entropy production has attracted much attention as it provides a variational principle to understand climate systems (e.g. Paltrige, 1975). On the other hand, entropy budget itself is also shown to be useful for predicting poleward eddy heat transport (Barry et al, 2002). We explored these entropy related theories with a dry idealized general circulation model. The model is GFDL spectral dynamical core forced by Held and Suarez (1994) physics, of which entropy production terms are physically defined and the state of maximum entropy production (MEP) can be analytically solved. We analyzed the entropy budget of the model and found model simulated entropy production is far from MEP. With the standard model settings that give to Earth-like climate, simulated entropy production is 2.3 w/m^2 while MEP is 8.6 w/m^2. To explain the difference, we considered MEP subject to an additional dynamical constraint. This is motivated by Lorenz (1967)'s work on available potential energy generation. We assumed the temperature distributions can be represented by a single potential temperature profile in vertical and a few Legendre polynomials in horizontal. Given the potential temperature profile taken from model simulated global mean values, we sampled the entropy production rates computed from various horizontal temperature structures and found the maximum among them. When planetary rotation rate is varied, this constrained MEP is close to model simulations for slowly rotating atmospheres but not fast rotating ones (Fig. 1). The latter appears to be when eddies take a leading role in transporting heat poleward. Based on scaling arguments for eddy heat flux, we concluded eddy mixing length scale is the limiting factor that determines the amount of available potential energy released and prevents the system to reach the constrained MEP.

References:

Barry, L., G. C. Craig, and J. Thuburn, 2002: Poleward heat transport by the atmospheric heat engine. Nature, 415, 774–777.

Held, I. M., and M. J. Suarez, 1994: A proposal for the intercomparison of the dynamical cores of atmospheric general circulation models. Bull. Amer. Meteor. Soc., 75, 1825–1830.

Lorenz, E. N., 1967: The nature and theory of the general circulation of the atmosphere. WMO Publ. 218, WMO, Geneva, Switzerland, 161 pp.

Paltridge, G. W., 1975: Global dynamics and climate—A system of minimum entropy exchange. Quart. J. Roy. Meteor. Soc., 101, 475–484.

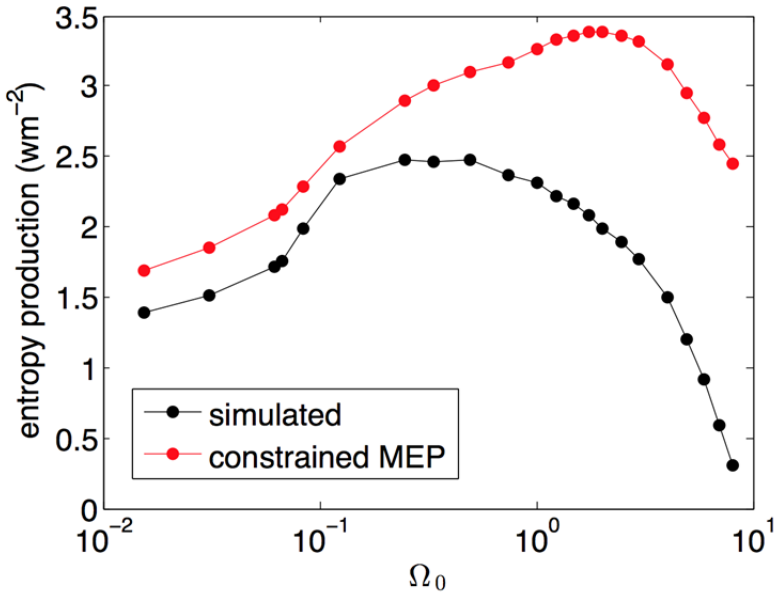


Figure 1. Model simulated entropy production (black) and constrained MEP (red) as a function of planetary rotation rate compared to Earth's rotation rate ($\mathbf{\Omega}_0$). All the entropy production rates are multiplied by 300K to express in the unit of w/m^2. For reference, the unconstrained MEP is 8.6 w/m^2.

Progress Report Title: **Development of GFDL Cubed-Sphere Dynamical Core and Dynamical Core Selection in the NGGPS Project**

Principal Investigator: Xi Chen (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Shian-Jiann Lin (GFDL), Rusty Benson (GFDL), Lucas Harris (GFDL), Bill Stern (GFDL), Tim Marchok (GFDL), Morris Bender (GFDL), Linjiong Zhou (Princeton), Junyi Chai (Princeton)

Other Participating Researchers: Jan-Huey Chen (UCAR), Zhi Liang (Engility), Shannon Rees (Engility), Matt Morin (Engility), Ming Zhao (UCAR), Weiye Yao (Princeton)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Weather-Ready Nation Goal: Society is Prepared for and Responds to Weather-Related Events

Objectives: Extending the grid-imprint-free A-grid shallow water dynamical core that developed in the previous Progress Report into a full hydrostatic 3D model; Helping FV3 to be selected as the atmospheric dynamical core of the NOAA's Next Generation Global Prediction System, which will be the foundation for the operating forecast guidance system for the next several decades for this nation

Methods and Results/Accomplishments:

As demonstrated in the previous progress report, I have created a non-staggered shallow-water dynamical core. This model is proven to be free of or have little impact from the so-called cubed-sphere grid imprint problem. In the past year, I have expanded this shallow water model into a full 3D hydrostatic dynamical core. In this model, a computationally efficient Riemann solver developed by Chen et al. (2013) is implemented with the 3D full compressible flow physics. This approximate Riemann solver provides "just enough" numerical diffusion to the dynamical core that makes the simulations to be stable without applying explicit diffusion, such as divergence damping or high-order hyper-diffusion etc. This new dynamical core is fully integrated into the GFDL FMS Runtime Environment (FRE), thus takes full advantage of the latest performance optimization.

Besides developing the new model, a large portion of my research effort has been contributed to the NOAA's Next Generation Global Prediction System or NGGPS project. This NWS R2O Initiative will expand and accelerate critical weather forecasting research to operation to address growing service demands, and increase the accuracy of weather forecasts through accelerated development and implementation of current global weather prediction models, improved data assimilation techniques, and improved software architecture and system engineering. One dynamical core will be selected by the NGGPS and will be the foundation for the operating forecast guidance system for the next several decades. After the Phase 1 evaluation conducted last year, GFDL's FV3 and NCAR's MPAS out performed NIM (EMC), NEPTUNE (NAVY) and NMMUJ (NCEP) and were down selected as the two candidate cores proceed to Phase 2 testing. NWS is scheduled to make a final selection of the dynamical core at the middle of 2016.

As a member of the GFDL's NGGPS team in this ongoing dynamical core evaluation process, I have been helping on diagnosing, debugging and developing the FV3 code. I have also created post-

processing/plotting tools for the team to evaluate FV3's output. During this model development, I have evaluated the GFS and FV3's vertical hybrid coordinates and developed a new algorithm to create a smooth vertical hybrid coordinate with arbitrary number of layers. I have also created the FV3 Data Assimilation Interface, which allows FV3 to work with the GSI or any arbitrary DA system for weather forecast applications.

The next Phase of the NGGPS development will require the deep-atmosphere implementation, which will be used for space weather applications. The non-staggered grid, Riemann solver based 3D dynamical core, which is developed earlier last year, would be a competent candidate for this implementation. Because with non-staggered grid for the wind, the 3D Coriolis force is less difficult to discretize in the dynamical core. The Riemann solver based flux calculation would be an effective tool to handle super-sonic flows in the upper atmosphere. Thus the new non-staggered grid dynamical core will be involved in the future development of FV3.

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

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.

Publications:

Chen, Xi and Shian-Jiann Lin. a generalized vertical hybrid coordinate for climate models. Journal of Computational Physics, in preparation.

Shian-Jiann Lin, Lucas M. Harris, Chen, Xi, Weiye Yao, and Junyi Chai. Colliding modons: A nonlinear test for the evaluation of global dynamical cores. Monthly Weather Review, to be submitted.

Chen, Xi and Shian-Jiann Lin. A computationally efficient Riemann solver based hydrostatic model on the cubed-sphere. Journal of Computational Physics, in preparation.

Progress Report Title: **Role of the Mean State Climate in Simulating ENSO**

Principal Investigator: Kit Yan Choi (Princeton Graduate Student)

CICS/GFDL Collaborator: Gabriel Vecchi, Andrew Wittenberg, and Isaac Held (GFDL), Stephan Fueglistaler (Princeton)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: Our studies explored the connections between ENSO characteristics and the mean state climate for understanding intermodel differences, model discrepancies from the observations, models' projection of ENSO in the future climate as well as changes in the observed ENSO characteristics in the past climate.

Methods and Results/Accomplishments:

We directly test the hypothesis that the intermodel differences in the simulated ENSO statistics and feedbacks are due to the intermodel differences in their ocean surface climatology. By flux adjusting the CM2.1 ocean surface climatology to those in a number of other CMIP5 coupled models, we found that the hypothesis holds for some but not all aspects of ENSO. Not only did we identify the ENSO characteristics and feedbacks that respond (and do not respond) positively to corrections in the mean ocean surface climatologies, we also quantified the extent to which these characteristics may depend on the ocean climatologies.

The results indicate that a lot of the feedbacks and features of ENSO are closely linked to ocean surface climatologies and therefore, linked to each other. The implication is that these feedback parameters cannot be viewed as independent metrics for evaluating how well a model simulates ENSO. On the other hand, processes that are insensitive to flux adjustments provide information in addition to ocean surface climatologies, and can be utilized while evaluating model performances.

Using flux adjustments as a tool to test the ENSO dependence on the mean state climate was not attempted before. Previous studies that have applied flux adjustment in coupled models generally correct the mean state climate towards the observations and test how different model physics parameterization may affect ENSO. The two approaches complement each other. While it is a triumph that most coupled climate models nowadays do not require flux adjustments to simulate a reasonable mean state climate and climatic variabilities, the results presented here prove that flux adjustment is still a valuable tool for sensitivity testing, aiding model developments and assessments.

Outreach Activities: Teaching activities at TASK

Publications:

El Nino-Southern Oscillation: Asymmetry, nonlinear atmospheric response and the role of mean climate by Choi, Kit Yan, Ph.D. Thesis, Princeton University, 2015.

Progress Report Title: **Implementation and Testing of Regional and Global Dust Forecasting**

Principal Investigator: Adrien Deroubaix (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Paul Ginoux (GFDL)

Other Participating Researchers: Carlos Perez (Columbia/NASA-GISS)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Weather-Ready Nation Goal: Society is Prepared for and Responds to Weather-Related Events

Objectives: We aim at improving dust prediction capabilities natural and anthropogenic dust sources at regional and global levels.

Methods and Results/Accomplishments:

Over the last 9 months, my research at GFDL has been focusing on the implementation and evaluation of new dust emission parameterizations in the Non-hydrostatic Mesoscale Model (NMMB) which is the NOAA-NCEP weather forecasting model over CONUS. This model is coupled with a dust model (*Perez et al., 2011*). Recently *Ginoux et al. (2012)* have proposed a new dust source map based on satellite data with both natural and anthropogenic sources. We have compared this new source with the previous one, and tested its prediction skills.

The evaluation of the modeled dust has been done by comparing the results to ground based measurements (Aerosol Optical Depth from the NASA-AERONET network and dust concentration measured in the Sahel and in the Caribbean), and to satellite retrieval (NASA-MODIS Deep-blue). The year 2012 has been extensively studied at a daily time step. Furthermore, a 5-year average (2010-2014) has been analyzed in order to investigate climatological features of the natural and anthropogenic dust cycles *(Figure below).* An article presenting this evaluation and an analysis of the uncertainties associated to the emission schemes is in preparation.

In addition, we are working on a detailed study of the very intense dust storm which has reached Israel in September 2015. This will be the first modeling study of "haboobs" in the Middle East. It will serve as test bed for NMMB to predict such extreme events over US in order to mitigate their impacts on human health, airplanes and road traffic. *This research is supported by NOAA/NWS Next Generation Global Prediction System (NGGPS) project.*

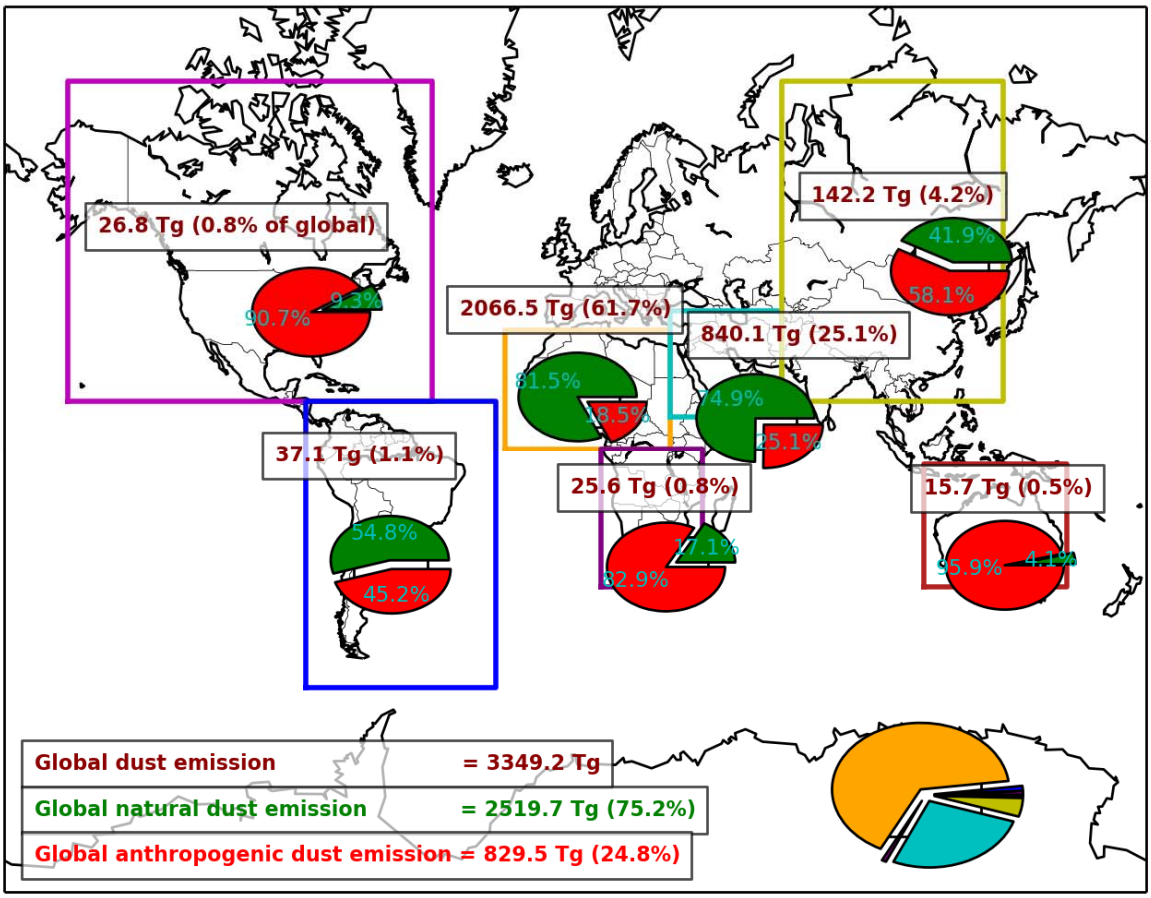


Figure: Global and regional annual dust emission for the year 2012 with the natural (green) and anthropogenic (red) contribution.

References:

Ginoux, P., Prospero, J. M., Gill, T. E., Hsu, N. C., and Zhao, M.: Global-Scale Attribution of Anthropogenic and Natural Dust Sources and Their Emission Rates Based on Modis Deep Blue Aerosol Products, pp. 1–36, doi:10.1029/2012RG000388.

Perez, C., Haustein, K., Janjic, Z., Jorba, O., Huneeus, N., Baldasano, J. M., Black, T., Basart, S., Nickovic, S., Miller, R. L., Perlwitz, J. P., Schulz, M., and Thomson, M.: Atmospheric dust modeling from meso to global scales with the online NMMB/BSC-Dust model; Part 1: Model description, annual simulations and evaluation, Atmospheric Chemistry and Physics, 11, 13 001–13 027, doi:10.5194/acp-11-13001-2011, 2011.

Publications:

Global Natural and Anthropogenic Dust Modeling, Deroubaix et al., in preparation.

Presentations:

Global Natural and Anthropogenic Dust Modeling, Deroubaix et al., American Meteorological Society conference, New Orleans, LA, January 2016.

Progress Report Title: **Process Level Investigations of the Connections between Tropical Pacific Biases and Parameterizations of Convection and Clouds in GFDL Next Generation Global Climate Models**

Principal Investigator: Stephan Fueglistaler (Princeton Professor)

CICS/GFDL Collaborator: J.-C. Golaz, Y. Ming, S.-J. Lin, and I.M. Held (GFDL)

Other Participating Researchers: Ming Zhao (UCAR)

Award Number: NA14OAR4320106

Task III: Individual Projects

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: Support the development of the next generation GFDL global atmospheric model (AM4) and its coupled climate model (CM4)

Methods and Results/Accomplishments:

Ming Zhao's team has incorporated (i) a new convection scheme ("double plume convection scheme"), which greatly improves, for example, Amazon rainfall; (ii) a new boundary layer scheme that improves AM4 simulation of stratocumulus clouds; (iii) new formulation of aerosol-cloud interaction and convective cloud microphysics; and (iv) a new formulation of ocean roughness. The effects of these changes on (i) the connection between convection, cloud feedback and climate sensitivity; (ii) the connection between convection, eastern Pacific ITCZ and SST cold bias; (iii) the spurious double ITCZ in coupled climate models, have been analyzed.

Progress Report Title: **The Dynamics of Ice Shelves and Ice Streams**

Principal Investigator: Marianne Haseloff (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Olga Sergienko (Princeton)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: Improve our understanding of ice sheet dynamics, in particular the mechanics and thermo-dynamics of ice shelves and ice streams

Methods and Results/Accomplishments:

Since joining the program in July 2015, my research has focused on the dynamics of ice shelves and grounding lines, and the dynamics of ice stream margins.

Ice shelves form when ice sheets grounded below sea level begin to float. They transmit ocean forcing (e.g. variations in basal melt rates) inland by changing the stress balance at the grounding line. However, modeling these mechanisms and quantifying their effects remains a major challenge for ice sheet models, and the conclusions drawn from these models often depend on the type of model used. Recent simulations with two-dimensional, plan view, ice-flow models suggest that ice shelves can change the stability properties of grounding lines through buttressing (Gudmundsson et al., 2012). In contrast, ice shelves can be excluded from the momentum balance in computationally efficient flowline models (Schoof, 2007). To investigate whether parameterized buttressing can bridge the gap between these two classes of models, we are extending a recently-developed boundary layer approach to calculate how the ice flux at the grounding line changes under different parameterizations. This will allow us to determine conditions under which lateral effects can be reproduced by flowline models. Our initial results indicate that commonly-used parameterizations of ice shelf buttressing do not change the stability properties of marine ice sheets in such models. In addition, we have derived analytical solutions for the thermal boundary layers in ice shelves, which form at the ice/ocean and ice/atmosphere contact. This line of research will facilitate computationally efficient thermo-mechanically coupled solutions of marine ice sheets.

Ice streams are fast-flowing regions of ice within the Antarctic ice sheet and are the main discharge routes for ice accumulated in the ice sheet interior. They are bordered by slowly moving ice and observations suggest that the margins of some of these ice streams can migrate over time. Our research focuses on the processes that control this migration, which is the result of locally high shear stresses and heat dissipation rates at the transition from fast to slow flow. Typically, this transition is modeled as a no slip to free slip transition at the ice stream bed. However, this assumption introduces singular stresses at the transition point and neglects the possibility that the high stresses or residual water films on the subtemperate part of the bed can lead to subtemperate sliding, which has been observed in other glaciological settings (Cuffey et al, 1999). We have therefore investigated how subtemperate sliding affects the formation of temperate ice in ice stream margins and their migration. By analyzing the boundary layer structure in the margin, we derived asymptotic solutions for the migration speed and

quantified this influence. We will use these results to derive a parametrization of ice stream widening that can be incorporated in continental-scale ice sheet models.

References:

Schoof, C. (2007). Marine ice-sheet dynamics. Part 1. The case of rapid sliding, J. Fluid. Mech., 573, 27–55, doi: 10.1017/S0022112006003570.

Gudmundsson, G. H., Krug, J., Durand, G., Favier, L., and Gagliardini, O. (2012). The stability of grounding lines on retrograde slopes, The Cryosphere, 6, 1497-1505, doi:10.5194/tc-6-1497-2012.

Cuffey, K. M., Conway, H., Hallet, B., Gades, A. M., & Raymond, C. F. (1999). Interfacial water in polar glaciers and glacier sliding at -17°C. Geophysical Research Letters, 26(6), 751-754.

Publications:

Haseloff, M. and Schoof, C. (2016): Ice stream dynamics: model insights into the roles of basal freeze-on, subglacial drainage and heating through lateral shear, J. Geophys. Res. (in review).

Presentations:

Haseloff, M., Schoof, C., Gagliardini, O. (2015): Modelling the migration of ice stream margins, WAIS Workshop, Sept. 16-19, 2015, Loveland, CO, USA.

Haseloff, M., Schoof, C., Gagliardini, O. (2015): The influence of subtemperate sliding on the formation of temperate ice in ice stream margins and their migration, AGU fall meeting, Dec. 14-18, 2015, San Francisco, CA, USA.

Progress Report Title: **Understanding the Transient Climate Sensitivity and Ocean Heat Uptake**

Principal Investigator: Jie He (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Gabriel Vecchi (GFDL), Mike Winton (GFDL)

Other Participating Researchers: Brian Soden (U. Miami)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: My goal is to understand the nonlinearity in the transient climate sensitivity. Specifically, I aim to study how the degree of warming depends on factors other than the intensity of radiative forcing, i.e., different starting points, model resolutions, etc.

Methods and Results/Accomplishments:

Since I arrived at GFDL in 11/15, I've been looking at the FLOR simulations with 1% per year CO_2 rise. Two parallel simulations were run with the same setting except the starting point of time – one starts from year 1860 and the other from 1990. A significant difference was found in their transient climate sensitivity. I compared their atmospheric radiative feedbacks and ocean heat uptake and found the latter to be the dominant cause of the surface warming difference.

The reason the two simulations have different ocean heat uptake efficiency is due to the fact that they have different mean ocean circulation and different circulation response. The difficulty lies in the separation of the two. However, by comparing their corresponding temporal development, I was able to differentiate them.

To test the robustness of my result, I've started learning to run the GFDL model. I've also discussed with my advisor, Gabriel Vecchi, about how the resolution of the atmospheric model may also impact the climate sensitivity, which will be the focus of my next research project.

In addition, I spent some time writing up my dissertation with my Ph.D. advisor, Brian Soden, from U. Miami. Two papers are currently under review in Nature and GRL.

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Publications:

J. He and B. Soden, What drives the projection of subtropical precipitation decline?, in review, Nature.

J. He and B. Soden, The Impact of SST Biases on Projections of Anthropogenic Climate Change: A Greater Role for Atmosphere-only Models?, in review, GRL.

Progress Report Title: **Constraining Future Rainfall Change in the Sahel Using the Moist Static Energy Budget**

Principal Investigator: Spencer Hill (Princeton Graduate Student)

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

Other Participating Researchers: Ming Zhao (UCAR)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: We perform perturbed physics and perturbed sea surface temperature experiments in the GFDL AM2.1 atmospheric model in order to understand why that model responds to ocean warming with severe drying in the Sahel region of Africa. We use the moist static energy budget to identify the relevant physical mechanisms, and then compare how they operate in other GFDL models, CMIP5 models, and observations in order to assess how plausible this projected drying in AM2.1 really is.

Methods and Results/Accomplishments:

The NOAA Geophysical Fluid Dynamics Laboratory AM2.1 atmospheric general circulation model (AGCM) responds to mean warming -- with or without spatial pattern -- of global sea surface temperatures by severely reducing precipitation in the Sahel region of Africa. We attempt to identify the underlying mechanisms by replacing AM2.1's default, Relaxed Arakawa-Schubert (RAS) convective parameterization with the University of Washington (UW) parameterization and comparing the Sahelian hydrological and surface climate responses to uniform 2 K sea surface temperature warming with either parameterization. The pertinent mechanisms are then elucidated via the moist static energy budget, for which spurious imbalances in the column integral are corrected through an adjustment procedure.

The severe precipitation decrease and resulting surface drying and warming with RAS are absent with UW. With either parameterization, the leading-order climatological region-average balance is between diabatic forcing by top-of-atmosphere radiative fluxes and divergence of energy by time-mean horizontal advection of dry, low-energy air from the Sahara. With RAS, this advective divergence by the rotational flow is enhanced with oceanic warming, due to an enhanced meridional free-tropospheric moist static energy gradient; this is balanced by anomalous convective energy convergence by the time-mean divergent circulation, due to severely suppressed time-mean ascent. With UW, the drying influence of increased Saharan air advection into the Sahel is more modest due to the meridional moist static energy gradient being enhanced less with warming. Based on thermodynamic scaling arguments, we speculate that this arises from the shallower climatological convective depth with UW. This line of reasoning suggests plausible links between observable climatological features of the region's circulation and its response to warming.

Outreach Activities: Introduction to weather and climate. 45 minute presentation + Q&A to 7th grade class at Forrestdale Middle School, Rumson, NJ. Co-presented with Sarah Schlunegger, April 10, 2015.

Introduction to climate models. 20 minute presentation to New Jersey Japanese School during their visit to NOAA Geophysical Fluid Dynamics Laboratory, Princeton, NJ, June 19, 2015.

Publications:

Towards constraining future rainfall in the Sahel using the moist static energy budget. Oral. AGU 2015 Fall Meeting, San Francisco, CA, December 14, 2015.

Towards constraining Sahel rainfall responses to global mean temperature changes. Invited oral. Linde Center for Global Environmental Science Monsoons: Past, Present and Future workshop, California Institute of Technology, Pasadena, CA, May 21, 2015.

Progress Report Title: **The Influence of the Hypohydrostatic Scaling on Convection and Baroclinicity in the Mid-Latitude Atmosphere**

Principal Investigator: Tsung-Lin Hsieh (Princeton Graduate Student)

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

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: To improve the representation of clouds in models of large-scale atmospheric circulation by decreasing the scale separation between convection and synoptic motions

Methods and Results/Accomplishments:

Clouds have a strong influence on the climate, despite the fact that they are much smaller than the synoptic scale. Unfortunately, with the computing power currently available, it is difficult to resolve clouds in models of the large-scale circulation, as the size of a grid cell is often too large to permit nonhydrostatic convection. As opposed to traditional approaches in which the influence of sub-grid-scale processes is parameterized, we examine a modeling technique that dynamically reduces the scale separation between the large-scale hydrostatic and small-scale nonhydrostatic motions in the model, so that it becomes feasible to resolve both motions explicitly. This is achieved by modifying the model equations according to the "hypohydrostatic" scaling, put forward by Kuang et al. (2005) and Pauluis et al. (2006).

The hypohydrostatic scaling is implemented in ZETAC, a fully-compressible, nonhydrostatic atmospheric model developed at GFDL. It is configured to generate realistic baroclinic life cycles, with the domain large enough to encompass a baroclinic eddy and small enough to run at cloud-permitting resolutions; therefore no convective parameterization is used. The direct impact of the scaling on nonhydrostatic convection in the model was measured and found to agree quantitatively with theoretical predictions. We are currently investigating whether this scaling would correct biases in low resolution solutions caused by poorly resolved convection.

References:

Kuang, Zhiming, Peter N. Blossey, and Christopher S. Bretherton. A New Approach for 3D Cloud-Resolving Simulations of Large-Scale Atmospheric Circulation. Geophysical Research Letters 32, no. 2 (January 1, 2005): L02809. doi:10.1029/2004GL021024.

Pauluis, Olivier, Dargan M. W. Frierson, Stephen T. Garner, Isaac M. Held, and Geoffrey K. Vallis. The Hypohydrostatic Rescaling and Its Impacts on Modeling of Atmospheric Convection. Theoretical and Computational Fluid Dynamics 20, no. 5–6 (October 5, 2006): 485–99. doi:10.1007/s00162-006-0026-x.

Progress Report Title: **Climate Prediction and Predictability on Seasonal and Sub-Seasonal Time Scales using a Suite of GFDL Climate Models**

Principal Investigator: Liwei Jia (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Gabriel Vecchi (GFDL), Honghai Zhang (Princeton), Nathaniel Johnson (Princeton)

Other Participating Researchers: Xiaosong Yang (UCAR), Di Tian (Princeton), Salvatore Pascale (California Institute of Technology), Wei Zhang (Princeton), H. Murakami (Princeton), Elizabeth Barnes (CSU), Etienne Dunn-Sigouin (Columbia University)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Weather-Ready Nation Goal: Society is Prepared for and Responds to Weather-Related Events

Objectives: The objectives are to improve the ability of seasonal climate prediction (including climate extremes) and to investigate the source of predictability.

Methods and Results/Accomplishments:

I studied the roles of radiative forcing, sea surface temperature, atmospheric and land initial conditions in U.S. summer heat waves. To this end, a set of sensitivity experiments were designed based on the high-resolution GFDL FLOR model. The results show that all of the above factors are important drivers and sources of predictability of U.S. summer heat waves. The probability of U.S. summer heat waves increases under global warming. ENSO also plays a role in the long-term variations of U.S. heat waves, with increased probability in La Nina years, but decreased probability in El Nino years.

I also investigated the impacts of atmospheric initial conditions on the seasonal and sub-seasonal climate prediction. We found the predictability of temperature and precipitation coming from the atmospheric initial conditions is limited for one month. Further studies estimating the role of atmospheric initial conditions in sub-seasonal predictability of other variables/phenomena are ongoing.

I am examining the atmospheric blocking activities in multiple GFDL climate models with different resolutions from 200km to 25 km, and estimating the impacts of blocking on surface climate (e.g., seasonal mean and extreme temperature, precipitation).

Publications:

Liwei Jia, Gabriel A. Vecchi, Xiaosong Yang, Richard G. Gudgel, Thomas L. Delworth, William F. Stern, Karen Paffendorf, Seth Underwood and Fanrong Zeng, 2016: The roles of radiative forcing, sea surface temperatures, and atmospheric and land initial conditions in U.S. summer warming episodes, Journal of Climate, in press.

Di Tian, Ming Pan, Liwei Jia, Gabriel Vecchi and Eric F. Wood, 2016: Assessing Water and Energy Budgets over African from AMIP Simulations of the GFDL High-Resolution Climate Model, to be submitted.

Ruonan Zhang, Chenghu Sun, Liwei Jia and Weijing Li, 2016: The Impact of Arctic Sea Ice on Interannual Variations of Summer Ural Blocking. Climate Dynamics, submitted.

Salvatore Pascale, Simona Bordoni, Sarah B. Kapnick, Gabriel A. Vecchi and Liwei Jia, 2016: Gulf of California Moisture Surges within the North American Monsoon in a Suite of High-resolution Coupled Global Models. Journal of Climate, submitted.

Wei Zhang, Gabriel A. Vecchi, Gabriele Villarini, Hiroyuki Murakami, Thomas Delworth, Liwei Jia, Richard Gudgel and Fanrong Zeng, 2016: Simulated Connections between ENSO and TCs near Guam in a High-Resolution GFDL Coupled Climate Model: Implications for Seasonal Forecasting, Journal of Climate, submitted.

W. Zhang, G. A. Vecchi, G. Villarini, H. Murakami, A. Rosati, X. Yang, L. Jia and Fanrong Zeng, 2016: Modulation of Western North Pacific Tropical Cyclone Activity by the Atlantic Meridional Mode, Climate Dynamics, in revision.

H. Murakami, G. A. Vecchi, T. L. Delworth, A. T. Wittenberg, X. Yang and Liwei Jia, 2016: More Central Pacific Cyclones in the Future as in the 2015 Summer Season?, Nature Climate Change, in revision.

Wei Zhang, Gabriel Vecchi, Hiroyuki Murakami, Gabriele Villarini and Liwei Jia, 2016: The Pacific Meridional Mode and the Occurrence of Tropical Cyclones in the Western North Pacific, Journal of Climate, 29, 381-398.

H. Murakami, G. A. Vecchi, T. Delworth, K. Paffendorf, R. Gudgel, L. Jia and F. Zeng, 2015: Investigating the Influence of Anthropogenic Forcing and Natural Variability on the 2014 Hawaiian Hurricane Season, Bulletin of the American Meteorological Society, 96, 120- 124.

Xiaosong Yang, G. A. Vecchi, T. L. Delworth, K. Paffendorf, R. Gudgel, Liwei Jia, Seth D. Underwood and F. Zeng, 2015: Extreme North America Winter Storm Season of 2013/14: Roles of Radiative Forcing and the Global Warming Hiatus, Bulletin of the American Meteorological Society, 96, 25-28.

Book Chapter:

Timothy DelSole, Michael K. Tippett and Liwei Jia, 2015: Multi-year Prediction and Predictability, World Scientific Series on Weather and Climate, Climate Change: Multidecadal and Beyond, Chapter 14, pp 219-233, 2015.

Presentations:

Dec. 2015, American Geophysical Union Fall Meeting, San Francisco: The Role of Radiative Forcing, Sea Surface Temperature, Atmospheric and Land Initial Conditions to U.S. Summer Warming Episodes (poster).

Sep. 2015, Workshop on using and interpreting climate information from NOAA/GFDL models for epidemiological studies in Africa and Asia, Princeton University: Improved Seasonal Prediction of Temperature and Precipitation over Land in a High-resolution GFDL Climate Model.

May 2015, American Geophysical Union Joint Assembly, Montreal, Canada: Skillful Seasonal Prediction of Temperature and Precipitation over Land in a new GFDL High Resolution Climate Model.

Progress Report Title: **Predicting and Explaining Extreme Events: Comparing Models and Observations to Assess Model Fidelity and Anthropogenic Influence**

Principal Investigator: Jonghun Kam (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Thomas R. Knutson, Andrew T. Wittenberg, and Fanrong Zeng (GFDL)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: This project is aimed at improved understanding of the causes of extreme weather and climate events. We used climate models and observations to assess the possible role of anthropogenic forcing in extreme events and to test whether historical model simulations are consistent with observations.

Methods and Results/Accomplishments:

For this project, we have analyzed some extreme climate events which occurred around world during 2014; we are currently working on a new analysis for 2015 extremes. For 2014 we focused on extreme annual mean warm surface temperature observed in three regions. This work was a contribution to an annually published article in BAMS which seeks to explain extreme weather and climate events during the past year in the context of long-term climate change. While much of the methodology follows previous contributions by Knutson et al., the new report which I led focused on 2014 extremes and on improved quantification of confidence intervals. A model/observational comparison, using CMIP5 models to simulate internal climate variability and the response to historical anthropogenic and natural forcings, was applied to the three regions exhibiting particularly unusual annual-mean warmth during 2014. A time-evolving long-term trend analysis and a focused attribution analysis for the 2014 anomalies was presented for each region, including an analysis of the fraction of attributable risk (FAR). Uncertainties in the analysis include: the climate model response to external forcings, the specification of the external forcing agents, and the simulation of internal climate variability. Limited model data (control run length, numbers of ensemble members) also increases uncertainties. We included an important enhancement relative to our previous studies: new confidence interval estimates for several of our key results, including the FAR and the magnitude contribution of anthropogenic forcing to the observed anomalies.

We found that extreme annual mean temperatures around the globe during 2014 were again, as in 2012 and 2013, very skewed toward warm extremes (~12% of area), rather than cold extremes (~0%), where extremes here refer to warm or cold anomalies that rank 1st, 2nd, or 3rd in the record of at least 100 years. Observations showed record annual-mean warmth much of Europe, the extreme northeast Pacific and northwest Atlantic. Temperatures in Europe exhibit century-scale warming trends that are generally detectable and attributable in part to anthropogenic forcing according to the CMIP5 models. The long-term warming trends in the northeast Pacific and northwest Atlantic were not generally detectable, except for trends over limited periods. According to our analysis of the CMIP5 models, the

risk of annual warm anomalies similar to those in 2014 in Europe and the northwest Atlantic, was essentially entirely attributable to anthropogenic forcing.

References:

Knutson, T. R., F. Zeng, and A. T. Wittenberg, 2013, Multimodel assessment of regional surface temperature trends: CMIP3 and CMIP5 twentieth-century simulations. J. Climate, 26, 8709–8743.

Publications:

Kam, J., T. R. Knutson, F. Zeng, and A. T. Wittenberg, 2015, Record annual-mean warmth over Europe, the northeast Pacific, and the northwest Atlantic during 2014: Assessment of anthropogenic influence, Bull. Amer. Meteor. Soc., 96, S61-S65.

Presentations:

Kam, Jonghun, Attribution assessment for recent climate extremes: Record annual-mean warmth during 2014 and the 2011-14 California drought, Invited Talk at Earth System Research Laboratory/NOAA, Feb. 9th, Boulder, CO.

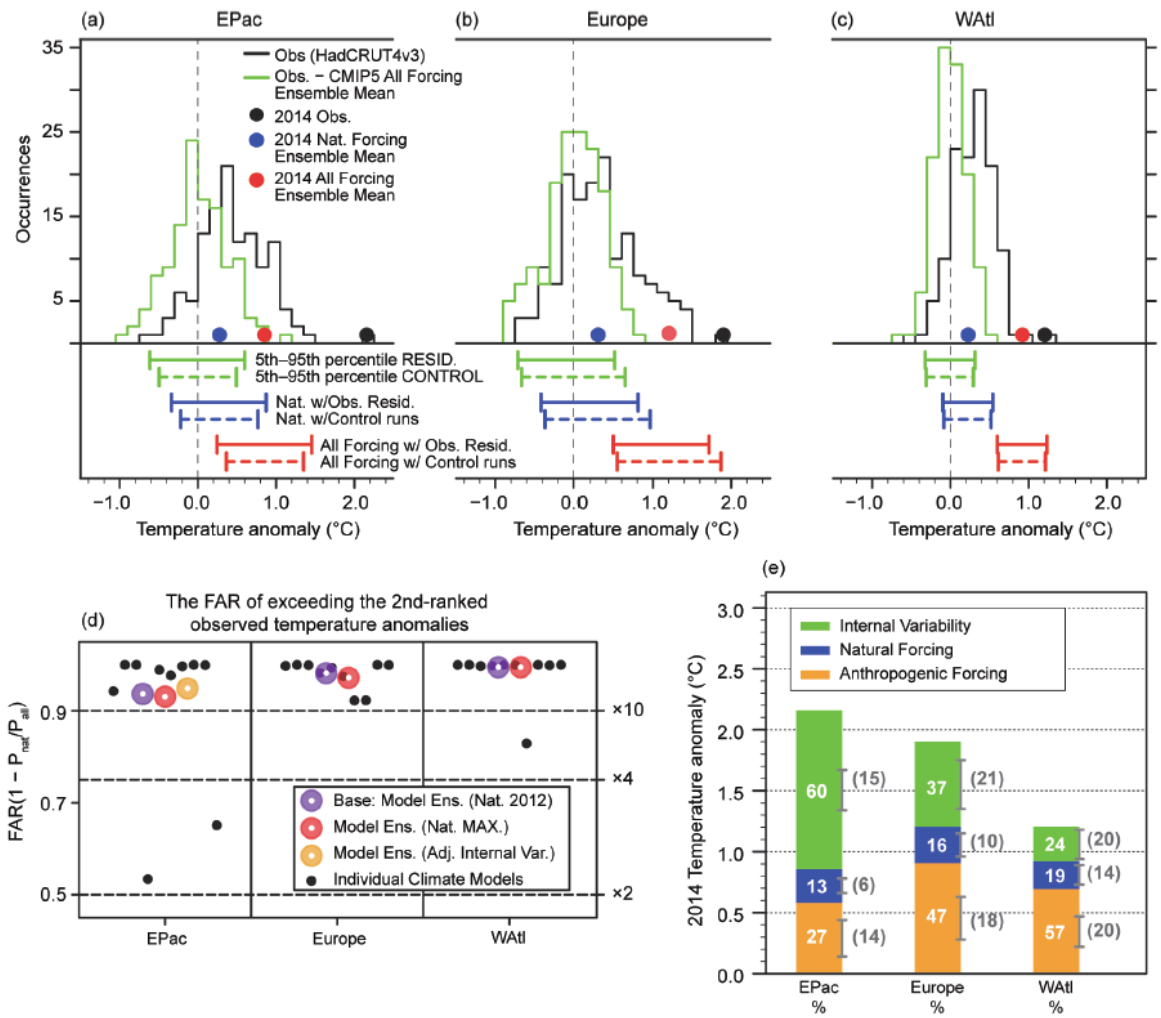

Fig. 1 (a)–(c): Histograms of "observed residuals" (solid green lines) and observed annual mean temperature anomalies (black lines) over the three regions. Observed residuals obtained by subtracting CMIP5-

All forcing ensemble means from observations and then subtracting any remaining long-term mean. The 5th to 95th percentile ranges of observed residuals and control run variations are depicted by green solid and dashed error bars. Blue (red) error bars depict the 5th–95th percentiles of observed residuals and CMIP5-Control runs, respectively, offset by ensemble means for 2014 from CMIP5-Nat (CMIP5–All) simulations. Black, red, and blue dots in (a)–(c) depict observed, CMIP5-All, and CMIP5-Nat anomalies for 2014. (d) Estimates of the FAR of exceeding the second-ranked observed temperature anomalies from the CMIP5 multi-model ensemble (large purple circle) and its uncertainty (black solid circles) as estimated from the 10 paired CMIP5-All and CMIP5-Nat runs from individual CMIP5 models. Large red circles depict FAR sensitivity tests using—for the 2014 CMIP5-Nat value—the maximum temperature anomalies in any one year from the CMIP5-Nat multi-model ensemble means; large yellow circle shows a test using adjusted (+22%) internal variability over the EPac region. Dashed lines labeled "×10", "×4", and "×2" indicate risk ratios (CMIP5-All vs. CMIP5-Nat). (e) Stack bars show the estimated contributions of anthropogenic forcing (CMIP5-All – CMIP5-Nat; orange), natural forcing (CMIP5-Nat; blue), and internal variability (Obs. – CMIP5-All; green) to 2014 anomalies (relative to 1881–1920) over the three regions, with ±1 standard error ranges (bar-whiskers).

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

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

Award Number: NA14OAR4320106

Task III: Individual Projects

NOAA Sponsor: V. Ramaswamy (GFDL)

Other Participating Researchers: Are Olsen (U.Bergen, Norway), Steven van Heuven (U.Bergen, Norway), Siv Lauvset (U.Bergen, Norway), Anton Velo (CSIC, Vigo, Spain), Toste Tanhua (GEOMAR, Kiel, Germany), Xiaohua Lin (Princeton), Alex Kozyr (CDIAC, Oak Ridge, Tenn.), Mario Hoppema (AWI, Bremerhaven, Germany), Toru Suzuki (JHA, Tokyo, Japan)

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

Methods and Results/Accomplishments:

The creation of GLODAPv2, an effort that has taken more than 12 years and thousands of man-hours, is complete. The final data product is composed of two parts: a calibrated data set composed of over a million water samples from 724 "cruises" covering the global ocean for the period 1973-2013 and a 1x1 degree three dimensional gridded data product. Calibration of the measurements for this product was much more uniformly executed than in prior efforts (GLODAPv1, CARINA, PACIFICA).

Details of the two GLODAPv2 components are described in some detail in 3 manuscripts (Olsen et al., Leuvaset et al. and Key et al). The first two manuscripts are almost through the review process at Earth System Science Data and the latter is available through CDIAC. Analysis of the data has just begun. We believe that this data product will have significant value to the community for the next decade or until it is updated. The current plan is to update v2 by addition of new cruises (calibrated toward v2) until sufficient new data are available to warrant a complete re-examination of the entire data set. We are hopeful that the data quality produced by the new biogeochemical floats (i.e. SOCCOM) will be sufficient for inclusion in the next version. Those new data certainly have the potential to redefine data distributions wherever the floats exist with reasonable density.

The data products and a tremendous amount of metadata regarding the cruises and measurements are available through CDIAC <http://cdiac.ornl.gov/oceans/GLODAPv2/>.

Publications:

Lauvset, S.K, R. M. Key, A. Olsen, S. van Heuven, A. Velo, X. Lin, C. Schirnick, A. Kozyr, T. Tanhua, M. Hoppema, S. Jutterström, R. Steinfeldt, E. Jeansson, M. Ishii, F.F. Perez, T. Suzuki, and S. Watelet, A new global interior ocean mapped climatology: the 1ºx1º GLODAP version 2, ESSD, MS No. essd-2015-43, Jan. 2016.

Olsen , Are , Robert M. Key, Steven van Heuven, Siv K. Lauvset, Anton Velo, Xiaohua Lin, Carsten Schirnick, Alex Kozyr, Toste Tanhua, Mario Hoppema, Sara Jutterström, Reiner Steinfeldt, Emil Jeansson, Masao Ishii, Fiz F. Pérez and Toru Suzuki, An internally consistent data product for the

world ocean: the Global Ocean Data Analysis Project, version 2 (GLODAPv2), ESSD, MS No. essd-2015-42, Jan. 2016.

Key, R.M., A. Olsen, S.K. Lauvset, S. van Heuven, , A. Velo, A. Kozyr, X. Lin, C. Schirnick, T. Tanhua, M. Hoppema, S. Jutterström, R. Steinfeldt, E. Jeansson, F.F. Pérez, M. Ishii, T. Suzuki, A global ocean carbon climatology: Results from Global Data Analysis Project (GLODAPv2), CDIAC NDP-093, 2015.

Presentations/Abstracts:

Olsen, A., R.M. Key, S. Lauvset, X. Lin, T. Tanhua, M. Hoppema, S. Jutterström, R. Steinfeldt, E. Jeansson, S. van Heuven, M. Ishii, T. Suzuki, A.Velo, A. Kozyr, B. Pfeil, Global Ocean Data Analysis Project Version 2 (GLODAPv2), Ocean Sciences Mtg, Honolulu, Hawaii, Feb. 23-28, 2014.

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Schuller, Daniel, Lynne Talley1, Susan Becker, Robert Key, Ken Johnson, Emmanuel Boss, SIO'S Oceanographic Data Facility: Providing high quality nutrient and oxygen data for the GO-SHIP and Argo communities, CLIVAR meeting, Qingdao, China, Sep. 18-25, 2016.

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Progress Report Title: **The Role of Temperature and Oxygen for the Remineralization of Sinking Organic Matter**

Principal Investigator: Charlotte Laufkötter (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: John P. Dunne, Charles Stock, and Jasmin John (GFDL)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Healthy Oceans Goal: Marine Fisheries, Habitats, and Biodiversity are Sustained within Healthy and Productive Ecosystems (50%)
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts (50%)

Objectives: An accurate representation of the remineralization of sinking particles of organic matter (POM) is crucial for reliable projections of the ocean's biogeochemical cycles, particularly that of carbon. Both water temperature and oxygen concentration are thought to influence the remineralization speed, but particularly temperature effects are difficult to explicitly observe and remain a major uncertainty in projections of the ocean carbon cycle. My work in the last 12 months has focused on using observations to find constraints for a temperature and oxygen dependence and developing a new parameterization of POM flux.

Methods and Results/Accomplishments:

Together with my co-workers, I have collected a compilation of depth-resolved POM flux measurements from 19 different sites, covering a wide range of temperature- and oxygen conditions. A statistical analysis of this database has resulted in a new parameterization of POM flux to depth which includes a Michaelis-Menten-type oxygen dependence and an exponential temperature dependence. By using a chi-squared test we could show that remineralization has a temperature dependence with a Q10 value between 1.65 and 2.22, and an oxygen dependence with a half-saturation constant between 6 and 12 umol/L with 95% confidence. Best results are achieved with a temperature coefficient that results in a Q10 of 2.06 and an oxygen half-saturation constant of 8.9 umol O2/L. Using those coefficients, the RMSE between the normalized POM measurements and the fit is reduced by 20%. We have tested the new parameterization in the ecosystem model "Carbon, Ocean Biogeochemistry and Lower Trophics" (COBALT) coupled to GFDL's ESM2M Coupled Climate–Carbon Earth System Model. After 500 years of preindustrial spin-up simulation, there are moderate differences between the new temperature-dependent version and the original temperature-independent version (both versions feature an oxygen dependence). In terms of carbon cycling, the temperature-dependent version has a 0.1 GtC/yr lower global particle flux at 100m depth and a 0.01 GtC/yr higher particle flux at 2000m depth, caused by stronger remineralization in the warmer surface water of the low latitudes and weaker remineralization in the colder intermediate-depth water. Both fluxes are still within observational constraints. Particularly in the low latitudes the deep ocean oxygen concentration is higher. The volume of water with oxygen concentration lower than 2 umol/L is now much closer to observational constraints, however the position and shape of the oxygen minimum zone is only barely affected. In a future strong climate change scenario (RCP8.5), the temperature-dependent version projects a 10% lower a carbon flux at 2000m

compared to the original temperature independent version, which results in a decrease in oceanic carbon uptake of 0.4 GtC/year.

Publications:

C. Laufkötter, M. Vogt, N. Gruber, M. Aita-Noguchi, O. Aumont, L. Bopp, E. Buitenhuis, S.C. Doney, J. Dunne, T. Hashioka, J. Hauck, T. Hirata, J. John, C. Le Quéré, I.D. Lima, H. Nakano, R. Seferian, I. Totterdell, M. Vichi, and C. Völker, Drivers and uncertainties of future global marine primary production in marine ecosystem models, Biogeosciences, 12 (2015), 6955-6984.

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C. Laufkötter, J. P. Dunne, N. Gruber and M.Vogt, Drivers of future changes in export production – a model comparison, 3rd Climate Change Symposium, Santos, Brazil (poster).

Progress Report Title: **Global River Nutrient Loading Responses to Land Use and Climate Changes**

Principal Investigator: Minjin Lee (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Charles Stock (GFDL), Elena Shevliakova (Princeton/GFDL), and Sergey Malyshev (Princeton)

Other Participating Researchers: Peter Jaffe (Princeton)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: We develop and apply a terrestrial-river nutrient cycling model to investigate global river nutrient loading in response to land use and climate changes.

Methods and Results/Accomplishments:

We applied LM3-TAN (Lee et al., 2014) to investigate the critical influence of climate variability/extremes, interacting with ecosystem (i.e., soil, groundwater) nitrogen (N) storage accumulated over multiple decades, on Susquehanna River dissolved nitrogen (DN) loads, known precursors of the hypoxia in the Bay (Lee et al., in review). The result indicates that possible future increases in climate variability/extremes – specifically, high precipitation occurring after multi-year dry spells – could likely lead to high DN-load anomalies and associated hypoxia. This work was presented at the 2016 Ocean Sciences Meeting in New Orleans.

We also developed a global implementation of LM3-TAN to simulate global dynamic river N loading in response to land use (and relevant anthropogenic N inputs) and climate changes. The applied anthropogenic N inputs include atmospheric deposition, fertilizer and manure applications, and sewage. Especially, we compiled country-specific sewage N emissions (Drecht et al., 2009) and administrative population data to produce sub-country level global sewage N inputs. Observed annual (1995) dissolved organic nitrogen (DON) and dissolved inorganic nitrogen (DIN) loads at the outlets of world's ten large rivers were compared with results by LM3-TAN (Pearson's correlations: $r_{DON} = 0.78$ and $r_{DIN} = 0.88$) and by Global NEWS ($r_{DON} = 0.87$ and $r_{DIN} = 0.90$) (Harrison et al., 2005; Dumont et al., 2005). These preliminary results indicate that the process model LM3-TAN is capable of capturing spatial variation of DON and DIN loads on a global scale with skill comparable to the widely used but highly empirical Global NEWS model for nutrient loadings from rivers.

In addition, we incorporated coupled algal and nutrient dynamics into LM3-TAN. The resultant model was applied for the study of five major rivers in the Southern Korean Peninsula (NEI, 2015). Overall, the model simulated well the spatial variation of chlorophyll-a, nitrate-N, and phosphate-P loads and concentration in the rivers, although it was less capable of capturing inter-annual variability of the chlorophyll-a concentration, perhaps contributed by unresolved processes (e.g., soil P dynamics).

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Publications:

Lee, M., Shevliakova, E., Malyshev, S., Milly, P.C.D, Jaffe, P. (in review), Capturing Climate Variability and Extremes, Interacting with Nitrogen Storage, Amplify Eutrophication Risk, Geophysical Research Lett.

Presentations:

Lee, M., Shevliakova, E., Malyshev, S., Milly, P.C.D., Jaffe, P. Stock, C. Climatic Variability and Extremes, Interacting with Nitrogen Storage, Amplify Risks of Coastal Eutrophication, Ocean Sciences Meeting, New Orleans, Louisiana, USA, 2016.

NEIR (National Institute of Environmental Research), Studies on Impact Assessment of Climate Change on Water Quality in a Regional Scale using a Land Surface Model (Ⅱ), Incheon, South Korea, 2015.

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

Principal Investigator: Sonya Legg (Princeton Senior Research Oceanographer)

CICS/GFDL Collaborator: Robert Hallberg and Stephen Griffies (GFDL), Alistair Adcroft, He Wang, Benjamin Mater, Robert Nazarian, and Gustavo Marques (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 (USM), Mehmet Ilicak (UBergen), Maxim Nikurashin (UTasmania), Angelique Melet (LEGOS), Jonas Nycander (UStockholm), Alberto Naveiro Garabato (USouthampton), Michael Meredith (BAS), Eleanor Frajka-Williams (USouthampton).

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

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 several aspects of ocean mixing, predominantly that due to tidally-generated internal waves, and that due to oceanic overflows.

The study of tidally-generated internal waves forms a component of the Internal Wave Driven Mixing Climate Process Team, headed by Jennifer MacKinnon at Scripps Oceanographic Institution and including Legg and Robert Hallberg as team members. Legg and Hallberg have co-supervised CPT postdocs Angelique Melet and Benjamin Mater, funded by NOAA through CICS. A dominant focus of the past year has been the fate of low-mode tidally generated internal waves, with one study of impacts internal wave dissipation on large-scale ocean climate in press (Melet et al, 2016), and another describing a ray-tracing based model of the distribution of low-mode dissipation in preparation, following a poster presented at the Ocean Sciences meeting (Mater et al, 2016).

Other work related to the Internal Wave Driven Mixing CPT includes studies of the scattering of low-mode internal waves at continental slope canyons, carried out by CICS/AOS graduate student Robert Nazarian under Legg's supervision, which was presented at the Ocean Sciences meeting (Nazarian et al, 2016). Another study of breaking of tidally-generated internal waves being carried out under Legg's supervision is that conducted by Young (Paul) Yi, a Princeton University geosciences undergraduate, as part of his junior year research project, funded by PEI. This work was presented at the Ocean Sciences meeting (Yi et al 2016), and will be written up for publication this summer.

A related project was the Internal Waves In Straits Experiment (IWISE) funded by ONR, for which a final team synthesis publication appeared in Nature this year (Alford et al, 2015).

Legg's overflow-related work includes supervision of CICS/AOS graduate student He Wang, who recently successfully defended his PhD thesis. His second manuscript, on the impact of transports of fresh water from the Arctic on North Atlantic deep water formation and climate, will be submitted soon. Legg

is also collaborating with the DynOPO project, [lead PIs Alberto Naveiro Garabato (Southampton University) and Michael Meredith (British Antarctic Survey)] to examine the mixing in Weddell Sea Deep Water as it flows through the Orkney Passage into the Scotia Sea, performing numerical simulations to guide their 2017 field program, and compare results with climate model parameterizations of mixing in overflows. AOS/CICS postdoc Gustavo Marques, whom Legg is co-supervising, is working on a related project, using GFDL's high resolution coupled ice-ocean model simulations to examine the export of dense water around Antarctica.

Finally, an important component of Legg's work on small scale mixing and climate is the collaboration between process studies and model developers, often through the mechanism of climate process teams (CPTs), funded by NOAA through CICS, with NSF funding of academic partners. As a member of the USCLIVAR scientific steering committee, Legg co-organized a workshop, held at GFDL, to assess the progress made by past CPTs, and examine the opportunities for future activities designed to translate process understanding into improved climate models. A whitepaper summarizing the workshop conclusions is currently in progress.

All the studies described above are contributing to the development of GFDL's new ocean model MOM6, and Legg takes an active role in the Ocean Working Group, including analysis of CM4 simulations.

Outreach Activities: Legg's outreach activities include coordination of AOS/CICS participation in the PPPL Young Women's science conference and the New Jersey Ocean Fun Days, involving several students and postdocs in demonstrating ocean dynamics and chemistry to children, from pre-school to middle school, and their parents. During the past year, Legg also participated in a science "staycation" at the Kreps Middle School, in East Windsor, and a STEM night at the Trenton Boys and Girls Club. Other outreach activities include guest lectures on Climate Change to an undergraduate non-science major environmental geology class at Rider University. Legg is also active in efforts to mentor women in oceanography, including participation in MPOWIR, PWiGs, and ESWN. A major new initiative which Legg has spearheaded is the CICS research internships, targeted at increasing diversity in earth and climate sciences, for which selection of the 1st year candidates is ongoing.

Publications:

Alford, M.H., T. Peacock, J.A. MacKinnon, J.D. Nash, M.C. Buijsman, L.R. Centurioni, S.-Y. Chao, M.-H. Chang, D.M. Farmer, O.B.Fringer, K.-H. Fu, P. Gallacher, H.C. Graber, K.R. Helfrich, S. Jachec, C. Jackson, J.M. Klymak, D.S. Ko, S. Jan, T.M.S. Johnston, S. Legg, I.-H. Lee, R.-C. Lien, M.J. Mercier, J.N. Moum, R. Musgrave, J.-H. Park, A.I. Pickering, R. Pinkel, L.R. Rainville, S. Ramp, D.R. Rudnick, S. Sarkar, A. Scotti, H.L. Simmons, L.C. St Laurent, K. Venayagamoorthy, Y.-H. Wang, J. Wang, Y.J. Yang, T. Paluszkiewicz, T.Y. Tang, 2015: The formation and fate of internal waves in the South China Sea. Nature v521, doi:10.1038/nature14399.

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Mater, B., R. Hallberg, S. Legg, A. Adcroft, and J. Nycander, Representing the propagation and far-field dissipation of internal tides in a global climate model. Ocean Sciences meeting 2016.

Legg, S., A. Melet, and R. Hallberg, Impacts of spatial distribution of parameterized local and remote tidal mixing on large-scale ocean circulation and climate. Ocean sciences meeting 2016.

R. Nazarian and S. Legg, Internal wave scattering in continental slope canyons: a parameter space study. Ocean sciences meeting 2016.

Yi, Y., S. Legg and R. Nazarian, Tidal mixing over rough topography: sensitivity to topographic length scale and steepness. Ocean sciences meeting 2016.

Progress Report Title: **Urban Model Development and Surface-Atmosphere Interaction**

Principal Investigator: Dan Li (Princeton Postdoctoral Research Associate)

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

Other Participating Researchers: Chris Milly (USGS)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

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 is not suitable to 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 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 been implemented and evaluated with prescribed atmospheric forcing. I also conducted high-resolution coupled land-atmosphere simulations to study the impacts of urbanization on local/regional climate. I am working on three papers related to this project at this moment.

In the meantime, a better understanding the interactions between the surface (e.g., urban surface) and the atmosphere is the fundamental basis for further improving our global climate and earth system models. I have been working on understanding the surface-atmosphere interaction from a turbulence perspective. In particular, the Monin-Obukhov similarity theory, which is used to parameterize surface-atmosphere interaction in almost all numerical models, is revisited from a theoretical point-of-view. In addition, I also work on a range of boundary layer problems with collaborators in the year 2015-2016 as reflected in the list of publications.

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Publications:

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Li, D., G. Katul, and P. Gentine (2016), The k^{−1} scaling of air temperature spectra in atmospheric surface layer flows, Q. J. Roy. Meteor. Soc. 142: 496–505, doi: 10.1002/qj.2668.

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Progress Report Title: **Understanding the Decline of Summer Arctic Sea Ice Extent**

Principal Investigator: Dawei Li (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Rong Zhang and Thomas R. Knutson (GFDL)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: We study the low-frequency variabilities of Arctic sea ice extent in coupled climate models to understand its rapid decline over the satellite era.

Methods and Results/Accomplishments:

In response to changes in anthropogenic radiative forcings, the multi-model ensemble mean summer Arctic sea ice extent (ASIE) in CMIP5 simulations shows a less dramatic decline than that observed during the recent global warming hiatus period (Zhang and Knutson 2013), implying that natural variability may have played an important role in the observed decline (Zhang 2015). We studied the mechanisms for low-frequency variability of summer ASIE using the available long control simulations from three coupled climate models: GFDL CM2.1, GFDL CM3, and NCAR CESM. We found that in all three models, the Atlantic/Pacific oceanic heat transport into the Arctic and the Arctic Dipole in the atmosphere are key players for the low-frequency variability of summer Arctic sea ice concentration (SIC) and surface air temperature (SAT). The low-frequency September ASIE anomalies are reconstructed by multiple regression models using these three predictors in all three models. There are strong linkage between September ASIE and March sea ice extent in Barents Sea in all three models and observation, indicating the importance of Atlantic inflow. We found that Bjerknes Compensation exists in all three models, thus variations in the atmospheric heat transport across the Arctic Circle are forced by anti-correlated variations in the Atlantic oceanic heat transport into the Arctic, and provides a negative feedback on summer ASIE variations at low frequency.

Among the three models, the simulated climatological September ASIE by GFDL CM3 is closest to the satellite observation (NSIDC, 1979-2015), while GFDL CM2.1 has a too small September ASIE, and NCAR CESM shows excessive September sea ice, especially on the Atlantic side. All models respond to a positive phase Arctic Dipole with a reduction of summer Arctic SIC on the Pacific side and an increase on the Atlantic side by transporting more ice from the Pacific side to the Atlantic side. NCAR CESM differs from the other two models in that due to the excessive climatological sea ice on the Atlantic side, the reduction of sea ice on the Pacific side is largely balanced by the expansion on the Atlantic side, resulting in an insignificant net impact of the Arctic Dipole on the summer ASIE.

References:

Zhang, R., and T. R. Knutson (2013), The role of global climate change in the extreme low summer Arctic sea ice extent in 2012 (in Explaining Extreme Events of 2012 from a Climate Perspective), Bull. Am. Meteorol. Soc., 94(9), S1–S74, doi:10.1175/BAMS-D-13-00085.1.

Zhang, R. (2015), Mechanisms for low-frequency variability of summer Arctic sea ice extent, Proc. Natl. Acad. Sci., 112(15), 4570–4575, doi:10.1073/pnas.1422296112.

Publications:

Li, D., R. Zhang, and T.R. Knutson, 2015: Comparison of Low-Frequency Variability of Summer Arctic Sea Ice in Three Coupled Climate Models, Journal of Climate, in preparation.

Li, D., R. Zhang, and T.R. Knutson, Comparison of Low-Frequency Variability of Summer Arctic Sea Ice in Three Coupled Climate Models, AGU Fall Meeting. San Francisco, CA, December, 2015.

Progress Report Title: **Statistical Modeling of Tropical Cyclones in a Changing Climate**

Principal Investigator: Ning Lin (Princeton Assistant Professor)

CICS/GFDL Collaborator: Thomas Knutson (GFDL)

Other Participating Researchers: Jianqing Fan (Princeton)

Award Number: NA14OAR4320106

Task III: Individual Projects

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: To develop a climate-variant probabilistic tropical cyclone model

Methods and Results/Accomplishments:

We have focused on developing two components of the tropical cyclone model: the intensity component and the size component. We developed statistical models to predict the storm intensity given storm environment parameters. We first applied advanced statistical methods to select a relative small set of the most relevant parameters from a large number of parameters considered in the literature. We then developed statistical relationships between the storm intensity and the selected environmental variables, considering linear/nonlinear relationships and homogenous/heterogeneous data structures. We obtain a set of models that require less input but provide better predictions, compared to existing models such as the statistical model used by the National Hurricane Center for real time forecasting.

We developed a simple physical model for the complete radial profile of the low-level azimuthal wind field of tropical cyclones. We applied various observational datasets to evaluate the model and found that the model can well capture the observed wind field variability. In particular, because the complete model connects the storm inner convecting region and non-convecting outer circulation, it can be used to estimate the storm radius of maximum wind from the storm outer radius. The storm radius of maximum wind, a critical storm size parameter in tropical cyclone risk modeling, is usually difficult to observe or model, while the outer radius can be better captured. Also, the climatology of the outer radius has been investigated by my group. This wind model thus provides us a method to predict or model the climatology of the storm radius of maximum wind.

Outreach Activities: Ning Lin gave four outreach talks in 2015:
Sustainable Princeton Great Ideas Breakfast on Climate Change, Princeton Public Library, 03/26/2015
Chevron Climate Energy Environment Series Webinar on Planning for Coastal Protection; 07/16/2015
Princeton Energy and Climate Scholars Group Seminar, Princeton University, 05/23/2015
Energy Table Discussion, Rockefeller College, Princeton University, 12/02/2015

Publications:

Chavas, D. Lin, N., Emanuel, K., 2015: A Model for the Complete Radial Structure of the Tropical Cyclone Wind Field. Part I: Comparison with Observed Structure. Journal of the Atmospheric Sciences, 72, 3647–3662, doi: 10.1175/JAS-D-15-0014.1.

Chavas, D. & N. Lin (2016). A model for the complete radial structure of the tropical cyclone wind field. Part II: wind field variability. Journal of the Atmospheric Sciences, minor revision.

Lin N., R. Jing, Y. Wang, J. Fan, and L. Xue. Statistical dependence of tropical cyclone intensity on the surrounding environment. In prep., to be submitted to Monthly Weather Review.

Progress Report Title: **Stratospheric Climate Change and its Influence on the Troposphere and Surface**

Principal Investigator: Pu Lin (Princeton Associate Research Scholar)

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

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: We seek to understand how stratosphere would change under different climate forcings and how these changes affect climate states in the troposphere and at the surface.

Methods and Results/Accomplishments:

Most climate models predict a warming at the tropical tropopause in the near future, but the mechanisms for such warming have not been fully understand (Gettelman et al. 2010, Kim et al. 2013). We explore this problem in two idealized perturbation experiments with the GFDL model AM3. In the first experiment, the atmospheric carbon dioxide concentration is quadrupled from its present-day value, but the sea surface temperature is held at the present-day condition. In the second experiment, we apply a 4K uniform increase in the sea surface temperatures, but the carbon dioxide concentration is unchanged. We then analyze changes in the heat budget at the tropical tropopause, which helps to quantify the contribution from different physical processes. We identify the direct radiative effect of carbon dioxide increase as a previously unappreciated contributor to changes in the tropical tropopause temperature. A paper summarizing this work is currently under internal review and is to be submitted to *Journal of Climate.*

The heat budget analysis employs the standalone radiative transfer model. I have evaluated, debugged and revised the existing codes. These revised standalone radiative transfer codes have been utilized for model development, and would serve as a useful diagnostic tool for many research problems.

Previous modeling and observational studies suggest ozone depletion over the past decades drives a cooling trend in the lower stratosphere over Antarctica, and a poleward shift of the jet in the troposphere during austral summer (e.g., Polvani et al. 2011). The circulation response to ozone depletion in GFDL models is found to be weaker than most other GCMs and weaker than what observations suggested. AM4 and AM3 also show different dynamical response to the same ozone forcing. Heat budget analysis shows that the lower stratospheric temperature response to ozone depletion has a large contribution from dynamics. It is the different dynamical response to ozone depletion that lead to different temperature and jet response in different models. Further analysis on the dynamical states of the two models is underway.

References:

Gettelman, A. and coauthors, 2010: Multimodel assessment of the upper troposphere and lower stratosphere: Tropics and global trends, JGR, 115, D00M08.

Kim, J., K. M. Grise and S.-W. Son, 2013: Thermal characteristics of the cold-point tropopause region in CMIP5 models, JGR, 118, 8827-8841.

Polvani, L. M., D. W. Waugh, G. J. P. Correa and S.-W. Son, 2011: Stratospheric ozone depletion: the main driver of twentieth-century atmospheric circulation changes in the Southern Hemisphere, J. Clim., 24, 795-812.

Publications:

Lin, P., D. Paynter, Y. Ming and V. Ramaswamy, 2015: Changes of the tropical tropopause layer under global warming, under internal review, to be submitted to J. Clim.

Progress Report Title: **The Response of an Idealized Atmosphere to Orographic Forcing: Zonal vs. Meridional Propagation**

Principal Investigator: Nicholas Lutsko (Princeton Graduate Student)

CICS/GFDL Collaborator: Isaac Held (GFDL)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: To isolate a regime in which an idealized model of the atmosphere responds linearly to orographic forcing. This is a step on the path connecting the (linear) theory of how the atmosphere responds to orography to the effect the real Earth's topography has on the atmosphere.

Methods and Results/Accomplishments:

Mountains play a key role in determining the stationary wave pattern of the Northern Hemisphere, particularly in winter. Understanding the present stationary wave pattern and how it will change in the future is important for understanding regional climates and predicting their future changes. However, the theory for orographically forced stationary waves is a linear theory (e.g Held (1983)), whereas the actual atmosphere is highly non-linear. In this project we have forced an idealized general circulation model (GCM) with a range of mountain heights, searching for a regime in which the model response is a linear function of the height of the mountain. Once such a regime has been found, the breakdown of linearity can be studied to learn more about the behavior of the real atmosphere.

For small enough mountain heights we find that the model does respond linearly to the orographic forcing. In contrast to previous results, which have emphasized the meridional propagation of orographically forced stationary waves (Hoskins and Karoly (1979)), the linear response here is dominated by a zonal wave, which propagates almost around the entire globe (see Figure 1). This is because the mid-latitude jet acts as a waveguide for the set-up considered here.

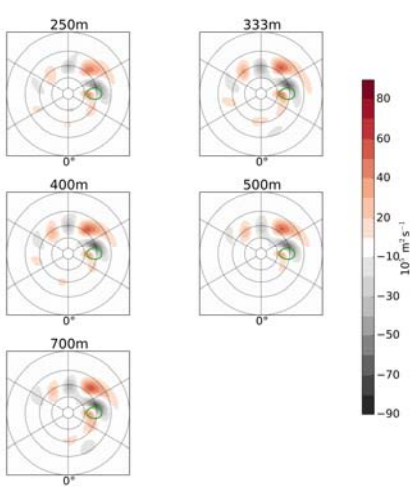

Figure 1. The eddy streamfunction response at 350hPa of the idealized GCM to five different mountain heights, plotted using a polar stereographic projection. The responses are normalized by 1000m / H, where H is the maximum height of the mountain, and the green ovals outline the H /2 contour.

As the height of the mountain is increased the response becomes non-linear and meridional propagation also becomes increasingly prominent. This transition can be recreated with a barotropic model on a sphere, but the transition is caused by different factors in the two models. In the barotropic model the transition is caused by leakage from the waveguide which distorts the equatorward critical layer and this then interferes with the stationary waves. The cause of the transition is less clear in the GCM, though it appears that the stationary waves erode the waveguide as the height of the mountain is increased. We are currently designing and performing model simulations to better understand this behavior.

Outreach Activities: Teaching assistant for Princeton class GEO 202: Ocean, Atmosphere, and Climate

References:

Held, Isaac M., 1983: Stationary and quasi-stationary eddies in the extratropical troposphere: theory. In: Large-scale Dynamical Processes in the Atmosphere, New York, NY, Academic Press, 127-168. Hoskins, B. J., and D. J. Karoly, 1981: The steady linear response of a spherical atmosphere to thermal and orographic forcing. Journal of the Atmospheric Sciences, 38 (6), 1179–1196.

Publications:

Lutsko, N. J. and Held, I. M., 2016: The Response of an Idealized Atmosphere to Orographic Forcing: Zonal vs Meridional Propagation. Journal of the Atmospheric Sciences (In Revision).

Progress Report Title: **Exploring Historical and Future Urban Climate in the Earth System Modeling Framework**

Principal Investigator: Sergey Malyshev (Princeton Professional Specialist)

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

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Weather-Ready Nation Goal: Society is Prepared for and Responds to Weather-Related Events (50%)
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts (50%)

Objectives: To understand the urban climate and its evolution in the present climate and in future in relationship to overall climate change

Methods and Results/Accomplishments:

Quantifying the impacts of global climate change on urban areas is of great importance, because more than 50% of the world's population is concentrated in urban areas. Also the impacts of urbanization on the climate system at various temporal and spatial scales is important for proper representation of land-atmosphere interactions, and has been the subject of active research for years.

In a series of studies led by Dr. Dan Li (CICS) we developed an urban component of the GFDL LM3 land model (LM3-UCM). The model is evaluated using observational datasets collected at three urban sites: Marseille in France, Basel in Switzerland and Baltimore in the United States. It is found that LM3-UCM satisfactorily reproduces canyon air temperature, surface temperatures, radiative fluxes, and turbulent heat fluxes at the three urban sites.

LM3-UCM was further used to explore the response of urban climate to historic and future climate change in the Continental US (CONUS). Simulations show that the spatial pattern of summer (JJA, i.e. June, July, and August) temperature differences between urban and natural vegetation systems is primarily controlled by the spatial pattern of differences in evapotranspiration, which further depends on the spatial distribution of precipitation. In winter (December, January, February), the magnitude of temperature differences is more controlled by the building heating than the precipitation amount. At high latitudes where snow is an important factor in radiative balance, the magnitude is also affected by a larger net shortwave radiation input for urban areas due to the lower albedo of cities.

As an illustration, Figure 1 shows the difference in near-surface air temperature between urban canyon and neighboring natural vegetation in different decades of historical period in summer (JJA) season.

Although both urban and natural vegetation temperatures increase as the climate warms, their increasing rates are different and hence their differences change with time. It is found that the multi-decadal trend of summer temperature difference is negligible. However, the winter temperature differences show a strong negative trend, which is caused by reduced building heating requirements under a warming climate.

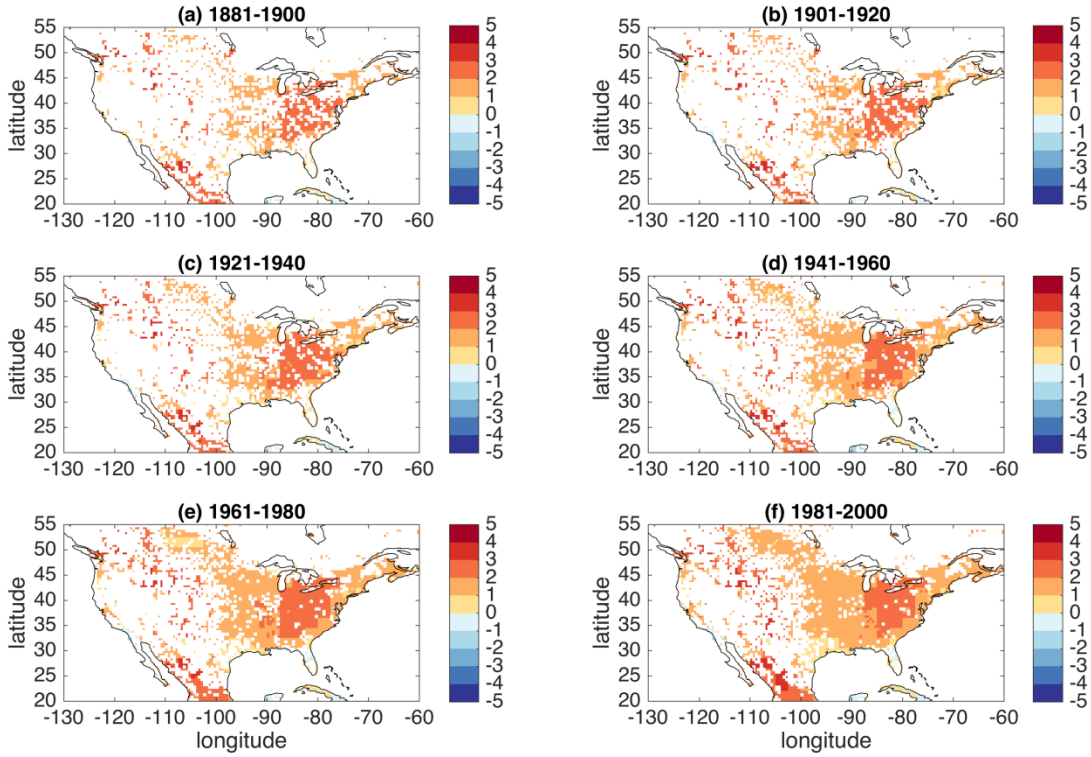

Figure 1: The simulated canopy air temperature difference between urban canyon and natural vegetation in the same grid cell in JJA averaged 1881 to 1900 (a), from 1901 to 1920(b), from 1921 to 1940 (c), from 1941 to 1960 (d), from 1961 to 1980 (e) and from 1981 to 2000 (f). The unit is °C.

Publications:

D. Li, S. Malyshev, and Elena Shevliakova: Exploring historical and future urban climate in the Earth System Modeling framework. Part I: model development and evaluation. J. of Advances in Modeling Earth Systems, in review.

D. Li, S. Malyshev, and Elena Shevliakova: Exploring historical and future urban climate in the Earth System Modeling framework. Part II: impact of urban land use over the Continental United States, J. of Advances in Modeling Earth Systems, in review.

Progress Report Title: **Ozone and Secondary Organic Aerosols over Southeast US**

Principal Investigator: Jingqiu Mao (Princeton Associate Research Scholar)

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

Other Participating Researchers: Songmiao Fan (GFDL), Arlene Fiore (Columbia U.), Jingyi Li (Princeton)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: To understand the interaction between natural and anthropogenic emissions over Southeast US

Methods and Results/Accomplishments:

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

We have hired a postdoc (Jingyi Li) with the grant funded by NOAA Climate Program Office (Mao is the PI). Dr. Jingyi Li is now working with Mao on comparing model results to field observations in Southeast US. She has given a talk at AGU fall meeting 2015, and submitted a paper to GRL on this work. She has also implemented a new version of Fast-JX (v7.1) in GFDL AM3 model. Two more papers are in the pipeline for her work.

We have developed a new secondary organic aerosol (SOA) module for GFDL AM4 model, coupled with newly developed gas-phase chemistry. This module represents the up-to-date knowledge on SOA formation.

We organized a workshop at GFDL with a grant from National Science Foundation (June, 2015). We also received travel support from EPA, NOAA and CICS/Princeton.

We have started a new project on coupling land model (LM3) with biogenic emission (MGEAN). Some preliminary results have been presented at the AGU and GEIA meetings.

During the course of this work, we have published over ten papers.

Outreach Activities: Became a doctoral committee member for a Ph.D. student, Kenneth Christian, at Penn State University; Started the supervision of a recently recruited postdoc, Jingyi Li, with my NOAA grant.

Publications:

Li., J. , J. Mao, R. A. Washenfelder, S. S. Brown , J. Kaiser, F. N. Keutsch, R. Volkamer, G. M. Wolfe and coauthors (2016), Observational constraints on glyoxal production from isoprene oxidation and its contribution to organic aerosol over the Southeastern United States, submitted.

Mao, J. et al. (2016), Southeast Atmosphere Studies Workshop: Intensive Observation Period Modeling to Improve Mechanistic Representation of Trends, Current Pollution Reports, Invited contribution, to be submitted.

Mao, J., S.-M. Fan, and L. W. Horowitz (2016), Fe speciation in aerosols sustained by HO2 uptake, submitted.

Nicely J., and many others including J. Mao. (2016), An Observationally Constrained Evaluation of the Oxidative Capacity in the Tropical Western Pacific Troposphere, Journal of Geophysical Research: Atmospheres, submitted.

M. C. Barth, M. M. Bela, A. Fried, P. O. Wennberg, J. D. Crounse, J. M. St. Clair, N. J. Blake, D. R. Blake, C. R. Homeyer, W. H. Brune, L. Zhang, J. Mao, X. Ren, and coauthors (2016), Convective Transport and Scavenging of Peroxides by Thunderstorms Observed over the Central U.S. during DC3, Journal of Geophysical Research: Atmospheres, submitted.

Wolfe, G. M., J. Kaiser, T. F. Hanisco, F. N. Keutsch, J. A. de Gouw, J. Gilman, M. Graus, C. D. Hatch, J. Holloway, L. Horowitz, B. H. Lee, B. Lerner, F. Lopez-Hilifiker, J. Mao, and coauthors (2016), Formaldehyde production from isoprene oxidation across NOx regimes, Atmos. Chem. Phys., 16(4), 2597-2610, doi:10.5194/acp-16-2597-2016.

Paulot, F., P. Ginoux, W. F. Cooke, L. J. Donner, S. Fan, M. Lin, J. Mao, V. Naik, and L. W. Horowitz (2016), Sensitivity of nitrate aerosols to ammonia emissions and to nitrate chemistry: implications for present and future nitrate optical depth, Atmos. Chem. Phys., 16, 1459-1477.

Fisher, J., D. Jacob, J. Mao and coauthors (2016), Organic nitrate chemistry and its implications for nitrogen budgets in an isoprene- and monoterpene-rich atmosphere: constraints from aircraft (SEAC4RS) and ground-based (SOAS) observations in the Southeast US, Atmos. Chem. Phys. Discuss., 2016, 1-38, doi:10.5194/acp-2016-52.

Warneke C., M., Trainer, J.A., de Gouw, J. Mao, and coauthors (2016): Instrumentation and Measurement Strategy for the NOAA SENEX Aircraft Campaign as Part of the Southeast Atmosphere Study 2013, Atmos. Meas. Tech. Discuss., 1-39, doi:10.5194/amt-2015-388.

Nault, B. A. Nault, C. Garland, P. J. Wooldridge, D. R. Blake, W. H. Brune , J. Mao, R. C. Cohen and coauthors (2015), Observational constraints on the oxidation of NOx in the upper troposphere, The Journal of Physical Chemistry A, doi:10.1021/acs.jpca.5b07824.

Mao, J., A.M. Carlton, L. W. Horowitz and coauthors, Southeast Atmosphere Studies Workshop 2015, IGAC Newsletter, 2015.

Alvarado, M., J. Mao, and coauthors (2015) : Advancing atmospheric chemistry through the use of satellite observations from the cross-track infrared sounder (CrIS), Report of the CrIS Atmospheric Chemistry Data User's workshop, NOAA Program Office, doi:10.7289/V50V89SS.

Fu, T., Y. Zheng, F. Paulot, J. Mao, and R. M. Yantosca (2015): Sensitivity of Southeast U.S. surface ozone to large-scale warming is positive but variable, Nature Climate Change, 10.1038/nclimate2567.

Arnold, S.R., L.K. Emmons, S.A. Monks, K.S. Law, D.A. Ridley, S. Turquety, S. Tilmes, J.L. Thomas, I. Bouarar, J. Flemming, V. Huijnen, J. Mao, and coauthors (2015): Biomass burning influence on high latitude tropospheric ozone and reactive nitrogen in summer 2008: a multi-model analysis based on POLMIP simulations, Atmos. Chem. Phys., 15(11), 6047-6068.

Emmons, L. K., Arnold, S. R., Monks, S. A., J. Mao, and coauthors (2015): The POLARCAT Model Intercomparison Project (POLMIP): overview and evaluation with observations, Atmos. Chem. Phys., 15(12), 6721-6744.

Monks, S.A., S.R. Arnold, L.K. Emmons, K.S. Law, S. Turquety, B.N. Duncan, J. Flemming, V. Huijnen, S. Tilmes, J. Langner, J. Mao, and coauthors (2015): Multi-model study of chemical and physical controls on transport of anthropogenic and biomass burning pollution to the Arctic, Atmos. Chem. Phys., 15(6), 3575-3603.

Presentations:

Mao, J. (Invited) University of Alaska Fairbanks (04/2016) Radical chemistry in the troposphere: from air quality to climate change.

Mao, J. (Invited) University of California Riverside (03/2016) Radical chemistry in the troposphere: from air quality to climate change.

Mao, J. (Invited) University of Houston (03/2016) Radical chemistry in the troposphere: from air quality to climate change.

Mao, J. AGU Fall meeting, San Francisco, CA, USA (12/2015) Development of a coupled biogenic emission module in an earth system model.

Mao, J. GEIA meeting, Beijing, China (11/2015) Development of a coupled biogenic emission module in an earth system model.

Mao, J. (Keynote Speaker) Nitrate Radicals and Biogenic Volatile Organic Compounds (VOCs): Oxidation, Mechanisms and Organic Aerosol, Georgia Institute of Technology, Atlanta, GA (06/2015) Organic nitrates and ozone over the Southeast US.

Mao, J. (Invited) ACS spring meeting, symposium "Transformations of Matter in the Troposphere", Denver, CO (03/2015) Observational constraints on isoprene oxidation over Southeast US.

Mao, J. (Invited) University of California Riverside (02/2015) Radical chemistry in the troposphere: from air quality to climate change.

Mao, J. (Invited) NOAA Earth System Research Levorotary, Boulder, CO (01/2015) Oxidation of biogenic volatile organic compounds over Southeast US: a modeling perspective.

Progress Report Title: **Changes in Bottom Water Formation in the Western Ross Sea Due to the Melting of Ice Shelves in West Antarctica**

Principal Investigator: Gustavo Marques (Princeton Postdoctoral Research Associate)

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

Other Participating Researchers: Sarah Purkey (LDEO, Columbia University)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: Investigate how the melting of ice shelves in West Antarctica affects the formation and export of dense shelf water in the western Ross Sea

Methods and Results/Accomplishments:

We use a global 1/8 degree isopycnal ocean and sea-ice general circulation model (MOM6 and SIS2), forced with hourly MERRA GEOS-5 atmospheric data from 1992-2014. Unique features of the model include: 1) thermodynamic coupling with Antarctic ice shelves; 2) a land model which incorporates a terrain-based hydrologic river and lake network; 3) an iceberg model; and 4) sea-ice constraint using freshwater flux increments.

Computed ice shelves melt rates are in good agreement with estimates derived from observations. In particular, the model shows a rapid increase in melt rate in the West Antarctic ice shelves starting around year 2000. One of the consequences of this strong melting is the formation of a coastal gravity current that carries freshwater towards the Ross Sea (Fig. 1). The observed salinity of dense shelf water (DSW) in the southwest Ross Sea has declined by 0.03 per decade from 1958 to 2000 (Jacobs and Giulivi, 2010). Our analysis supports the previous hypothesis that the freshening is a result of the accelerated input of glacial meltwater in the West Antarctic region.

In terms of bottom water formation, the model is able to capture the export of DSW through the main troughs in the western Ross Sea (Fig. 1 top), although the modeled fluxes are low compared to the observations. Nonetheless, consistent with observations (Gordon and Huber, 2015), the simulation shows a significant decrease in the offshore transport of DSW after 2005. A snapshot of bottom temperature taken at the end of the run clearly highlights how bottom water export has decreased (Fig. 1 bottom). We hypothesize that the accelerated input of glacial meltwater is the primary reason for the variability in the offshore transport of DSW. However, additional factors, such as changes in the strength of the polar easterlies, may have also contributed to the decrease in bottom water export and this is will be investigated in the near future.

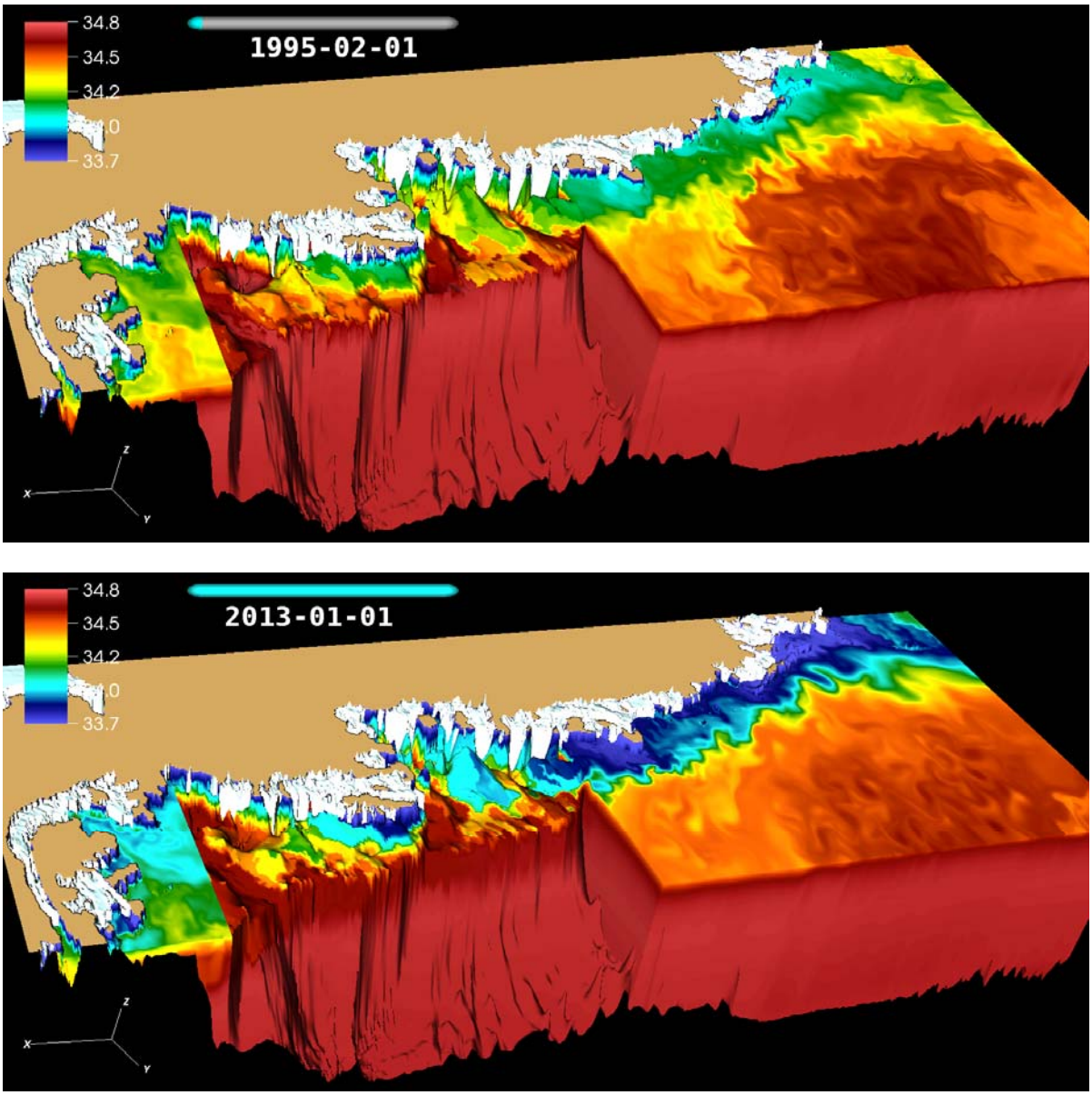

Figure 1: 3D view of the salinity field in the West Antarctic region at two different times. The maps display values at the bottom and below the mixed layer (z ~ -400 m). Ice shelves are shown in white.

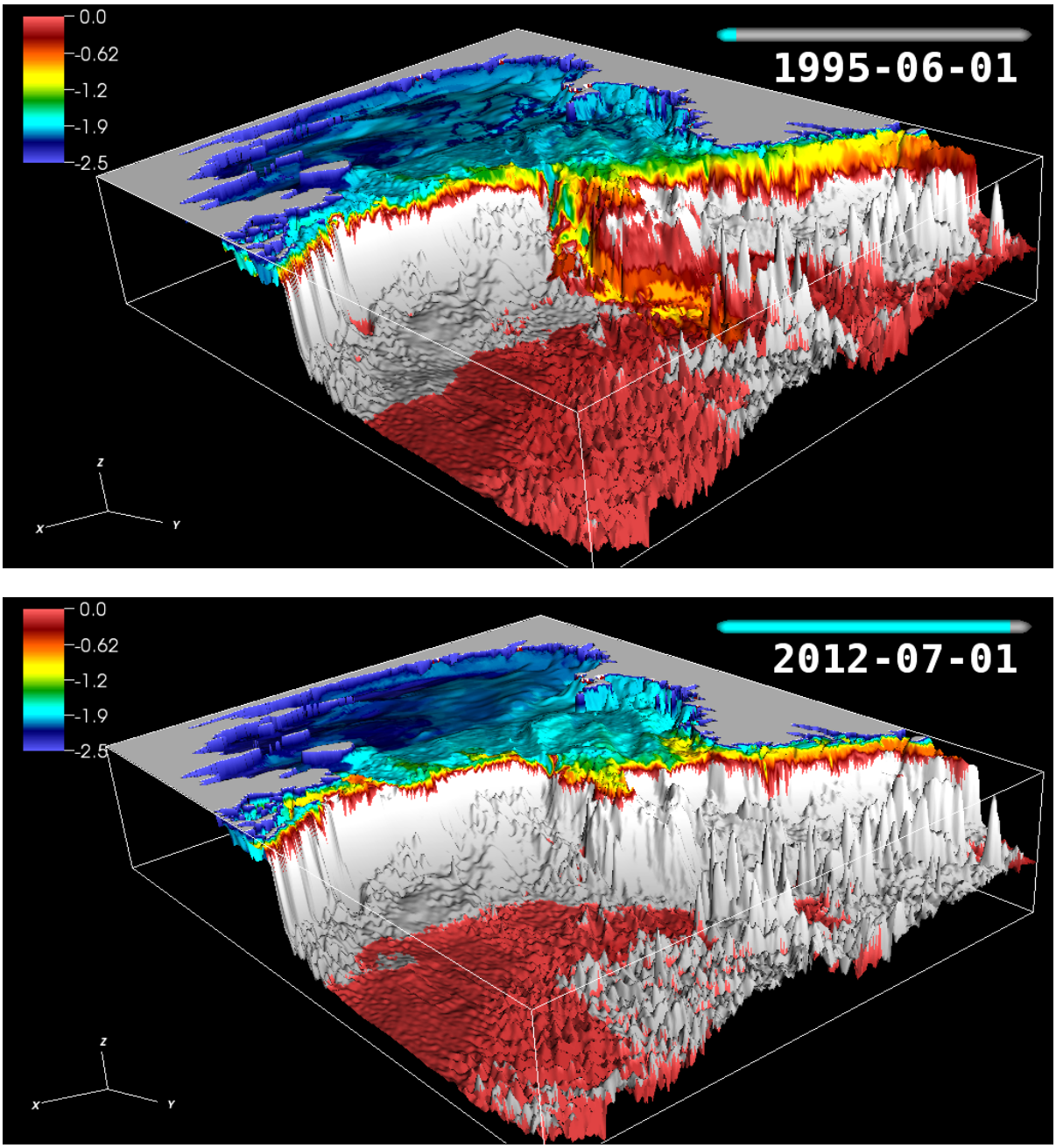

Figure 2: Snapshots of bottom temperature (^{o}C) in the Ross Sea at two different times. Values outside the range -2.5 to 0 ^{o}C have been masked.

Outreach Activities: Poster presentation on the GFDL Winter 2016 Poster Expo held at GFDL on January, 27th 2016.

References:

Jacobs, S.S. and Giulivi, C.F., 2010. Large multidecadal salinity trends near the Pacific-Antarctic continental margin. Journal of Climate, 23(17), pp.4508-4524.

Gordon, A.L., Huber, B.A. and Busecke, J., 2015. Bottom water export from the western Ross Sea, 2007 through 2010. Geophysical Research Letters,42(13), pp.5387-5394.

Progress Report Title: **Parameterization of Internal Wave-Driven Mixing in GFDL's Global Climate Model**

Principal Investigator: Benjamin D. Mater (Princeton Postdoctoral Research Associate)

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

Other Participating Researchers: Jonas Nycander (U. Stockholm)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An informed society anticipating and responding to climate and its impacts

Objectives: To develop, test, and implement dynamically appropriate parameterizations for diapycnal mixing due to internal-wave breaking for use in global climate models

Methods and Results/Accomplishments:

Our research has been to develop a physically-based parameterization of ocean mixing due to breaking internal waves for use in GFDL's global ocean model. In particular we are interested in far-field propagating low-mode internal waves of tidal frequencies (i.e., the internal tides). Because the generation, propagation, breaking, and mixing associated with these waves involves an array of physical processes, our approach has been to build an adaptable framework into which various "sub-parameterizations" can be invoked or "plugged in." The goal, therefore, is not to explicitly represent every process, but rather provide a vehicle for introducing new and improved representations of these processes into the global ocean model. The effort is heavily supported by the products of and in collaboration with the Climate Process Team on internal wave-driven mixing headed by Jennifer MacKinnon of Scripps Institute of Oceanography. Since the last CICS report, the framework has been completed and implemented in GFDL's MOM6 ocean model. The work has been presented at both the final annual CPT meeting in October 2015 and at the Ocean Sciences Meeting in February 2016. A manuscript describing the parameterization framework is currently in development.

Outreach Activities: Ocean Fun Days 2015 (NJ Sea Grant Consortium)

Progress Report Title: **Improving the Cropland Parameterization in the GFDL Land Model LM3**

Principal Investigator: Denise L. Mauzerall (Princeton Professor)

CICS/GFDL Collaborator: Xin Zhang (Princeton), Elena Shevliakova (Princeton/GFDL), Sergey Malyshev (Princeton)

Award Number: NA14OAR4320106

Task III: Individual Projects

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: The main objectives of this grant are to improve the GFDL land model version 3 (LM3) by: 1) advancing the crop-specific parameterizations of phenology, physiology, and management characteristics; and 2) enabling the LM3 to use information provided by the CMIP6 land-use and management scenario prototype, which was released in January 2015 through the CMIP6 Land Use Model Intercomparison Project (LUMIP).

Methods and Results/Accomplishments:

In its previous form LM3 only had tiles designated as cropland, but did not have specific crop types. However, the impact of various crops on the earth system vary considerably due to differences in their biophysical and biogeochemical processes. We therefore introduced a crop module to input information on global crop distributions, and improved the parameterization of major crop types, including crop phenology, planting and harvesting dates, and nitrogen fertilization rates.

The distribution of 26 major crop types on a 5' by 5' grid from MRICA 2000 (Portmann et al., 2010) was imported into LM3 and we implemented a flexible framework so that the crop distribution information could be used in different grid-designs. Two methodologies are implemented to determine the planting and harvesting dates, one is based on global survey information on the planting and harvest dates for 26 crop types (Sacks et al., 2010), the other is based on historical climate conditions and day-to-day weather conditions (Bondeau et al., 2007; Waha et al., 2012). Two harvesting treatments for annual and perennial crops from Drewniak et al. (2013) were implemented: 1) harvested components -- whether the wood, leaf, or root is harvested and 2) harvest index -- the percentage of the biomass harvested as crop product.

Regarding fertilization, we assembled information from FAO (2014) and Heffer (2009, 2013) to provide the first set of estimates for nitrogen fertilization rates by country and crop categories from 1961-2011. The results were published in Zhang et al. (2015). Using this data and in collaboration with Steve Frolking and George Hurtt, we developed spatially explicit and long term (from 1900s to 2050) nitrogen fertilizer input scenarios for LM3. The nitrogen fertilizer input scenarios, along with the crop yield records acquired from FAO (2014), can now be used in LM3 to better simulate crop growth in response to nitrogen addition.

Outreach Activities: Xin Zhang served as a panelist at the Princeton Food Entrepreneurship Symposium, Feb. 19, 2016. The purpose of the conference was to engage undergraduate and graduate students in research and outreach efforts related to Food and the Environment.

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Sacks, W.J., Deryng, D., Foley, J.A. and Ramankutty, N., 2010. Crop planting dates: an analysis of global patterns. Glob Ecol Biogeogr, 19(5): 607-620.

Waha, K., Van Bussel, L., Müller, C. and Bondeau, A., 2012. Climate-driven simulation of global crop sowing dates. Glob Ecol Biogeogr, 21(2): 247-259.

Zhang, X. et al., 2015. Managing nitrogen for sustainable development. Nature. 528(7580): 51-59. doi: 10.1038/nature15743.

Publications:

X Zhang, EA Davidson, DL Mauzerall, TD Searchinger, P Dumas, Y Shen, 2015. Managing Nitrogen for Sustainable Development, Nature, 528(7580): 51-59. doi: 10.1038/nature15743.

Presentations:

X Zhang, DL Mauzerall, EA Davidson, Managing Nitrogen Managing Nitrogen for Sustainable Intensification of Crop Production, The Second International Conference on Global Food Security, Ithaca, NY, USA, Oct. 13, 2015

DL Mauzerall, Nitrogen, Ozone and Water: Key Factors Impacting Sustainable Intensification of Crop Production, Food Security Group seminar, Stanford University, February 22, 2016.

DL Mauzerall, X Zhang, EA Davidson, TD Searchinger, P Dumas, Y Shen, Managing Nitrogen for Sustainable Development, EMBO conference, Nitrogen Nutrition of Plants, Montpellier, France, August 2016.

Progress Report Title: **Critical Processes and Parameters Governing the Spring Bloom In Antarctica**

Principal Investigator: François Morel (Princeton Professor)

CICS/GFDL Collaborator: John Dunne and Charles Stock (GFDL), Johanna Goldman (Princeton)

Other Participating Researchers: Jodi Young (Princeton)

Award Number: NA14OAR4320106

Task III: Individual Projects

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: Our aim is to assess the sensitivity of Earth System Models with respect to temperature and CO_2-driven physiological mechanisms of phytoplankton growth, diversity, elemental composition, and ecological functioning under bloom conditions of extremely low temperature, slow respiration, high biomass, and low pCO_2. Determination of the physiological constraints on primary production in polar ocean environments will be achieved through the laboratory cultured psychrophilic phytoplankton.

Methods and Results/Accomplishments:

During the spring/summer season on the Western Antarctic Peninsula, phytoplankton blooms occur between the months of December to March but the timing and magnitude of the bloom varies year to year with little predictability (Schofield, 2014). During the growing season, day length varies from 20 h of light in December to only 12 h in March. To understand the effect of day length on phytoplankton physiology, cultures of the psychrophilic diatom, *Proboscia alata*, were grown at 0 °C under a 12:12 light:dark cycle, in nutrient replete media, to emulate the coastal conditions in March, during the latter half of the growing season near Palmer Station, Antarctica. Generation of biomass (particulate organic carbon, POC), chlorophyll concentrations, protein content and photosynthetic efficiency were measured, along with rates of gross and net primary production. Rates of net oxygen production (ΔO_2/Ar, NP) and gross oxygen production (generation of ^{18}O gas from the splitting of $H_2{}^{18}O$, GP) were compared with ^{14}C fixation rates at 20, 40 and 60 min. Respiration was calculated as the difference between NP and GP.

Figure 1 shows a subset of our results. Both GP and NP show diel regulation that is driven by circadian rhythm rather than by light intensity (which is a constant intensity during the 12 h of daylight for this study). GP reaches maximum rate at midday and remains high throughout the afternoon, whereas the rate of NP is similar in the morning and afternoon, with a slight dip at midday. The difference between NP and GP can be explained by increasing rates of respiration throughout the day, from almost no respiration in the morning to ~40% of GP at midday and ~30% of GP in the afternoon. From the results of the ^{14}C assays, recycling (or respiration) of all the newly fixed carbon takes between 40 – 60 min at midday but less than 20 min in the afternoon. Our finding of high GP in the afternoon is similar to that found in the field at Palmer Station during a spring bloom (Goldman *et al.*, 2015). While our finding of increased respiration rates over the day is in agreement with that found in warmer phytoplankton species, the length of time taken to recycle fixed carbon seems to differ between polar and temperate phytoplankton (Halsey and Jones, 2015, Halsey *et al.*, 2010).

Our results from this study highlight the strong diel cycle of primary production that could influence net yields achievable during the large shift in day length over the growing season at high latitudes. Determining mechanisms for energy balance and composition of the carbon pool during a diel cycle in polar phytoplankton is important to understand their intense outbursts of rapid growth, interspersed with extended periods of darkness, which lead to the high productivity of the region. The results from this work are being written up for publication.

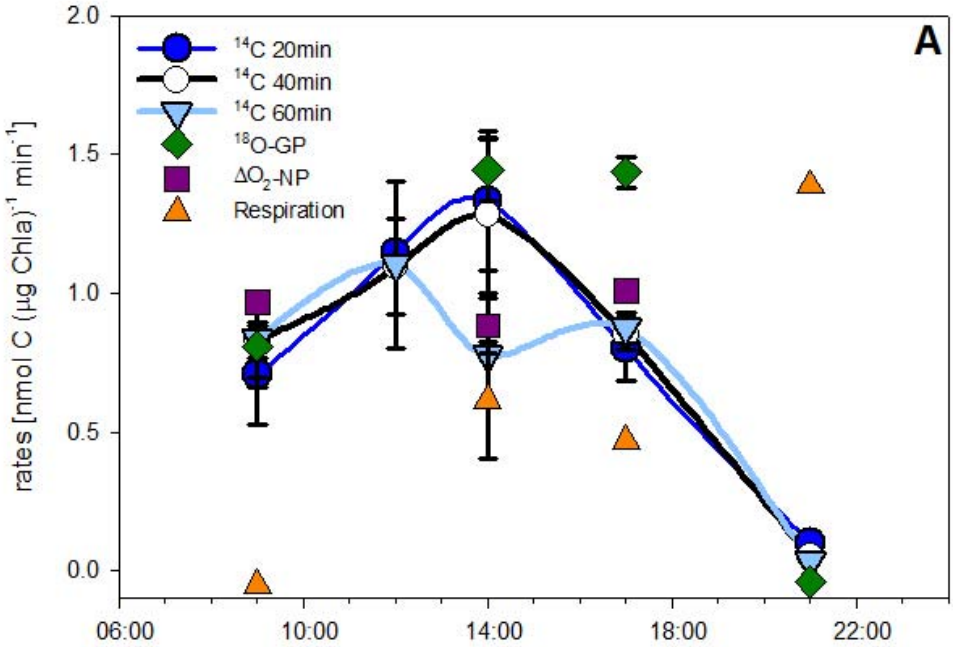


Figure 1: Diel cycle measurements in the polar diatom *Proboscia alata*. Light goes on at 8:00 and goes off at 20:00. (A) productivity measurements normalized to Chlorophyll a. The symbols with lines represent $^{14}CO_2$ assimilation during 20 min (blue circles), 40 min (white circles) and 60 min (light blue inversed triangles). Gross photosynthesis (GP; green diamonds) is measured for 2h via the increase of $^{18}O^{16}O$, Net photosynthesis (NP; purple squares) via change in O_2 concentration, and respiration (orange triangle) is the difference of the two. Error bars represent standard deviation of duplicate

Outreach Activities: Jodi Young participated in the Princeton Women in Geosciences program at Princeton University, including the mentorship of a first-year graduate student (Anna FitzMaurice) of Atmospheric and Oceanic Sciences. This funding also enabled one undergraduate student to gain invaluable experience under the supervision of Jodi Young as part of the Princeton Environmental Institute (PEI) Summer Internships. This internship program offers Princeton undergraduates a unique opportunity to complement their academic interests with hands-on and engaging research through the summer months. The student (Derek Ou) had an independent research project to develop techniques for the accurate measurement of cell cycling in the phytoplankton cultures. The PEI Internships are paid summer assignments, which are full-time for a minimum of eight contiguous weeks. In addition, Jodi Young and François Morel supervised a successful Senior Thesis of a Geosciences undergraduate (Tiffany Cheung) conducting complementary experiments on temperate phytoplankton species to draw comparisons with results from this proposal.

References:

Goldman JA, Kranz SA, Young JN, Tortell PD, Stanley RH, Bender ML, Morel FM. 2015. Gross and net production during the spring bloom along the Western Antarctic Peninsula. New Phytologist 205(1): 182-191.

Halsey KH, Jones BM. 2015. Phytoplankton strategies for photosynthetic energy allocation. Annual review of marine science 7: 265-297.

Halsey KH, Milligan AJ, Behrenfeld MJ. 2010. Physiological optimization underlies growth rate independent chlorophyll-specific gross and net primary production. Photosynthesis research 103(2): 125 137.

Schofield, O. (2014) Chlorophyll and phaeopigments from water column samples, collected at selected depths aboard Palmer LTER annual cruises off the coast of the Western Antarctic Peninsula 1991-present. Palmer Station Antarctica LTER: Long Term Ecological Research Network.

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)

Other Participating Researchers: Madeleine Hamann and Matthew Alford (Scripps)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

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 am conducting a study of the parameter space of internal wave interaction with canyon topography. This parameter study has a two-pronged approach: ray-tracing theory and high-resolution GCM simulations. We use very idealized V-shape canyons so that we can identify the leading topographic parameters controlling the amount of incoming wave energy transferred to mixing. 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. Additionally, this algorithm allows us to track ray density, a proxy for energy density, another metric for potential instability. Thus, this ray-tracing algorithm allows us to monitor the change in wavenumbers upon subsequent reflections off of topography, as well as to explore scenarios in which the wave is trapped in the canyon topography – both processed by which canyons could lead to internal wave breaking and subsequent mixing.

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, of M2-tidal frequency, propagating towards a continental slope canyon. The wave is allowed interact with and scatter off the topography. Model simulations are conducted with two setups: low-resolution and hydrostatic and high-resolution and non-hydrostatic. We show that the energy loss from the wave field is comparable for both types of model setup. To quantify the energy loss we calculate both the divergence of the energy flux over the faces of the canyon region as well as the dissipation integrated over the entire canyon. We also use the Richardson number to identify regions within the canyon where there is the potential for instabilities to form. Ray tracing is conducted for each of the model simulations to form a direct comparison.

Using both the ray tracing algorithm and MITgcm simulations, we find that, for a certain parameter space, continental slope canyons are capable of dissipating more energy than the surrounding continental slope. Specifically, we find that flat bottom canyons (canyons with vertical sidewalls) are most efficient at dissipating internal tidal energy. This class of canyons is most efficient at dissipating the internal waves

when the length of the canyon is one-half to four times the length of the canyon. As the sidewall steepness is decreased, from vertical walls to near-critical walls, less internal wave energy is dissipated. The mechanism for energy loss in the flat bottom (vertical side wall) canyons is ray trapping, and thus high energy concentration, while for the more gradual canyon sidewalls both ray trapping and increased vertical wavenumber are both potential mechanisms for instability. We are currently preparing these results for publication. While initial model simulations have a relatively simple V-shaped geometry, future simulations will more closely mirror observed submarine canyons, such as Veitch and La Jolla Canyons (collaboration with M. Hamann and M. Alford, SIO).

Once this parameter space dependence has been validated in the realistic continental slope canyons, we will formalize the appropriate parameterization for ocean global circulation models and implement it in one of the GFDL ocean models.

Outreach Activities: Mentored undergraduate summer and Junior project with Sonya Legg (Princeton University Junior, Paul Yi); Volunteered at 2015 Ocean Fun Day at Sandy Hook Beach, NJ; Taught weekly math and science classes at the Trenton Area Soup Kitchen for adults returning to the classroom to receive their high school equivalency degree; Served on the Advisory Committee at the Trenton Area Soup Kitchen, which oversees all curriculum for the adult education program

Presentations:

Nazarian, R., and S. Legg, February 24, 2016: Internal Wave Scattering in Continental Slope Canyons: A Parameter Space Study. American Geophysical Union. 2016 Ocean Sciences Meeting.

Yi, P., S. Legg, and R. Nazarian, February 24, 2016: A Process Study of Tidal Mixing Over Rough Topography. American Geophysical Union. 2016 Ocean Sciences Meeting.

Nazarian, R., and S. Legg, June 16, 2015: A Parameter Space Study of Internal Wave Dynamics in Continental Slope Canyons. American Meteorological Society. Atmospheric and Oceanic Fluid Dynamics Conference.

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

Principal Investigator: Isidoro Orlanski (Princeton Senior Meteorologist)

CICS/GFDL Collaborator: Isaac Held and Fanrong Zeng (GFDL)

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

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (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 (80%)
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts (20%)

Objectives: To understand and quantify the atmosphere extra-tropical climate changes due to Polar and/or Equatorial changes

Methods and Results/Accomplishments:

Climate Change over the Southern Hemisphere: The Tale of five reanalyzes and its ensemble.

Evidence of climate change over the Southern Hemisphere during the last 50 years has been discussed in several articles (IPPC 2014). Climate change has been identified from a variety of diagnostics, using near surface temperature, wind, sea level pressure and rainfall. Recently Solman and Orlanski (2014) based on results derived using the ERA40 reanalysis data-set showed that precipitation changes from 1961-2000 over the subtropical and mid-latitudes were partially explained by changes in the frontal activity, in response to the poleward shift of storm-tracks. Present results are not robust because the lack of large land masses over the Southern Hemisphere preclude the use of direct measurements over a large part of its surface.

Two novel approaches were introduced in the present study: First, the estimation of different metrics that are related by themselves, for example, storm track activity, frontal dry and moist activity, and precipitation. Fronts are related to eddies that compose the storm tracks and precipitation is associated with fronts. Since the assimilation of data from reanalysis is different for each metric, consistent changes between themselves could make the climate change signal more robust. Second, different data sets have been used in this study: Data from five reanalyzes ERA Interim, MERRA2, NCEP/DOE R2, 20CR and CFSR. The period used 1979-2010 benefits from satellite coverage over the vast ocean areas. Still, those data sets have considerable differences between themselves mainly due to the different techniques in data assimilation and model resolution used in each reanalysis. To improve the quality of the results, a simple variance weighted average was used to build an ensemble of all the reanalyzes.

It was concluded definitively that there is a climate change in the summer (ONDJFM) and winter (AMJJAS) months over the Southern Hemisphere. In each season, there is a shift for most of the metrics to the poleward regions. Moreover, it seems the shift for the summer period was induced by ozone depletion, whereas in the winter months, the increase of tropical temperatures due to global warming

seems to be responsible for the poleward move of the weather systems (similar conclusions can be found in Orlanski 2013).

The Anomalous Behavior of Polar Stationary Waves (in collaboration with Isaac Held).

The Arctic region has warmed more than twice as fast as the global average — a phenomenon known as Arctic amplification (a review article in Nature Geosciences by J. Cohen et al 2014). The rapid Arctic warming has contributed to dramatic melting of Arctic sea ice and spring snow cover, at a pace greater than that simulated by climate models. These profound changes to the Arctic system have coincided with a period of ostensibly more frequent extreme weather events across the Northern Hemisphere mid-latitudes, including severe winters. The possibility of a link between Arctic change and mid-latitude weather has spurred research activities that reveal three potential dynamical pathways linking Arctic amplification to mid-latitude weather: changes in storm tracks, the jet stream, and planetary waves and their associated energy propagation. Through changes in these key atmospheric features, it is possible, in principle, for sea ice and snow cover to jointly influence mid-latitude weather. However, because of incomplete knowledge of how high-latitude climate change influences these phenomena, combined with sparse and short data records, and imperfect models, large uncertainties regarding the magnitude of such an influence remain.

We designed an experiment with the use of a spectral global model and a modified Held Suarez climatology. To the model conditions used in the control, we added a local thermal forcing in the temperature equation. The shallow localized thermal forcing is introduced at different longitudes in the high latitudes center 70N and run to a statistical equilibrium The response of these sensitivity runs shows a considerable longitudinal asymmetry. The local forcing acting in different places of the stationary waves of the control solution produced a considerable difference in the deep atmospheric response thus affecting differently the middle latitudes circulation. These results could explain why there is variability in the influence of the AA in the middle latitudes.

References:

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.

Judah Cohen, James A. Screen, Jason C. Furtado, Mathew Barlow, David Whittleston, Dim Coumou, Jennifer Francis, Klaus Dethloff, Dara Entekhabi, James Overland and Justin Jones (2014): Recent Arctic amplification and extreme mid-latitude weather. Nature Geoscience 7, 627–637. (2014), doi:10.1038/ngeo2234).

Publications:

Solman S. And I. Orlanski. 2016: Climate Change over the Extratropical Southern Hemisphere: The tale from an ensemble of reanalysis datasets, DOI: 10.1175/JCLI-D-15-0588.1.

Progress Report Title: **Impact of Land-Use on Surface Particulate Matter and Nitrogen Deposition**

Principal Investigator: Fabien Paulot (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Larry Horowitz (GFDL), Sergey Malyshev (Princeton), Elena Shevliakova (Princeton/GFDL)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: I am contributing to the development of a fully interactive nitrogen cycle within the GFDL Earth System model. In particular, I am working on the impact of land-use and land management on nitrogen deposition.

Methods and Results/Accomplishments:

I have implemented a representation of the surface removal of gases and aerosols in the GFDL land model. I am using this new model to examine the impact of land-use (e.g., transition from forest to pasture), land-management (e.g., cropping schedule), and climate on nitrogen deposition and surface air pollution.

I find that natural vegetation receives more oxidized nitrogen (primarily from fossil fuel combustion) than managed vegetation (crop, pasture) and water bodies. This implies that oxidized nitrogen deposition to natural ecosystems (e.g., national parks) may be underestimated in the US, where unmanaged and managed land often coexist within a model grid box (~100-200km horizontal resolution). Land use has a smaller impact on reduced nitrogen (primarily from agriculture) deposition. In the context of increasing awareness about the adverse impact of excess of N deposition for biodiversity and ecosystem services, these results suggest that the ongoing decline of oxidized nitrogen emissions may be especially beneficial for natural ecosystems. In contrast, the shift from oxidized to reduced nitrogen emissions will present challenges for reducing nitrogen deposition for water bodies.

In the coming months, I will use this new dry deposition model to examine the impact of land-use for surface particulate matter (in particular ammonium nitrate) and for the impact of N deposition for soil N and N runoff (in collaboration with Benjamin Sulman (CICS)).

Publications:

Paulot, F., Ginoux, P., Cooke, W. F., Donner, L. J., Fan, S., Lin, M.-Y., Mao, J., Naik, V., and Horowitz, L. W.: Sensitivity of nitrate aerosols to ammonia emissions and to nitrate chemistry: implications for present and future nitrate optical depth, Atmos. Chem. Phys., 16, 1459-1477, doi:10.5194/acp-16-1459-2016, 2016.

Presentations:

Dry deposition of nitrogen: impact of climate and land-use change, CCMI Meeting, Rome (2015).

Sensitivity of nitrate aerosols to ammonia emissions and to nitrate chemistry: Implications for present and future nitrate optical depth, AEROCOM meeting, Rome (2015).

Global oceanic emission of ammonia: Constraints from seawater and atmospheric observations, OCB Meeting, Woods Hole (July 2015).

Progress Report Title: **Implementation and Testing of Regional and Global Dust Forecasting**

Principal Investigator: Carlos Perez Garcia-Pando (NASA-GISS/Columbia Associate Research Scientist)

CICS/GFDL Collaborator: Paul Ginoux (GFDL), Adrien Deroubaix (Princeton)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Weather-Ready Nation Goal: Society is Prepared for and Responds to Weather-Related Events

Objectives: We aim at improving dust prediction capabilities and quantify natural and anthropogenic dust contributions at regional and global levels.

Methods and Results/Accomplishments:

The identification of dust sources is one of the crucial aspects for representing dust mobilization in models. Traditionally, models used aridity as a criterion to identify potential dust sources. Satellite retrievals subsequently showed that the most prolific sources occupy only a small fraction of arid regions. These so-called 'preferential sources' are found within enclosed basins, where easily eroded soil particles have accumulated after fluvial erosion of the surrounding highlands. The implementation of preferential source functions based on topography (Ginoux et al. 2001) has significantly improved the skill of models by approximately locating large-scale natural sources. However, this approach is limited for representing small-scale dust sources and regions where the main sources are anthropogenic (cropland and pasture), which can make a significant contribution to the dust load.

I have implemented a new global-scale high-resolution mapping of dust sources based on high- resolution MODIS Collection (Ginoux et al., 2012) within the NMMB/BSC-CTM model (Perez et al., 2011). The new source map combines the MODIS data with land use databases to distinguish between natural and anthropogenic (primarily agricultural) dust sources. The model is now able to simulate natural and anthropogenic dust as separate tracers. In addition to the new source and the separate tracers, I have updated some model schemes (a mass fixer for the tracer advection scheme, and updated the available explicit and implicit sedimentation numerical schemes). I have also included additional options for the dust emission scheme (in addition to the NMMB scheme, options for the well-known GOCART scheme and the new KOK scheme are available), a monthly MODIS LAI dataset and new emitted size distribution assumptions.

The results highlight the challenge to constrain the anthropogenic fraction of dust as it strongly depends on assumptions regarding the implementation of the new source, the emission scheme and the treatment of vegetation and soil humidity. Together with Paul Ginoux, I have co- mentored a postdoctoral scientist (Adrien Deroubaix) who has mainly performed the model evaluation based on ground based measurements (Aerosol Optical Depth from the NASA- AERONET network and dust concentration measured in the Sahel and in the Caribbean), and satellite retrievals (NASA-MODIS Deep-blue). The year 2012 was extensively studied at a daily time step. Furthermore, a 5-year average (2010-2014) is being analyzed in order to investigate climatological features of the natural

and anthropogenic dust cycles. An article presenting this evaluation and an analysis of the uncertainties associated to the emission schemes is in preparation.

I am also contributing to the study of the very intense dust storm that affected Israel in September 2015 by testing high-resolution (2 km) dust and weather simulations with the NMMB/BSC-CTM model. The results show that the model is able to capture the main features of the event, including the suite of cold pools that are clearly visible from measurements. This represents the first modeling study of "haboobs" in the Middle East. It will serve as test bed for the NMMB to predict such extreme events over the US. This research is partially supported by NOAA/NWS Next Generation Global Prediction System (NGGPS) project.

References:

Ginoux, P., M Chin, I Tegen, J M Prospero, B Holben, O Dubovik, and Shian-Jiann Lin, 2001: Sources and distributions of dust aerosols simulated with the GOCART model. Journal of Geophysical Research, 106(D17), 20,255-20,273.

Ginoux, P., Prospero, J. M., Gill, T. E., Hsu, N. C., and Zhao, M.: Global-Scale Attribution of Anthropogenic and Natural Dust Sources and Their Emission Rates Based on Modis Deep Blue Aerosol Products, pp. 1–36, doi:10.1029/2012RG000388.

Perez, C., Haustein, K., Janjic, Z., Jorba, O., Huneeus, N., Baldasano, J. M., Black, T., Basart, S., Nickovic, S., Miller, R. L., Perlwitz, J. P., Schulz, M., and Thomson, M.: Atmospheric dust modeling from meso to global scales with the online NMMB/BSC-Dust model; Part 1: Model description, annual simulations and evaluation, Atmospheric Chemistry and Physics, 11, 13001–13027, doi:10.5194/acp-11-13001-2011, 2011.

Progress Report Title: **Detection and Attribution of Dust Sources to Understand Dust Effects on Climate and Air Quality**

Principal Investigator: Bing Pu (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Paul Ginoux (GFDL), Fabien Paulot (Princeton)

Other Participating Researchers: Mian Chin (NASA), Arlindo da Silva (NASA), N. Christina Hsu (NASA)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: To understand how dust emission and optical depth vary in North America and the interactions between dust and climate.

Methods and Results/Accomplishments:

My current research focuses on understanding the variations of dust optical depth over the United States and its connection with drought development. In this study I use both observational data, including satellite (e.g., MODIS Aqua and Terra, AVHRR) and station (e.g., IMPROVE) data, reanalyzes, and GFDL climate model, which will be used to examine the feedbacks and interactions between dust emission and the climate. Specifically, we will investigate several severe drought events in U.S. and how those events interact with dust emission.

In the past three months, I'm learning to use the GFDL model, including running test cases, and analyzed some coupled model output. It is found that the dust emission over the U.S. is largely affect by near surface wind and precipitation. Over the Great Plains, there is also a positive connection between the wintertime dust optical depth and springtime precipitation in the model, indicating a possible feedback from dust emission to the climate. Next step will be running the new version of the model to simulate the historical drought events, e.g., the 1930s dust bowl, and examine influences of dust on drought versus other remote forcings such as sea surface temperatures.

I also processed IMPROVE station data of fine dust concentration and working on understanding the trend of dust concentration and possible causes in the recent two decades, which will also provide some insights on our model simulations in the next step.

Progress Report Title: **Understanding Tropical Pacific Biases in Climate Simulations and Initialized Predictions**

Principal Investigator: Sulagna Ray (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Andrew T. Wittenberg (GFDL)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: The project is to advance understanding, simulation, and forecasting of tropical Pacific climate and its variability. Its objectives are to (1) diagnose the spatiotemporal structure of tropical Pacific climatological biases in GFDL's coupled simulations, reanalysis systems, and forecasts; (2) identify and understand how the biases can be linked to model parameterizations, assimilation methods, and observational inputs; (3) understand the processes which seed and amplify tropical Pacific biases; (4) assess how these biases affect the simulation and prediction of climate fluctuations; and (5) develop methods to mitigate these biases and their impacts on forecast skill.

Methods and Results/Accomplishments:

In year 1 we took advantage of available GFDL computer resources to analyze the full suite of FLOR simulations and perform additional model run: 1) A 30-year segment of FLOR control run with fixed 1990 forcings diagnosed at daily frequency, with all the terms necessary for a comprehensive ocean heat budget. A 1-year segment was also run with output at hourly frequency, to characterize the diurnal cycle heat budget and its interactions with longer time scales. 2) A 30-year segment of FLOR climatologically flux-adjusted (FA) control simulation with fixed 1990 forcings was diagnosed at daily frequency, with full heat budget diagnostics.

To evaluate these simulations, we obtained and used numerous observational datasets. These included several 3d ocean reanalyses (WOA.2013, SODA 2.2.4, ECMWF ORA-S4, NCEP GODAS, and GFDL ECDAv3.1), and the OSCAR.v2009 near-surface current analysis, to evaluate the FLOR climatology; and high-frequency temperature and current data from the TAO/TRITON buoys, to evaluate the FLOR diurnal cycle. These ocean datasets were in addition to the large suite of SST and atmospheric datasets (ERA-Interim, GPCP.v2.2, OISST.v2, ERSST.v4, TropFlux.v1) that were already part of our existing GFDL analysis suite.

Intercomparison of the subsurface ocean fields revealed substantial differences among the ocean reanalyses, particularly for the equatorial zonal currents and upwelling. This reflects the significant challenge in reconstructing the real-world currents -- and thus the ocean heat budget -- using sparse observations and imperfect assimilation systems.

To develop a tropical Pacific mixed layer heat budget, we first surveyed the existing methods in the literature; most, including the version currently in use at NCEP (Huang et al. 2010), involved ad-hoc formulations for the mixed-layer entrainment. While these work reasonably well for diagnosing certain aspects like ENSO's deviations from climatology, they prove unsatisfactory for closing the climatological

heat budget -- especially in the presence of strong TIW activity and the diurnal cycle of shortwave radiation, which have only recently been captured in coupled GCMs.

We proceed with the exact mixed layer heat budget formulation developed by Lee et al. (JPO, 2004) and Kim et al. (JAOT, 2006). Their method follows the time-varying fluctuations in mixed layer depth to diagnose both entrainment and detrainment, and also treats advection in a "relative-flux form" to more clearly identify the external drivers of regional temperature changes (in contrast to simple "advective form" redistributions of heat within the given region). Using the intense-diagnostic 30yr epochs that we performed for the FLOR and FLOR-FA control runs, we implemented the Kim et al. (2006) heat budget and achieved exact closure for hourly data, and also excellent closure for daily-means. These new diagnostics have proved to be a powerful new tool for diagnosing the ocean biases in FLOR, and should be a boon for analysis of future coupled models as well.

Analysis of the FLOR ocean heat budget has already highlighted the critical importance of vertical diffusion, particularly at night when the tropical ocean mixed layer is deep. The cooling from vertical diffusion is large in regions of equatorial cold bias , implying being a source of the cold bias. On decomposing the vertical diffusion into its components having curvature of temperature and the gradient of diffusivity showed that the former dominates the diffusive cooling in the eastern equatorial region. On comparing with the diffusive cooling using the vertical temperature profile from an ocean reanalysis (SODA 2.2.4) reveals more cooling in FLOR indicating the thermal structure being the cause of excess dynamic cooling. The surface heat flux acts only to damp this excess cooling. The source of this cooling in the vertical diffusion is linked to the vertical mixing effect generated locally or remotely via bias in off-equatorial shortwave penetration.

Sub-monthly eddy advection (especially from TIWs in boreal autumn) also has very important rectified effects on the climatological mean state. On analysing the mixed layer heat budget in the western equatorial Pacific reveals a large contribution from the bottom flux during La Nina events in sub-monthly variability, the timing of which matches with the generation of the TIWs in September-November. The analyses reflects the necessity for daily to 5-day averaged fields and their significance in climatological mean state processes. The mixed layer heat budget showed perfect closure using hourly, daily means however monthly means lacked resolving the sub-monthly eddy advection leading to poor closure of the monthly heat budget. This also suggests the necessity of having ocean reanalyses as daily or 5-day average means for comparative analysis using closed heat budget.

References:

Huang, B., Y. Xue, D. Zhang, A. Kumar, and M. J. McPhaden (2010) The NCEP GODAS ocean analysis of the tropical Pacific mixed layer heat budget on seasonal to interannual time scales. J. Clim., 23, 4901-4925.

Kim, S-B., I. Fukumori, and T. Lee (2006) The closure of the ocean mixed layer temperature budget using level-coordinate model fields. J. Atmos and Oceanic Tech., 23, 840-853.

Lee, T., I. Fukumori, and B. Tang (2004) Temperature advection: Internal versus external processes. J. Phys. Ocean., 34, 1936-1944.

Presentations:

Ray, S., and A. T. Wittenberg, 2016: The Equatorial Pacific Warm Pool Mixed Layer Heat Budget. AGU Ocean Sciences Meeting, February, 2016, New Orleans, USA.

Ray, S., and A. T. Wittenberg, 2015: Climatological heat budget of the equatorial Pacific upper ocean in the GFDL FLOR global coupled GCM. NCEP Climate Diagnostic Workshop. October, 2015, Denver, USA.

Progress Report Title: **Development of an Ice-Sheet Model, its Iceberg Component, and Coupling with Other Climate-Model Components**

Principal Investigator: Olga Sergienko (Princeton Research Glaciologist)

CICS/GFDL Collaborator: Alistair Adcroft (Princeton), Robert Hallberg (GFDL), Marianne Haseloff (Princeton), Matthew Harrison (GFDL), Alon Stern (Princeton)

Other Participating Researchers: Douglas R. MacAyeal (University of Chicago), Alison Banwell (Cambridge University)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: Improve understanding of the fundamental mechanisms governing behavior of ice sheets, its components (ice streams, ice shelves, icebergs) and their interactions with other components of the climate system

Methods and Results/Accomplishments:

The floating extents Antarctic ice sheets (ice shelves) are in contact with the surrounding ocean. The ice-shelf/ocean interactions have strong effects on both ice shelf behavior and ocean circulation. In collaboration with R. Hallberg and M Harrison, the effects of thermodynamic coupling between Antarctic ice shelves and surrounding ocean have been investigated using a newly developed GFDL ocean circulation model, MOM6 coupled to a sea-ice model SIS. The ocean circulation model has been configured to simulate the ocean circulation in the ice-shelf cavities. The performed simulations are the first simulations performed in the global configuration. All earlier simulations have been done in regional settings. The long-period variability of simulated melting/freezing rates of Antarctic ice shelves differs across geographic locations: ice shelves located in Antarctic Peninsula, Amundsen and Bellingshausen sea embayments and the Amery Ice Shelf experience an increase in melting over the last several years of the simulations, while ice shelves in other regions remain steady in their melting/freezing rates.

In addition to sub-marine melting, ice shelves lose their mass through calving icebergs. After calving, icebergs float in the Southern Ocean and affect numerous aspects of the ocean circulation (e.g. they modify the ambient water masses, change the ocean primary productivity acting as sources of iron, etc.). The iceberg representation in climate models is non-trivial. The GFDL ocean model is one of very few climate models that accounts for the iceberg-ocean interactions. Currently, icebergs are represented in the model as point particles. However, with increasing model resolution there is a need to account for spatial extent of large tabular icebergs. In collaboration with A. Adcroft and A. Stern, new methods of iceberg representation in climate models have been developed and implemented in the GFDL climate model.

In collaboration with Prof. MacAyeal from the University of Chicago and Dr. Banwell from Cambridge University, a new theory of ice-shelf flexure was developed. In contrast to two traditionally used treatments of ice shelves – elastic and viscous that describe the ice deformation on very short (from

seconds to day) and very long (months to millennia) time scales, the new theory allows for treatments of ice deformation on intermediate time scales using viscoelastic rheology. This theory provides explanations of the effects of recently observed supraglacial lakes on ice-shelf stress-regime and their flexure (MacAyeal et al., 2015).

Outreach Activities: Supervision of a Princeton University undergraduate student, Kasturi Shah. Senior Thesis "Evolution of Himalayan Glaciers under changing climate conditions."

References:

MacAyeal D. R., O. V. Sergienko and A. F. Banwell. 2015. A model of viscoelastic ice-shelf flexure. J. Glac. 61(228), 635-645 doi:10.3189/2015JoG14J169.

Publications:

Sergienko O. V. 2015. Cryosphere: Order in Antarctic Ice Streams. Nature Geosciences, 8, 822, doi:10.1038/ngeo2536.

MacAyeal D. R., O. V. Sergienko and A. F. Banwell. 2015. A model of viscoelastic ice-shelf flexure. J. Glac. 61(228), 635-645 doi:10.3189/2015JoG14J169.

Presentations:

Sergienko O., M. Harrison, R. Hallberg and A. Adcroft (2015). Strong effects of thermodynamic ice-shelf/ocean interactions in a global sea-ice-ocean isopycnal model. IGS Symposium on Contemporary Ice-Sheet Dynamics: ocean interaction, meltwater and non-linear effects. Cambridge, UK, 16-21 August, 2015.

Hindmarsh R. C. A., O. V. Sergienko and T. T. Creyts (2015). Diagnostics of basal conditions – the formation of the extensive zones of surface ribs in ice sheets and streams. EGU General Assembly, Vienna, Austria, 12-17 April, 2015.

Progress Report Title: **Towards Development of the New Land Model LM4 for Use with CM4 and ESM4**

Principal Investigator: Elena Shevliakova (Princeton Senior Climate Modeler/GFDL Professional Specialist)

CICS/GFDL Collaborator: Sergey Malyshev, Ben Sulman, Dan Ward, Nathaniel Chaney, Minjin Lee, and Dan Li (Princeton), R. Stouffer, P. Ginoux , and L. Horowitz (GFDL)

Other Participating Researchers: Peter Jaffe, Sam Rabin, Sampo Smolander, Stuart Evans, Xinning Zhang, Steve Pacala, and Claire Zarakas (Princeton), J. Dukes and N. Smith (Purdue U.), A. Porporato and M. Bartlett (Duke U.), D. Lawrence (NCAR), G. Hurtt (UMD), C. Milly (USGS)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: To enhance the physical and biogeochemical capabilities of the GFDL land model for use with new climate and earth system models

Methods and Results/Accomplishments:

During 2015, I have co-led with Chris Milly the development of the new GFDL land LM4 model. The new modeling capabilities were originally implemented in the LM3 framework and tested in the global and regional stand-alone simulations and coupled configurations, including: 1) with C. Medichi, X. Zhang, B Sulman, and S. Malyshev - coupled soil carbon-nitrogen model with explicit treatment of microbial dynamic. This new model will allow us to capture effects of nitrogen availability on soil carbon respiration and plant uptake to be included in future ESM4 simulations. 2) with M. Lee, S. Malyshev, P. Jaffe and C. Milly - analysis of interactions between hydrological extremes and water quality in the Susquehanna basin using the new version of the coupled land-river nitrogen cycling model (Lee et al, in review); 3) with N. Chaney and C. Milly -development of a new hyper-high resolution, initialized land model for CONUS for use in the GFDL seasonal prediction AGCM ; 4) with S. Pacala and S. Malyshev- implementation of the tropical age-height structured dynamic vegetation model LM3-PPA, previously developed for temperate deciduous vegetation (Weng et al 2015); 5) with J. Dukes, N. Smith, and S. Malyshev - a new parameterization of photosynthetic and respiratory acclimation LM3 (Smith et al, 2015); The new manuscript also examined implications of photosynthetic acclimation for future carbon uptake. 6) with S. Smolander -The new model for CH4 dynamics coupled to LM3 carbon dynamics with 5 microbial functional groups; The prototype and first simulations were presented at the 2015 Fall AGU meeting. 7) with S. Rabin, S. Malyshev and S. Pacala - The new fire model constrained by observations has been developed and integrated into the GFDL land model as the main focus of S. Rabin's Ph.D. dissertation. The model has a different treatment of fires for managed and unmanaged lands. As a part of this effort, a new dataset was designed for pasture evaluation (Rabin et al 2015). 8) with D. Ward and S. Malyshev - The new scheme for coupling fire emissions with atmospheric aerosols and chemistry has been developed in CM3 framework. Preindustrial variability in the fire carbon emissions in the GFDL

ESM2Mb and NCAR CESM models has been examined (Ward, et al in prep). 9) with D. Li and S. Malyshev- developed and evaluated urban climate model into GFDL LM3 model; The model has been exercised both as a stand-alone (Li et al, in review) and in the stretched grid GFDL AGCM (manuscript in preparation). 10) with S. Evans, S. Malyshev and P. Ginoux - developed an interactive land-atmosphere dust capability and evaluated it in a multi-century CM3 control simulations. The findings of this work were presented by S. Evans at the 2015 Fall AGU meeting and a manuscript is in preparation (Evans et al, in prep).

I have served on the steering committee of the CMIP6 Land-Use Model Intercomparison Project. I have designed the new land-use specific diagnostics set recommended for CMIP6 experiments and have contributed to the LUMIP experimental design (Lawrence et al, submitted).

I have contributed to the Anderegg et al 2015 analysis of implications of droughts for carbon uptake in CMIP5 ESMs experiments.

I have collaborated with GFDL and Princeton scientists on the development of four proposals. Two proposals have been funded, with L. Horowitz to NOAA/CPO: "Reactive nitrogen biogeochemical cycling in the GFDL Earth System Models: Advancing understanding of atmosphere-land interactions under changing climate and land use" and with J. Metcalf to the Welcome Trust (UK): "Seasonal drivers of human movement and aggregation in a changing climate: consequences for infectious disease dynamics and control."

Outreach Activities: I supervise NOAA/Hollings undergraduate intern Claire Zarakas (Princeton University).

Publications:

Anderegg WR, Schwalm C, Biondi F, Camarero JJ, Koch G, Litvak M, Ogle K, Shaw JD, Shevliakova E, Williams AP, Wolf A. Pervasive drought legacies in forest ecosystems and their implications for carbon cycle models. Science. 2015 Jul 31; 349(6247):528-32.

Anderegg, William RL, et al. Tropical nighttime warming as a dominant driver of variability in the terrestrial carbon sink. Proceedings of the National Academy of Sciences 112.51 (2015): 15591-15596.

Evans, S.M., P.A. Ginoux, S. Malyshev, and E. Shevliakova (in prep): The importance of the land surface to Australian dust variability in models and observations, Geophysical Research Letters.

Lawrence, D.M. G.C. Hurtt, A. Arneth, V. Brovkin, K.V. Calvin, A.D. Jones, C.D. Jones, P.J. Lawrence, N. de Noblet-Ducoudré, J. Pongratz, S. I. Seneviratne, and E. Shevliakova (submitted). The Land Use Model Intercomparison Project (LUMIP): Rationale and experimental design, GMD.

Lee, M., Shevliakova, E., Malyshev, S., Milly, P.C.D., Jaffe, P. (in review), Climate variability and extremes, interacting with nitrogen storage, amplify eutrophication risk, Geophys. Res. Lett.

Li, D, S. Malyshev and E, Shevliakova (in review a), Exploring historical and future urban climate in the Earth System Modeling framework. Part I: Model development and evaluation, Journal of Advances in Modeling Earth Systems.

Li, D, S. Malyshev and E, Shevliakova (in review b), Exploring historical and future urban climate in the Earth System Modeling framework. Part II: Interactions between urban heat islands and climate change over the Continental United States, Journal of Advances in Modeling Earth Systems.

Malyshev S, Shevliakova E, Stouffer RJ, Pacala SW. Contrasting Local versus Regional Effects of Land-Use-Change-Induced Heterogeneity on Historical Climate: Analysis with the GFDL Earth System Model. Journal of Climate. 2015 Jul; 28(13):5448-69.

Rabin SS, Magi BI, Shevliakova E, Pacala SW. Quantifying regional, time-varying effects of cropland and pasture on vegetation fire. Biogeosciences. 2015 Nov 19;12(22):6591-604.

Smith NG, Malyshev SL, Shevliakova E, Kattge J, Dukes JS. Foliar temperature acclimation reduces simulated carbon sensitivity to climate. Nature Climate Change. 2015 Dec 7.

Ward D.S., Shevliakova E., Malyshev S., Lamarque J.-F., Wittenberg A. (in prep), Implications of natural climate variability for wildfire emissions: insights from Earth System models, Environmental Research Letters.

Weng ES, Malyshev S, Lichstein JW, Farrior CE, Dybzinski R, Zhang T, Shevliakova E, Pacala SW. Scaling from individual trees to forests in an Earth system modeling framework using a mathematically tractable model of height-structured competition. Biogeosciences. 2015 May 7;12(9):2655-94.

Progress Report Title: **Probing Interactions between Clouds and the Large-Scale Circulation**

Principal Investigator: Levi G. Silvers (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Max Popp (Princeton)

Other Participating Researchers: Ming Zhao (UCAR), Huan Guo (UCAR), Rick Hemler (Engility), Brian Medeiros (NCAR), Thorsten Mauritsen (MPI-M)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: The research I am working on seeks a better understanding of the role played by clouds in the Earth system. I am specifically focused on clarifying cloud feedbacks to forcing and determining how the large-scale circulation couples with diabatic atmospheric processes.

Methods and Results/Accomplishments:

One of the prominent ways in which clouds impact the Earth system is through their interaction with radiation. This interaction is strongly dependent on both short- and long-wave radiation (Radel et al. 2016, Armour et al. 2013). My methodology is to examine both Atmospheric GCM and Aquaplanet GCM experiments (APE) with the influence of clouds divided into the short- and long-wave effects. One set of experiments has different components of the cloud radiative effect turned off/on, and another set of experiments is examining AMIP type experiments with perturbed sea surface temperature patterns.

The aim of the AMIP type experiments is to better assess the influence of different sea surface temperature patterns on cloud feedbacks. The aim of the APE experiments is to determining the role of the short- and long-wave cloud radiative effects on the large-scale circulation. Over the next year I will be working extensively with the experiments that have been chosen as part of the CFMIP6 project. These experiments are ideally suited to assist us in further development and improvement of the GFDL models as well as move us closer to realizing our research goals.

The following are some preliminary steps that have been completed: 1) Modification of the latest prototype GFDL atmospheric model (am4XX) to allow for APE experiments; 2)Implementation of switches which turn on and off the use of short- and long-wave radiation in the am4XX model;
3) Preliminary work to use and improve the necessary diagnostics for the upcoming CFMIP6 series of experiments which will be a part of CMIP6, in particular I am working to make the COSP diagnostic package available for use at GFDL (Bodas-Salcedo et al. 2011); 4) Initial experiments and analysis of the AMIP and APE experiments outlined above

Outreach Activities: Participation in the 2016 Monmouth Junction Elementary School Science Fair (Feb 27th) and organizer of the GFDL Climate Sensitivity Journal Club (with Max Popp)

References:

Armour, K.C., C.M. Bitz, and G.H. Roe, 2013: Time-varying climate sensitivity from regional feedbacks. J. Climate, 26, 4518-4534.

Bodas-Salcedo, A., M.J. Webb, S. Bony, H. Chepfer, J.-L. Dufresne, S.A. Klein, Y. Zhang, R. Marchand, J.M. Haynes, R. Pincus, and V.O. John, 2011: COSP: Satellite simulation software for model assessment. Bull. Amer. Met. Soc., 92(8), 1023-1043.

Radel, G., T. Mauritsen, B. Stevens, D. Dommenget, D. Matei, K. Bollomo, and A. Clement, 2016: Amplification of El Nino by cloud longwave coupling to atmospheric circulation. Nature Geo., 9, 106-110.

Publications:

Silvers, L.G., B. Stevens, T. Mauritsen, and M. Giorgetta 2016: Radiative Convective Equilibrium as A Framework for Studying the Interaction Between Convection and its Large-Scale Environment. Submitted to the Journal of Advances in Modeling Earth Systems.

Presentations:

Silvers, L.G., B. Stevens, T. Mauritsen, and M. Giorgetta, 2015: Parameterized Radiative Convective Equilibrium Across a Range of Domains: A Unifying Tool for General Circulation Models and High Resolution Models. GFDL Poster Expo January 2016.

Silvers, L.G., B. Stevens, T. Mauritsen, and M. Giorgetta, 2015: Parameterized Radiative Convective Equilibrium Across a Range of Domains: A Unifying Tool for General Circulation Models and High Resolution Models. AGU, December 2015.

Silvers, L.G., B. Stevens, C. Hohenegger, and M. Giorgetta, 2015: Bridging the Gap Between GCMs and CRMs: A Look at Equilibrium Climate Sensitivity. GFDL Seminar, January 2015.

Progress Report Title: **Terrestrial Ice Mass Loss and the Sea-Level Budget**

Principal Investigator: Frederik J. Simons (Princeton Associate Professor)

CICS/GFDL Collaborator: Christopher Harig (Princeton)

Award Number: NA14OAR4320106

Task III: Individual Projects

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: Since 1990, the second largest contributor (behind thermal expansion) to global mean sea level rise has been the melting of mountain glaciers and ice caps, which have together shed more ice mass than the land ice sheets on Greenland and Antarctica. The glaciers in the Canadian Archipelago and the Gulf of Alaska have experienced some of the largest estimated mass changes in the past decade. In this study we investigate ice mass changes in and around the Gulf of Alaska, the Canadian Archipelago, and Greenland since 2003, using time-variable gravimetry from the GRACE mission.

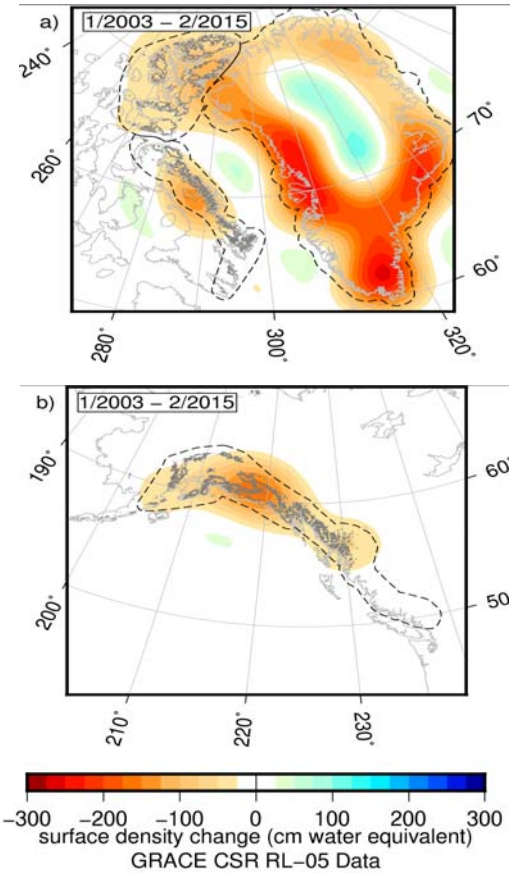
Methods and Results/Accomplishments:

Future projections of 21st century sea level rise depend on the quantity and location of land ice mass changes, which require long-term continuous measurement to determine with high accuracy. Earth's time-variable gravity field, as observed since 2002 by the Gravity Recovery and Climate Experiment (GRACE), has provided a highly detailed record of land ice mass change over the past decade. From the orbits and the range (rates) between twin satellites, a global gravity field is determined each month, or more frequently. Changes in the geopotential resolve the surface density to within centimeters of water-equivalent. Laser altimetry and GRACE gravimetry have both been used to determine the past ice mass loss rate of the Gulf of Alaska, ranging from -61 Gt/yr to -75 Gt/yr. While overall trends show little acceleration, the region displays large interannual variations in mass, linked in some cases to climatic events. Observations in the Canadian Archipelago indicate that ice mass loss accelerated during the 2000s. Recent estimates agree that from 2003 to 2010 mass loss rates have risen to roughly -30 Gt/yr for each of the northern and southern regions of the Canadian Archipelago. Continued long-term monitoring is needed to determine if these accelerations fall within the variance of interannual variations, which can significantly impact the estimated ice mass loss rate.

Studying the cryosphere from GRACE data requires "localization." We have a bandlimited global field on the sphere and wish to estimate its behavior over a specific geographic location, such as over an ice sheet. To this end we use a “spherical Slepian functions”, designed to minimize the "leakage" of the signal out of the region of interest. Our method has previously been applied to estimate the mass changes of Earth's large ice sheets; however the small regions considered here approach the resolution limit for its applicability using GRACE, and the various findings reported here constitute new evidence of system variability that will be targets for detection and analysis by other, non-gravimetric studies.

Ice mass losses continue steadily around the Gulf of Alaska with the total mass trend showing no significant acceleration. Variability in these regions is dominated by the seasonal mass cycle which is roughly three to four times as strong as the seasonal cycle around Greenland on a per square meter basis. Ice mass losses in Greenland and the Canadian Archipelago continue to accelerate over time, increasing

the contribution of these areas to sea level rise. Since the summer of 2013 these regions have experienced a positive ice mass anomaly, where the yearly mass changes diverge from the long-term decadal trend. In the case of Greenland this anomaly reached nearly 500 Gt through the end of 2014. Independent verification of our findings by other, non-gravimetric, studies, is underway.



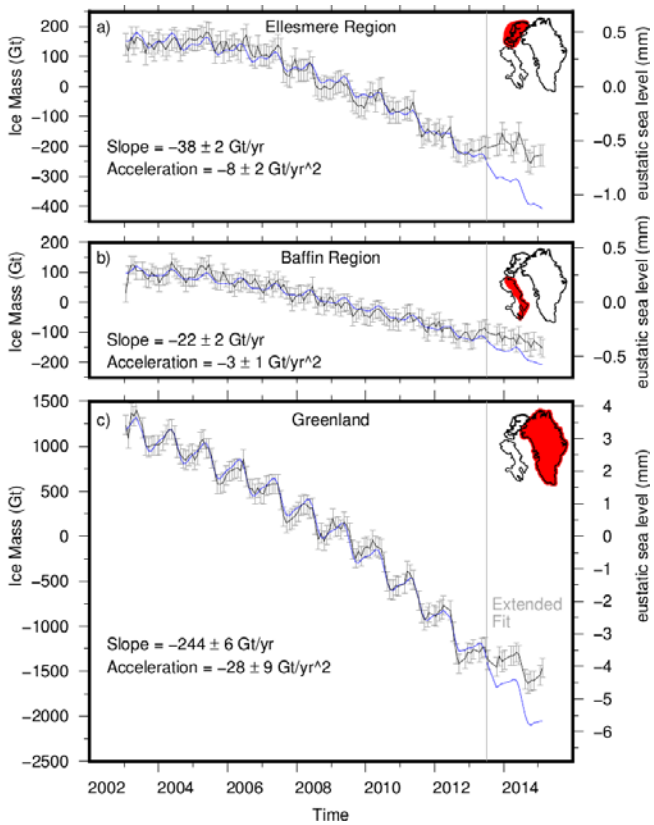


Figure 1: The total ice mass change (corrected for glacio-isostatic adjustment) for the regions (black dashed lines) around (a) Greenland and (b) Gulf of Alaska. Coastlines are shown in light grey. Glaciated regions, determined from the Randolph Glacier Inventory (RGI) v 3.2, are outlined in dark grey.

Figure 2: Ice mass changes (corrected for glacio-isostatic adjustment) in gigatons (Gt) for regions of (a) Ellesmere Island, (b) Baffin Island, and (c) Greenland. The regions covered by each localization are shaded red in the top right inset. The black lines are monthly GRACE observations with 95% confidence (grey) error bars determined from our analysis. The solid blue lines are the best-fit estimates including a quadratic curve and the periodic annual and semi-annual terms. Estimates are fit using data prior to June 2013 (left of vertical grey lines), and then extrapolated forward through 2014 (right of vertical grey lines) to show the departure of recent data from the long-term trends.

Outreach Activities: F. J. Simons, Polar Ice: A Story of Global Melting**,** Littlebrook Elementary School Science Expo, <http://geoweb.princeton.edu/people/simons/PDF/Littlebrook-05212015.pdf>

Publications:

Harig, C. and F. J. Simons, Ice mass loss in Greenland, the Gulf of Alaska, & the Canadian Archipelago: Seasonal cycles and decadal trends, Geophys. Res. Lett. (2015), doi: 10.1002/2016GL067759.

Harig, C. and F. J. Simons, Accelerated West Antarctic ice mass loss continues to outpace East Antarctic gains, Earth Planet. Sci. Lett. (2015), doi: 10.1016/j.epsl.2015.01.029.

Harig, C., Lewis, K. W., Plattner, A., and F. J. Simons, A suite of software analyzes data on the sphere, EOS Trans. Am. Geophys. Union (2015), doi: 10.1029/2015EO025851.

Progress Report Title: **Next-Generation Carbon and Nitrogen Cycling in the GFDL Land Model**

Principal Investigator: Benjamin N. Sulman (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Elena Shevliakova (Princeton/GFDL), Sergey Malyshev (Princeton), Minjin Lee (Princeton)

Other Participating Researchers: Xin Zhang (University of Maryland), Edward Brzostek (West Virginia University), Richard Phillips (Indiana University), Duncan Menge (Columbia University)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: To improve simulation of carbon and nitrogen cycling and related climate feedbacks in the GFDL land model by implementing and testing new biological mechanisms

Methods and Results/Accomplishments:

In cooperation with other researchers (Xin Zhang and Chiara Medici), I refined and tested nitrogen cycle processes in the soil carbon model that I had previously developed (Sulman et al, 2014). The soil model explicitly simulates microbial activity, root-soil interactions, and protection of organic matter by interactions with mineral particles as well as leaching of carbon and nitrogen with water flow. In addition, I developed a new plant nitrogen model within the GFDL land model. The new plant nitrogen model explicitly simulates plant allocation of carbon to nitrogen acquisition and nitrogen fixation, allowing the simulation of dynamic feedbacks between plant growth, nitrogen uptake, and soil decomposition. This important set of interactions is not simulated in the majority of biogeochemical models, and has not been included in any earth system model to date. Adding nitrogen cycling to this model represents a significant advance in earth system modeling, allowing the model to improve its representation of soil decomposition and plant growth responses to changing climate and atmospheric CO_2 concentrations. I have tested the soil and plant nitrogen models in single-point and global simulations and gathered observational datasets for quantitative evaluation of the simulations.

In addition to model development, I conducted an analysis of a large database of soil carbon profiles, and identified patterns related to land cover and land use history. I also analyzed CO_2 and water vapor fluxes from an Indiana forest and quantified their responses to variations in soil moisture and vapor pressure deficit, identifying important controls on forest responses to droughts and warming climate. Finally, I collaborated with other research groups developing microbial-explicit soil carbon models in order to develop frameworks for evaluating and benchmarking this new class of models.

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B. N. Sulman, D. T. Roman, T. M. Scanlon, L. Wang, and K. A. Novick (in review): Comparing methods for partitioning a decade of carbon dioxide and water vapor fluxes in a temperate forest. Agricultural and Forest Meteorology.

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B. N. Sulman, M. Bradford, C. Averill, J. Schimel, Y. Luo, W. Feng, J. Moore, B. Sridhar, A. Salazar, W. Wieder, R. Abramoff, M. Mayes, and A. Classen (in preparation): Evaluating process uncertainty in mechanistic soil carbon models.

B. N. Sulman, X. Zhang, C. Medici, E. Brzostek, S. Malyshev, and E. Shevliakova (in preparation): Coupling plant N acquisition to soil microbial dynamics in the GFDL land model.

Presentations:

B. N. Sulman, R. P. Phillips, E. Shevliakova, E. R. Brzostek, and S. W. Pacala: Microbes, minerals, and roots in a soil organic matter model at local to global scales (invited poster presentation). INTERFACE RCN 2016 workshop: Integrating models and experiments to explore climate feedbacks in a managed and warming world, St. Pete Beach, FL, Jan 2016.

B. N. Sulman, L. Nave, C. Treat, Y. He, and C. Koven: Controls on vertical soil carbon distributions in the continental United States: Applications for model evaluation (invited oral presentation). American Geophysical Union 2015 Fall Meeting, San Francisco, CA, Dec 2015.

B. N. Sulman, E. R. Brzostek, and R. P. Phillips: Modeling plant N acquisition and soil biogeochemical feedbacks in a temperate forest (oral presentation). Ecological Society of America Annual Meeting, Baltimore, MD, Aug 2015.

B. N. Sulman, R. P. Phillips, E. Shevliakova, A. C. Oishi, and S. Pacala: Root exudation, priming, and protection: Advanced soil carbon processes in a global model (poster presentation). North American Carbon Program PI meeting, Washington, DC, Jan 2015.

Progress Report Title: **The Impact of Large Phytoplankton on Biogeochemical Modeling of Primary Production and Response to Climate-Induced Ecosystem Changes**

Principal Investigator: Bess B. Ward (Princeton Professor)

CICS/GFDL Collaborator: Nicolas Van Oostende and Andrew Barton (Princeton), Charles Stock and John P. Dunne (GFDL)

Award Number: NA14OAR4320106

Task III: Individual Projects

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Healthy Oceans Goal: Marine Fisheries, Habitats, and Biodiversity are Sustained within Healthy and Productive Ecosystems (50%)
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts (50%)

Objectives: The main goal of this study is to provide a mechanistic explanation for the high chlorophyll (chla) biomass accumulation (and secondary production) that occurs in intermittently highly productive marine systems, such as coastal upwelling, but which is not captured by current state of the art biogeochemical models. More specifically, does the decoupling of production by large diatoms, which are not currently implemented in GFDL's COBALT biogeochemical model, from large zooplankton grazing pressure and decreased aggregation in a nutrient-replete environment constitute necessary conditions/mechanisms for the observed peaks of high chlorophyll (>5 mg m^{-3}) and high fisheries yields in these systems?

Methods and Results/Accomplishments:

We chose the California coastal upwelling system as our test case because it is part of a long-standing time series and thus is well documented (e.g. CalCOFI). Large and chain-forming diatoms are known to be responsible for the intermittent high biomass accumulation in coastal upwelling systems (Venrick 2002, Taylor et al. 2012, Van Oostende et al. 2015). We first ascertained that the high chla concentrations observed by remote sensing were accurate and not biased because of deviation from Case-1 water properties (Kahru et al. 2014). To enable the simulation of high biomass episodes we amended the current Carbon Ocean Biogeochemistry And Lower Trophics model (COBALT; Stock and Dunne (2010); Stock et al. (2014)) to include the large diatom functional group. This approach is based on the concepts articulated by Thingstad (1998) and Armstrong (2003), in which size-based trophic interactions can explain the size-structure of the phytoplankton community and the upper limits to chla in size classes. We performed a literature survey to determine which species were thriving in upwelling bloom conditions and compiled parameter value estimates representative for their growth rate, nutrient uptake characteristics, chla content and light affinities, and grazing susceptibility. We then adapted the model configuration to adjust the implicit size characteristics of the three non-diazotrophic phytoplankton functional groups (i.e. PS 0.5-5 µm, PM 5-20 µm, PL >20 µm compared to the existing two: PS 0.5-2 µm and PL 2-10 µm), as well as their grazing pathways.

These new parameterizations will be implemented in a new version of the COBALT model. The very recent development of a Regional Ocean Modeling System (ROMS) implementation of COBALT by Raphael Dussin (Rutgers) applied to the California Current System will allow us to test the mechanism by

which such nutrient-rich systems episodically accumulate high levels of biomass (i.e. mainly by bottom-up, top-down effects or a combination thereof). First, we will test whether refinements in the physical representation of the system improve the high chla representation, by implementing and comparing the existing 1° and 0.25° COBALT model configuration with the even higher resolution ROMS (i.e. control climatology). We will then use the ROMS version of COBALT to test permutations of improved ecological/biogeochemical configurations to assess mechanisms of acute high chla accumulation. Runs of 4 to 10 year perturbations will be used to test model sensitivities to 1) nutrient and light assimilation rates, 2) grazing rate (e.g. gut transit time) and 3) nutrient-dependent aggregation loss of the largest phytoplankton group.

Outreach Activities: Two undergraduate students, one GEO major and one CEE major, are doing JP or ST work in the lab on projects related to CICS project. They are growing diatom cultures and performing nutrient uptake experiments in order to determine growth and nutrient kinetic parameters for future use in ecosystem models. Both students meet regularly with Ward and Van Oostende and are advised in the lab by Van Oostende.

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Progress Report Title: **Emissions from Fires: Interactions and Impacts in the Coupled Land-Atmosphere**

Principal Investigator: Daniel Ward (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Elena Shevliakova (Princeton/GFDL), Sergey Malyshev (Princeton), John Dunne (GFDL)

Other Participating Researchers: Paul Ginoux (GFDL), Sam Rabin (Princeton)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: To add interactive fire emissions into the coupled land-atmosphere model such that feedbacks between global fire activity and atmospheric processes can be simulated. Furthermore, to study the impacts of this coupling onto atmospheric chemistry, aerosols, clouds and radiation, as well as onto the terrestrial biosphere and carbon/nitrogen cycles.

Methods and Results/Accomplishments:

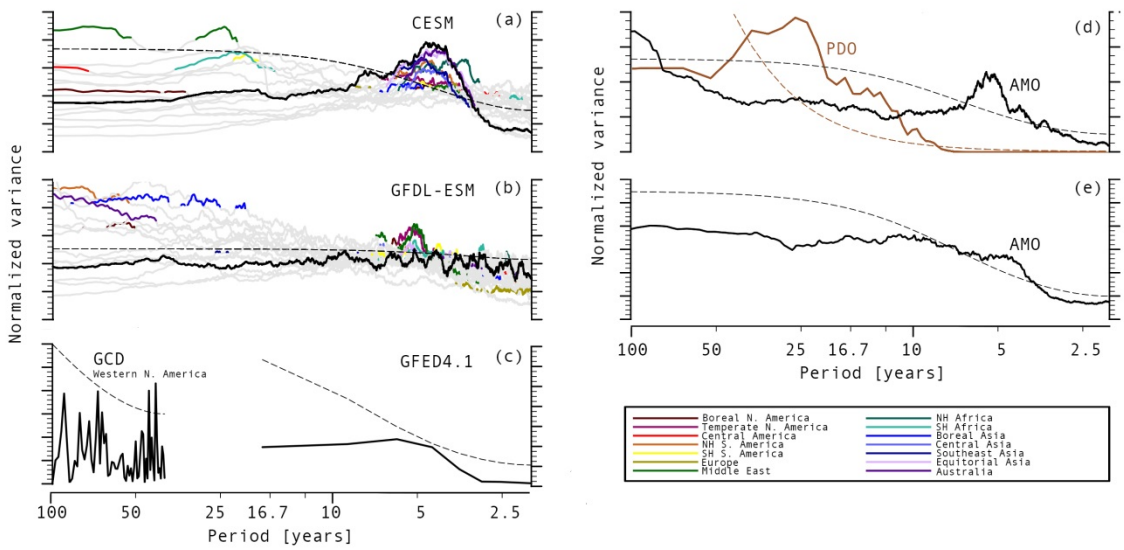
My major task and contribution during this past year has been developing code in the GFDL Land Model and Atmosphere Model that computes emissions of trace gas and aerosol species from fires and couples these emissions to the chemistry and aerosol schemes in the atmosphere model. The code is designed to be user-friendly, allowing for fire tracers to be added to or removed from simulations without requiring code modifications. Results of the model development are being used in long (500yr) fully coupled runs to test the impact of coupled fire emissions on climate mean state and variability.

As part of this project, I performed assessments of several injection height schemes for fire aerosol emissions and also the general capability of the model to simulate the aerosol optical depth (AOD) from fire emissions. Results from these assessments show underprediction of fire AOD compared to satellite datasets in most regions, which is characteristic of many global models (e.g. Nevison et al., 2008; Ward et al., 2012; Veira et al., 2015), and is sometimes attributed to uncertainties in emissions factors, combustion completeness, or aerosol composition (Chin et al., 2009). Injection height schemes were found to be of low-order importance for simulating AOD on a global scale compared to the above-mentioned uncertainties, consistent with some previous studies (val Martin et al., 2010; Tosca et al., 2011).

In addition, I carried out the first (to my knowledge) investigation of the relationship between global and regional fire emissions and modes of climate variability in the long control runs of two Earth System models, the GFDL ESM2M and CESM1. The response of fires to climate oscillations such as ENSO and the PDO is often speculated about or studied for a small region where fires were historically observed, or where some proxy for fire activity, such as tree-ring scars, exist. To examine this question on a global scale and for regions without extensive fire records (including most of the tropics/subtropics) requires an investigation of large ensemble Earth System model simulations that include a fire model. Analysis of the two long control runs mentioned above show a strong global response in fire emissions to different phases of ENSO and in CESM, select regions show significant variability in fire emissions on

decadal and multidecadal timescales (Fig. 1) driven by precipitation patterns associated with the AMO and PDO (although the PDO signal is very weak). This work has been invited for submission to a focus issue on changing fire regimes in Environmental Research Letters and is in preparation. It will serve as a primer for future studies of the impact of fires on climate mean state and variability in the GFDL ESM.

Figure 1: Power spectra of fire emissions (black line) with variance required for statistical difference from red noise with 95% confidence (black dashed line) for a) the CESM1.1 long control run, b) the GFDL-ESM long control run and c) the GFED4.1s. The spectrum of charcoal influx data from 10 western North America sites interpolated to 20-year time resolution are also included in c). Regional spectra are shown as gray lines for a) CESM1.1 and b) GFDL-ESM with frequencies for which the spectra are significantly different from red noise with 95% confidence highlighted by color. Spectra and 95% confidence level curves are plotted for the PDO (brown) and AMO (black) indices for d) CESM1.1 and e) GFDL-ESM. There is no PDO plotted for GFDL-ESM since this long control run did not produce a strong PDO pattern.



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Progress Report Title: **Assessing the Seasonal Predictive Skill of FLOW over AFRICA**

Principal Investigator: Eric F Wood (Princeton Professor)

CICS/GFDL Collaborator: Gabriel Vecchi (GFDL)

Award Number: NA14OAR4320106

Task III: Individual Projects

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Weather-Ready Nation Goal: Society is Prepared for and Responds to Weather-Related Events

Objectives: The project focused on assessing the hydroclimatology and seasonal forecasting skill of FLOR over Africa, which are critical metrics in evaluating the model.

Methods and Results/Accomplishments:

Evaluation of seasonal and sub-seasonal forecast skill of FLOR We evaluated the value of FLOR-B01 seasonal and sub-seasonal forecast for hydrological applications and water managements. We used FLOR-B01 hindcast from 1981-2012, that were made available via the NMME-II sub-seasonal hindcasting experiment. We found a relatively low skill of FLOR-B01 for the short leads (the first month), due to the missing land initialization in the FLOR-B01 hindcast in NMME-II. However, after week four we found a constant increase in the forecast skill of FLOR-B01 that is caused by the reduced impact of the land initialization. It is found that this forecast skill in the 1-3 months lead carries over to the longer leads, while comparable models lose skill (see attached Figure). Significantly positive anomaly correlations are mostly found over the tropics and extra tropics as can be expected from previous studies. This increase skill for the longer leads is also carried over to our hydrological forecasting framework, that uses a set of hydrological models to predict sub-seasonal water availability. Hydrological forecasts that use FLOR as their meteorological input show a significant improvement compared to our statistical benchmark. This enhances the forecast value of the hydrological predictions, and makes them more valuable for decisions support system that really on long-range forecasts, like agricultural planning or reservoir management.

Paper: Wanders and Wood, 2016. Improved sub-seasonal meteorological forecast skill using weighted multi-model ensemble simulations, Environmental Research Letters, under review

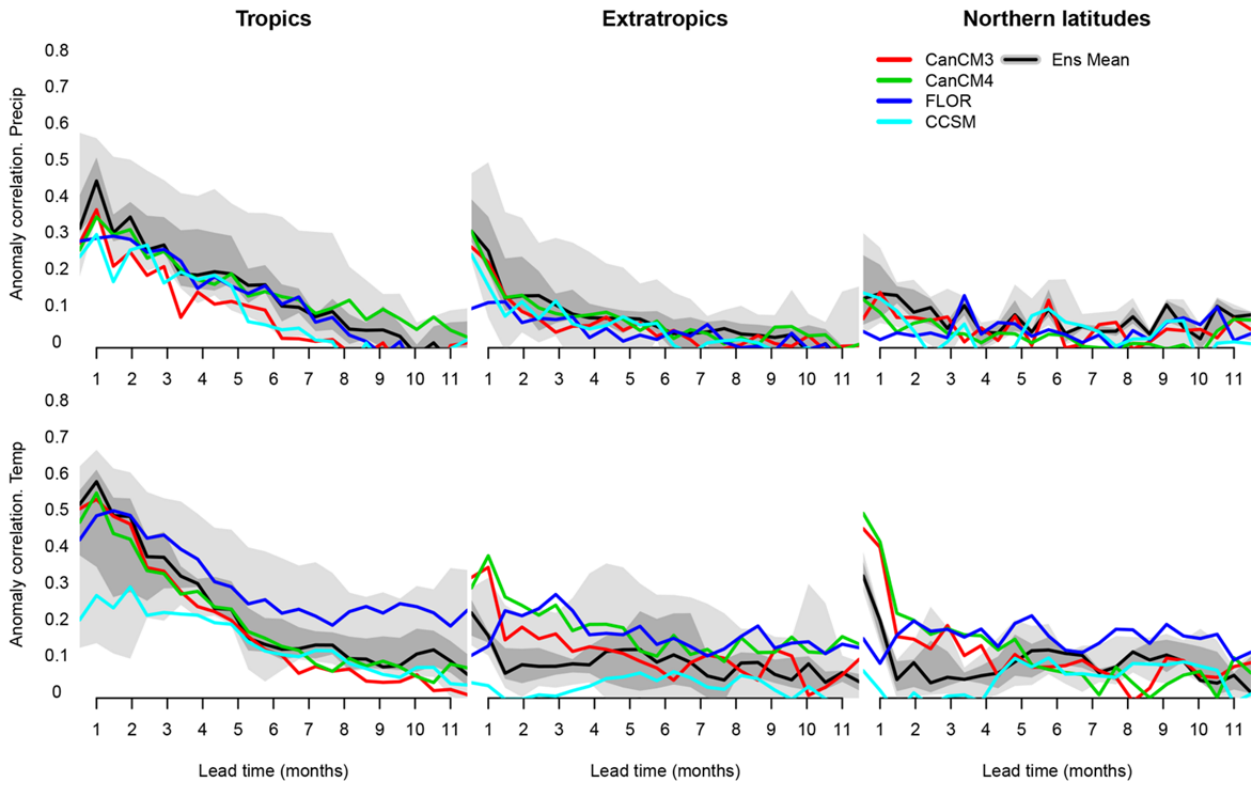

Figure 1 Anomaly correlations of four seasonal forecast models from NMME-II for the period 1981-2012. The forecasts are evaluated against the Princeton Global Forcing dataset, which was used as a reference. CanCM3, CanCM4 and CCSM are the other models that are available through the NMME-II hindcast experiment. In black we provide the ensemble mean of all NMME-II models.

Assessing GFDL High-Resolution Climate Model Water and Energy Budgets from AMIP simulations over Africa Improvements can be made in medium-range to seasonal-scale predictions by improving the surface water and energy budgets representations of forecast models. This study assessed surface water and energy budgets in AMIP simulations of a coupled atmosphere-land model developed by Geophysical Fluid Dynamics Laboratory [Atmospheric General Circulation Model (AM2.5)], which was used as initial conditions of the Forecast-Oriented Low Ocean Resolution model (FLOR). The AM2.5 water and energy budget variables were compared with four reanalyses datasets and an observational-based reference, the Variable Infiltration Capacity model simulations forced by Princeton Global Meteorological Forcing (PGF/VIC) over 20-year period during 1991-2010 in nine major African river basins. Results showed that AM2.5 have closed water and energy budgets in the nine African river basins. However, the discrepancies between AM2.5 and other datasets were notable in terms of their long-term averages. For the water budget, the AM2.5 mostly overestimated precipitation, evapotranspiration, and runoff compared to PGF/VIC and reanalyses. The AM2.5, reanalyses, and PGF/VIC showed close seasonal cycles but discrepant amplitudes. For the energy budget, while the AM2.5 has relatively consistent net radiation with other datasets, it generally showed higher latent heat, lower sensible heat, and lower Bowen ratio than reanalyses and PGF/VIC. In addition, the AM2.5 water and energy budgets terms mostly had the smallest interannual variability compared to both reanalyses and PGF/VIC. The spatial differences of long-term mean precipitation, runoff, evapotranspiration, and latent heat between AM2.5 and other datasets were reasonably small in dry regions. Figure 2 shows comparisons across Africa of AM2.5 and MERRA with PGF/VIC. The bias in AM2.5 water and energy budget terms may be associated with the overly wet surface and parameterization of moisture convection from ocean to land.

Paper: Di Tian, Ming Pan, Liwei Jia, Gabriel Vecchi, and Eric F. Wood. Assessing GFDL High-Resolution Climate Model Water and Energy Budgets from AMIP simulations over Africa, J Geophys. Res.(in review).

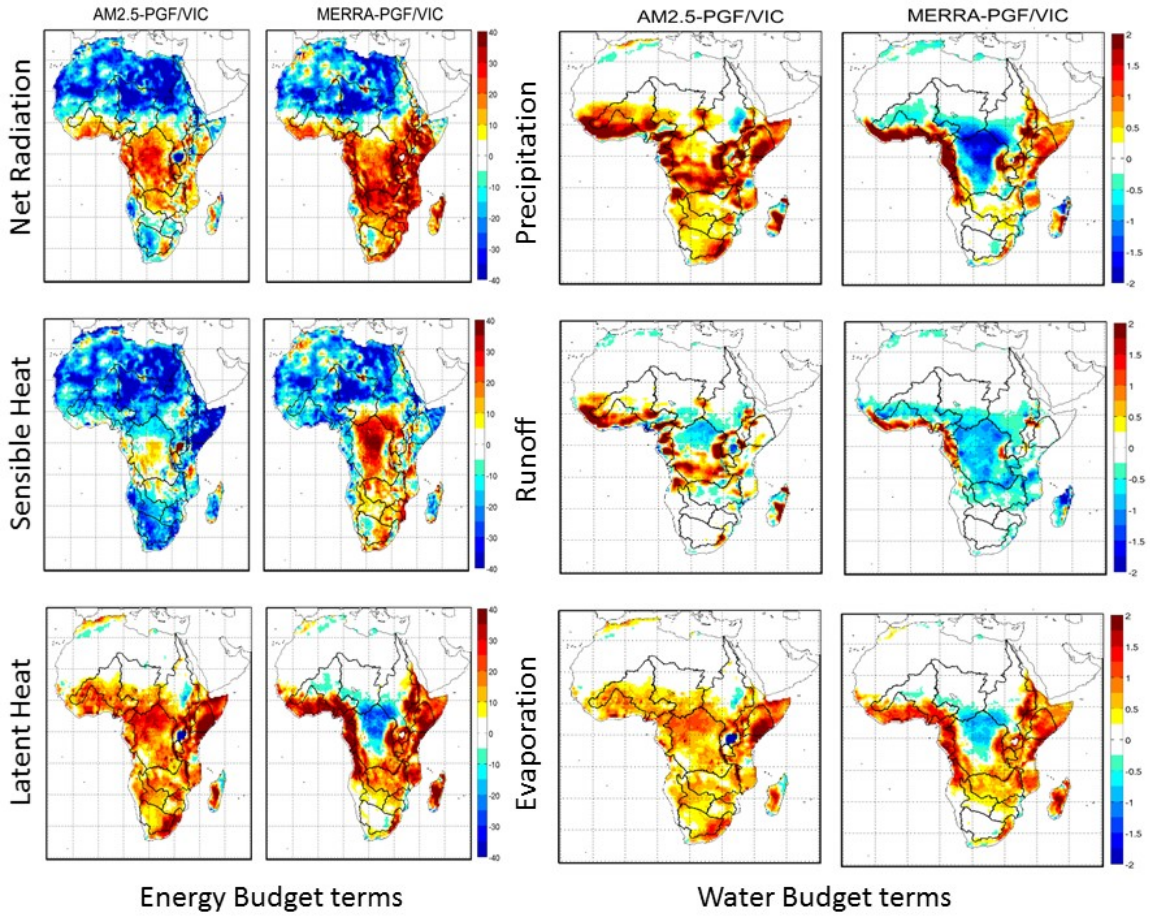

Figure 2. Spatial differences of energy budget and water budget terms between AM2.5 and PGF/VIC, and between MERRA and PGF/VIC.

Publications:

Di Tian, Ming Pan, Liwei Jia, Gabriel Vecchi, and Eric F. Wood. Assessing GFDL High-Resolution Climate Model Water and Energy Budgets from AMIP simulations over Africa, J Geophys. Res.(in review).

Wanders and Wood, 2016. Improved sub-seasonal meteorological forecast skill using weighted multi-model ensemble simulations, Environmental Research Letters, under review.

Presentations:

Di Tian, Eric F. Wood, Gabriel Vecchi, Liwei Jia, and Ming Pan 2015, Surface Water and Energy Budgets for sub-Saharan Africa in GFDL coupled climate models. Presented at 2015 AGU Fall meeting, San Francisco, CA.

Wanders, N. and E.F. Wood Assessment of (sub-) seasonal prediction skill using a canonical event analysis, Presented at 2015 AGU Fall meeting, San Francisco, CA.

Progress Report Title: **Implementation and Evaluation of the NCEP GFS Physics with the FMS Prototype NGGPS Model**

Principal Investigator: Linjiong Zhou (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Shian-Jiann Lin and Lucas Harris (GFDL)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Weather-Ready Nation Goal: Society is Prepared for and Responds to Weather-Related Events

Objectives: To build the 3-13km weather-climate NGGPS model in the FMS framework

Methods and Results/Accomplishments:

NCEP's current operational global atmospheric model dynamical core, the GSM, or Global Spectral Model, has been evolving, but in continuous use for over 30 years. The horizontal resolution of the GSM (~13-km in 2015) is approaching a grid spacing at which cloud processes can no longer be treated through parameterizations; explicit predictions with non-hydrostatic assumptions will be required. In addition, the current GSM may not be able to scale up to take advantage of peta- and exascale high-performance computing (HPC) systems. These factors will require adoption of a new atmospheric dynamical core (dycore) for operational global prediction in the NWS within a decade. Since the global model touches almost every operational forecast NCEP produces, transitioning a new dycore into operations is difficult and costly. Therefore, the NWS needs to ensure the new dynamical core is "future proof" and can serve NOAA's needs for at least 20 years.
(http://www.nws.noaa.gov/ost/nggps/DycoreTestingFiles/HIWPP_3kmfcst_reportv3.pdf) The HIWPP (Sandy-Supplemental funded High Impact Weather Prediction Project) and NGGPS (Next-Generation Global Prediction System) projects are collaborating to choose the best non-hydrostatic dynamical core from 6 candidates (FV3, MPAS, NIM, NMMB-UJ, NEPTUNE and IFS). After level-1 software evaluation, idealized test cases, 3-km, three-day simulations, FV3 and MPAS are the two finalists.

These two candidates were required to roll into the phase 2 test schedule. Phase 2 includes conservation JW test, TC test, global 12.5km 10-day forecast using GFS physics, 3-15km forecast using GFS physics et al. When I first joined this project at the end of September, the implementation of GFS physics into FMS framework just began. My contribution at first was to get familiar with the interface of GFS physics, understand the procedure of different physic parameterizations, parameters used in GFS physics that are specified for Gaussian grid and learn the physics schemes. Most of the time was devoted to reading code, papers, technical reports, and official websites. Rusty, the computational scientist in GFDL, helped implement the GFS physics into FMS framework, while using FV3 (original from HiRAM) as its dynamical core. My contribution was to go over the code, double check the implementation at the physical side, find and fix any bug with him and any other group member. During the early development stage, I had provided many scientific supports. Such as "calculation of geopotential height in GFS and HiRAM", "radiation time stepping in GFS", "ozone prognostic in GFS", "calculation of Rayleigh friction in GFS", "calculation of gravity wave drag in GFS", "GFS physics flow chart", "GFS output list" et al. All these assistants helped Rusty correctly build the interface. For a 10-day weather forecast, initial condition is crucial and decisive. SJ proposed a reversed algorithm to calculate the initial

air temperature using initial geopotential height. I extended it to use geopotential height and relative humidity to derive air temperature. This algorithm can conserve the initial geopotential height and relative humidity.

Model evaluation was conducted at the same time when building the global 12.5km model. My contribution was doing forecast and analysis. Every time we have new tuning parameters, I will performance a 10-day forecast, every 5 days from January 16th, 2015 to January 16th, 2016 plus August 1st, 2015, totally 75 cases. There is huge data output from the model. At the same time running the model, I gradually built a series of analysis tools for forecasting diagnosis. Northern hemisphere h500 acc is the first and the most important indicator to judge whether the tuning parameter is worthy or not. Besides, acc, bias, rmse for northern hemisphere, southern hemisphere, tropics of 200hPa, 500hPa, 850hPa, surface temperature, height, wind speed et al. are all diagnosed in my analysis. From such analysis, we can have an overall understanding of how our model performs, and find any possible issues. We then raise another tuning point. Furthermore, all surface fields, such as precipitation, radiation flux, latent/sensible heat flux, soil moisture/temperature, temperature/wind/specific humidity were compared with GFS output, ensuring our implementation is correct. I also set up a set of diagnostic tools to study hurricanes/typhoons. With the help of all these and those analyses, we have found and fixed many bugs, inconsistencies, and improved the performance a lot.

3-13km forecast with GFS physics is another challenge in this competition. We have prepared two kinds of variable-resolution solutions. One is nested grid, the other is stretched grid. My research focuses on stretched grid transformation. Harris et al. (2016) applied Schmidt transformation to HiRAM and got successful and better simulations. Schmidt transformation provides a smooth, analytic means of deforming any spherical grid by "attracting" grid points to a specific central location. This method was applied to the current building 3-13km model. The result of C1280 cubed-sphere grid plus Schmidt transformation is that the area we concern (CONUS) will have a grid resolution as high as 3km while the opposite side is about 13km. Constrained by the shortest grid length, we had to narrow the time step. With the addition of high resolution, this model is very expensive. After learning of Schmidt transformation and the application to HiRAM, I proposed a revised Schmidt transformation that can keep the highest resolution, while increasing the opposite side resolution. This new algorithm has the ability to decrease the amount of global grid points from C1280 to C1024, which can save 25% computational cost. This new algorithm is still under testing at C384.

References:

http://www.nws.noaa.gov/ost/nggps/DycoreTestingFiles/AVEC%20Level%201%20Benchmarking%20Report%2008%2020150602.pdf

http://www.nws.noaa.gov/ost/nggps/DycoreTestingFiles/HIWPP_idealized_tests-v8%20revised%2005212015.pdf

http://www.nws.noaa.gov/ost/nggps/DycoreTestingFiles/HIWPP_3kmfcst_reportv3.pdf

Harris, L., S.-J. Lin, C.-Y. Tu, 2016: High resolution climate simulations using GFDL HiRAM with a stretched global grid. J. Clim., accepted.

Publications:

Zhou, L., S.-J. Lin, L. Harris, et al., 2016: 8-day Forecast of a 3-50 Variable-resolution GCM, in preparation.

Progress Reports:

Earth System Model Applications

Progress Report Title: **Subseasonal Hurricanes Forecast in the GFDL Nested Grid Prediction System**

Principal Investigator: Usama Anber (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Lucas Harris and Shian-Jian Lin (GFDL)

Other Participating Researchers: Jan-Huey Chen (UCAR)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Model Applications

NOAA Goals:
Weather-Ready Nation Goal: Society is Prepared for and Responds to Weather-Related Events

Objectives: Predictability of tropical cyclones on subseasonal (30-60 days) timescale using a mesh refinement method in the GFDL HiRAM

Methods and Results/Accomplishments:

The Geophysical Fluid Dynamics Laboratory (GFDL) High-Resolution Atmospheric Model (HiRAM) (Zhao et al. 2009) has proven to have remarkable skills in predicting tropical cyclones (TC) counts on interannual and seasonal timescales in the Northern Atlantic basin (Chen and Lin 2011 and 20113) with a resolution of approximately 25 km. However, or a subseasonal time scale of 30-to-60 days in which intensity is the measure of interest, global climate models including HiRAM have serious limitations.

For that matter, a new promising mesh-refinement technique was implemented in HiRAM by regionally nesting a higher resolution grid that updates in two-way the interpolated boundary conditions (Harris and Lin 2013, and 2014). The model utilizes the same parameterization physics as the global HiRAM except that the single plume convective scheme is now replaced with the new double plume scheme (Zhao, M. 2014 unpublished manuscript) that better simulates tropical intraseasonal variability. The model's regional grid resolution is 8 km and is nested in the tropical North Atlantic. Persistent sea surface temperatures are used as prescribed boundary conditions as in Chen and Lin 2011, and 2013.

A series of sub-seasonal forecast runs were performed for the years 2005 and 2006 with a set of rolling initial conditions every 5 days starting June 26 until October 30. Every run lasts for 30 days, and the following run starts 5 days before the last day of the previous run. Initial conditions are generated by a simple nudging technique to NCEP/GFS dataset. TCs are identified in the model using a detection-and tracking algorithm (Harris et al. 2016) on the 6 hourly model output, storms are then categorized based on Saffir-Simpson scale.

Research is still undergoing to investigate TC sensitivity to the model's physics, initial, and boundary conditions.

References:

Chen, J.-H, and S.-J. Lin, 2013: Seasonal Predictions of Tropical Cyclones Using a 25-km-Resolution General Circulation Model. J. Climate, 26, 380–398.

Chen, J.-H., and S.-J. Lin (2011), The remarkable predictability of inter-annual variability of Atlantic hurricanes during the past decade, Geophys. Res. Lett., 38, L11804, doi:10.1029/2011GL047629.

Harris, L. M., S.-J. Lin, and C. Y. Tu, 2016: High resolution climate simulations using GFDL HiRAM with a stretched global grid. J. Climate, in press.

Harris, L. M. and S.-J. Lin, 2014: Global-to-Regional Nested Grid Climate Simulations in the GFDL High Resolution Atmospheric Model. J. Climate, 27, 4890–4910.

Harris. L. M. and S.-J. Lin, 2013: A Two-Way Nested Global-Regional Dynamical Core on the Cubed-Sphere Grid. Mon. Wea. Rev., 141, 283–306.

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

Outreach Activities: Princeton Postdoctoral Entrepreneurs

Progress Report Title: **Diverse Impacts of Orography on Asian Climate**

Principal Investigator: Jane Wilson Baldwin (Princeton Graduate Student)

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

Other Participating Researchers: Michael Oppenheimer, Jay Dessy, and Robert Socolow (Princeton), Chris Milly (USGS)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Model Applications

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: The primary objective of my research is to understand how large-scale atmospheric circulations impact regional climates, with particular foci on deserts and the influences of orography. An additional project aims to explore the risks and policy implications of extreme heat events.

Methods and Results/Accomplishments:

This year, Gabriel Vecchi and I have refined a study of the influence of the Tianshan Mountains on arid extratropical Asia using the GCM GFDL-FLOR. We have clarified the strong influences of these mountains on the East Asian Monsoon and the Taklimakan Desert, and their dynamical mechanisms. Using a new high resolution Asian precipitation dataset called APHRODITE, we also explored the variability of the sparse precipitation in this region. We found that even with improved observations the variability of precipitation in this region is largely indistinguishable from noise. This result redirected our focus to examining influences of orography on climate. We are currently using GFDL-FLOR to examine the remote influences of Asian orography, including that on typhoons in the Pacific and Indian Oceans, and precipitation in Africa.

In collaboration with Michael Oppenheimer and as part of a WWS-STEP fellowship, I am also analyzing the risk of compound heat wave events (i.e., heat wave followed by another heat wave) using reanalyzed observations, large-ensemble output of GFDL-FLOR, and the CMIP5. This work is motivated by policy implications for health, insurance, and agriculture.

Finally, along with Robert Socolow and other students in Princeton Energy and Climate Scholars (PECS; an honors group of graduate students studying energy and climate related topics), I have co-authored a report that aims to be an objective analysis on the potential of fusion energy. This report being published by Princeton's Andlinger Center, and will be distributed broadly to policy makers and educators.

Outreach Activities: This year I have piloted an outreach program with PECS and Princeton Day School. Each month we have presented about these topics to a group of ~15 high school students interested in sustainability, inspiring students in the group to pursue careers in these areas. As an adviser to the undergraduates in Rockefeller College at Princeton, I have hosted a number of dinner discussions about women in science, and with Princeton professors studying energy/climate/sustainability. Finally, with

Michael Oppenheimer, I am co-supervising undergraduate Jay Dessy on his senior thesis in the Princeton Geosciences department.

Publications:

Baldwin, Jane and Gabriel Vecchi, "Influence of the Tianshan Mountains on Arid Extratropical Asia." Submitted to Journal of Climate.

Chou, Cleo, Janam Jhaveri, Jane Baldwin et al, Nuclear Energy from Magnetic Confinement Fusion: An Energy Technology Distillate from the Andlinger Center for Energy and the Environment, Princeton University." Accepted March 2016.

Progress Report Title: **Plankton Community Dynamics in a Changing Climate**

Principal Investigator: Andrew Barton (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Charlie Stock (GFDL), Fernando González-Taboada (Princeton)

Other Participating Researchers: Andrew Irwin & Zoe Finkel (Mt. Allison University, Canada), Angus Atkinson (Plymouth Marine Laboratory, UK)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Model Applications

NOAA Goals:
Healthy Oceans Goal: Marine Fisheries, Habitats, and Biodiversity are Sustained within Healthy and Productive Ecosystems (50%)
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts (50%)

Objectives: My work has centered around two objectives: a) Understand how plankton biogeography, community composition, and diversity may respond to changing climate over the coming century and b) Diagnose the prevalence of regime shifts in plankton communities in observations and models, and understand their primary drivers.

Methods and Results/Accomplishments:

My research accomplishments center on the two objectives note above. Firstly, my colleagues (Stock, Irwin, Finkel) and I have investigated how individual phytoplankton species ranges, and consequently entire phytoplankton communities, may respond to anthropogenic climate change. Using historical environmental and phytoplankton observations, we characterized the realized ecological niches for 141 North Atlantic diatom and dinoflagellate taxa, and projected changes in species biogeography between mean historical (1951-2000) and future ocean conditions (2051-2100), using data taken from GFDL ESM2G simulations. We found that the central positions of the core range of 74% of taxa shift poleward at a median rate of 12.9 km dec^{-1}, and 90% of taxa shift eastwards at a median rate of 42.7 km dec^{-1}. The poleward shift was faster than previously reported for marine taxa, and the predominance of longitudinal shifts is driven by dynamic changes in multiple environmental drivers, rather than a strictly poleward, temperature-driven redistribution of ocean habitats. Overall, the North Atlantic phytoplankton community appears poised for marked change, which may have broad impacts on food webs and biogeochemical cycles. The results of this study appear in *PNAS* (citation below).

Secondly, my colleagues and I (Stock, González, Atkinson) have examined the character of low frequency variability, including regime shifts, in the plankton community observed at the L4 station in the English Channel. We have tested the hypothesis ("Double Integration Hypothesis") that low frequency variability in the plankton arises from a two-step process whereby noisy atmospheric variability is first filtered through the relatively sluggish ocean surface before secondarily imprinting on plankton with relatively long lifetimes. Rather than confirming this hypothesis, our analysis indicates that plankton populations, from small phytoplankton to krill, closely track anomalies in ocean surface conditions. We are now complementing this observational analysis by diagnosing the prevalence of regime shifts (defined here as long-lasting and dramatic changes in community structure) in the plankton community simulated

in the GFDL ESM2M under preindustrial greenhouse gas conditions. Our initial results indicate that model regime shifts are more likely for larger organisms and higher trophic levels. Taken together, these observation and model analyses provide new context for the existence of regime shifts in marine plankton communities, and why they occur.

Over the coming year, I plan to extend these latter activities in two main ways: 1) Collect, curate, and analyze the character of low frequency variability and occurrence of regime shifts in many plankton time series from around the globe, with an aspirational goal of ~50 time series from many different ecosystems; and 2) Using output from GFDL suite of ESM's, diagnose the triggers in the Earth System (e.g., changes in ocean circulation, winds, temperature, and nutrient conditions) for regime shift events in marine plankton populations.

Additionally, I organized a focused workshop for 100 people for the fall of 2015 on "Trait-based approaches to ocean life" (http://www.whoi.edu/workshop/traitworkshop2015/home). This workshop brought together biologists, ecologists, chemists, mathematicians, and physicists working on different aspects of trait-based descriptions of life in the oceans across all trophic levels and scales, from viruses to top predators and from fine-scale turbulence to global climate change. I wrote a successful funding proposal to Ocean Carbon and Biogeochemistry (and NSF- and NASA-funded organization), and also secured funding from the Gordon and Betty Moore and Simons Foundations.

Outreach Activities: I was recently elected to the US Ocean Carbon and Biogeochemistry (OCB) Scientific Steering Committee (SSC). The role of OCB is to build interdisciplinary partnerships between scientists and with complementary US and international programs to address high-priority research questions in ocean biogeochemistry, and the members of the SSC coordinate these activities, principally through organizing and funding workshops, meetings, and outreach activities.

Publications:

Barton, AD, Irwin, AJ, Finkel, ZV, Stock, CA (2016) Anthropogenic climate change drives shift and shuffle in North Atlantic phytoplankton communities. Proceedings of the National Academy of Sciences, 10.1073/pnas.1519080113.

Dave, A.C., Barton, A.D., Lozier, M.S., and G.A. McKinley (2015). What drives seasonal change in oligotrophic area in the subtropical North Atlantic? Journal of Geophysical Research Oceans 120, doi:10.1002/2015JC01078.

Presentations:

Barton, A.D., González-Taboada, F., Atkinson, A., and C.A. Stock, (2016). Environmental variability and plankton population dynamics in the English Channel. Oral presentation at the Ocean Sciences Meeting, New Orleans, LA, February 22-26.

Barton, A.D., González-Taboada, F., Atkinson, A., and C.A. Stock, (2015). Drivers of regime shifts in marine plankton communities. Poster presented at the "Trait-based Approaches to Ocean Life" workshop, Waterville Valley, NH, October 5-8.

Barton, A.D. (2015). Toward a global plankton trait database. Invited oral presentation at the EMODnet Biology Workshop, Heraklion, Greece, June 9-10.

Barton, A.D., Ward, B.A., Williams, R.G., and M.J. Follows (2015). The roles of turbulence and zooplankton grazing in shaping phytoplankton community structure and carbon export. Invited oral presentation at the ASLO Aquatic Sciences Meeting, Granada, Spain, February 22-27.

Progress Report Title: **Regional Predictability of Arctic Sea Ice**

Principal Investigator: Mitch Bushuk (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Michael Winton and Gabriel Vecchi (GFDL)

Other Participating Researchers: Rym Msadek (CNRS-CERFACS)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Model Applications

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: To understand and quantify the sources of regional predictability for Arctic sea ice, and use this knowledge to improve operational forecast systems for seasonal prediction of Arctic sea ice

Methods and Results/Accomplishments:

Our work has focused on the regional forecast skill of Arctic sea ice in the GFDL seasonal prediction model framework. Analyzing hindcasts spanning 1982-present made with CM2.1, FLOR and FLOR-FA, we have quantified forecast skill using a number of different skill metrics. All models show skill in predicting the detrended pan-Arctic sea ice extent (Msadek 2014). Skill is present at leads of 2-6 months, depending on the initialization month. The forecasts have less skill regionally, due to errors made in the initialization of sea-ice concentration and sea-ice thickness.

To examine the effect of improved thickness initialization of regional forecast skill, we have run a suite of perturbation experiments in which we modify initial conditions for sea ice thickness. These experiments include (1) initialization with an anomaly relative to the FLOR thickness climatology, which is more realistic than the thin-biased CM2.1 model; and (2) initializing forecasts with sea ice thickness satellite observations from the CRYOSAT-2 mission. These thickness perturbations have a significant impact on the sea ice extent in September, which is the month in which sea ice extent is at its minimum.

Studying the memory of these thickness perturbations, we have found that winter and spring sea-ice thickness anomalies tend to be enhanced over the summer months. This enhancement is a robust feature of all of our initialized prediction runs, as well as a 1400-year 1990 control integration of the FLOR model. Analysis of the surface energy budget reveals that the summer volume enhancement is driven by a positive feedback between the SIT state and the surface albedo. The SIT state affects surface albedo through changes in the melt onset date, ice thickness distribution, and sea ice concentration, yielding an anomaly in the total absorbed shortwave radiation between May and August, which enhances the existing SIT anomaly. This phenomenon highlights the crucial importance of accurate SIT initialization in seasonal forecast systems.

References:

Msadek, R., G. Vecchi, M. Winton, and R. Gudgel, 2014: Importance of initial conditions in seasonal predictions of Arctic sea ice extent. Geophys. Res. Lett., 41 (14), 5208-5215.

Publications:

Bushuk, M., R. Msadek, M. Winton and G. Vecchi (2016), Summer enhancement of Arctic sea-ice volume anomalies in the September sea-ice zone, in preparation for Journal of Climate.

Progress Report Title: **The Role of Water Vapor and Moist Convection in the Intertropical Convergence Zone (ITCZ) Response to Hemispherically Asymmetric Forcings**

Principal Investigator: Spencer Clark (Princeton Graduate Student)

CICS/GFDL Collaborator: Yi Ming and Isaac Held (GFDL), Stephan Fueglistaler (Princeton)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Model Applications

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: Through this work, we aim to gain a better understanding for what controls the sensitivity of the ITCZ to changes in the inter-hemispheric energy budget. Specifically we would like to isolate the impacts of the water vapor radiative feedback and convection scheme in an idealized moist climate model.

Methods and Results/Accomplishments:

The intertropical convergence zone (ITCZ) is a sharply defined maximum in the zonal mean precipitation rate in the tropics (Xie and Arkin, 1997). In the current climate, in the annual mean it lies just north of the equator. Paleoclimate evidence suggests that the annual mean position of this precipitation maximum has changed throughout the last 100,000 years, shifting northward in response to warming events centered in the northern hemisphere (Peterson et al., 2000), and southward in response to cooling events in the northern hemisphere (Sachs et al., 2009). Evidence also exists that the position of the ITCZ has changed more recently during the 20th century in response to anthropogenic forcings (Bollasina et al., 2011; Hwang et al., 2013). Given its narrow structure, understanding what controls the position of the ITCZ is an important question from a societal impact point of view.

In recent years, studies have used idealized models to attempt to gain a clearer theoretical understanding for what controls the position of the ITCZ. While these idealized models include water vapor as a tracer that evaporates and condenses in the atmosphere, releasing latent heat, they do not include the radiative effects of water vapor (Frierson et al., 2006; Bischoff and Schneider, 2014). To isolate the impacts of water vapor and convection scheme, we run a new version of an idealized moist model (an atmospheric dynamical core, with simplified sub-grid parameterizations of convection, boundary layer fluxes, a slab ocean, and radiation (Frierson et al., 2006)) in four different configurations. These configurations are all combinations of convection being turned on or off, and dynamic water vapor interacting with radiation or fixed climatological water vapor interacting with radiation.

The new aspect of this idealized moist model is that it is coupled to a full radiative transfer code. This means that changes in the water vapor field (when the dynamic water vapor interacts with radiation) change the optical depth of the atmosphere in the model. Prior studies using this type of idealized model do not have a dynamic optical depth (Kang et al., 2008; Bischoff and Schneider, 2014). We find that water vapor plays a role in amplifying the response of the ITCZ shift to a given magnitude asymmetric solar forcing — for a given forcing asymmetry (northern hemisphere average minus southern hemisphere average) water vapor nearly doubles the latitudinal shift of the ITCZ. Running the model without

convection makes the ITCZ more sensitive to a given forcing asymmetry as well; this appears to be a consequence of a shallower omega profile leading the circulation at the ITCZ to converge moist static energy rather than diverge it.

Outreach Activities: Mentoring a high school student completing a year-long research project. I have introduced him to programming in python to do some basic analysis of air quality near his hometown in Staten Island, New York.

References:

Bischoff, T. and Schneider, T. (2014). Energetic Constraints on the Position of the Intertropical Convergence Zone. Journal of Climate, 27:4937–4951.

Bollasina, M. A., Ming, Y., and Ramaswamy, V. (2011). Anthropogenic aerosols and the weakening of the south Asian summer monsoon. Science, 334(6055):502–505.

Frierson, D. M. W., Held, I. M., and Zurita-Gotor, P. (2006). A Gray-Radiation Aquaplanet Moist GCM. Part I: Static Stability and Eddy Scale. Journal of the Atmospheric Sciences, 63:2548–2566.

Hwang, Y.-T., Frierson, D. M. W., and Kang, S. M. (2013). Anthropogenic sulfate aerosol and the southward shift of tropical precipitation in the late 20th century. Geophysical Research Letters, 40:1–6.

Kang, S. M., Held, I. M., Frierson, D. M. W., and Zhao, M. (2008). The Response of the ITCZ to Extratropical Thermal Forcing: Idealized Slab-Ocean Experiments in a GCM. Journal of Climate, 21:3521–3532.

Peterson, L. C., Haug, G. H., Hughen, K. A., and Rohl, U. (2000). Rapid changes in the hydrologic cycle of the tropical Atlantic during the last glacial. Science, 290(5498):1947–1951.

Sachs, J. P., Sachse, D., Smittenberg, R. H., Zhang, Z., Battisti, D. S., and Golubic, S. (2009). Southward movement of the pacific intertropical convergence zone ad 1400-1850. Nat. Geosci., 2(7):519–525.

Xie, P. and Arkin, P. A. (1997). Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. Bulletin of the American Meteorological Society, 78(11):2539–2558.

Presentations:

Clark, S. K., Ming, Y., and Held, I. M. "Climate Impacts of Inter-hemispherically Asymmetric Radiative Forcing." AGU Fall Meeting, San Francisco, CA, December 2015. Poster Presentation.

Clark, S. K., Ming, Y., and Held, I. M. "Climate Impacts of Inter-hemispherically Asymmetric Radiative Forcing." Gordon Research Conference, Lewiston, ME, July 2015. Poster Presentation.

Progress Report Title: **Southern Ocean Surface Buoyancy Fluxes and Circulation: The Role of Sea Ice and Icebergs**

Principal Investigator: Anna FitzMaurice (Princeton Graduate Student)

CICS/GFDL Collaborator: Robert Hallberg (GFDL)

Other Participating Researchers: Adele Morrison (Princeton), Fiamma Straneo (WHOI), Claudia Cenedese (WHOI)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Model Applications

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: We seek to understand the potential impact of changing surface buoyancy fluxes on Southern Ocean circulation. As part of this study we hope to improve modelling of icebergs' motion and melt, and their contribution to surface buoyancy fluxes.

Methods and Results/Accomplishments:

The importance of the Southern Ocean for the exchange of heat and carbon with the atmosphere motivates attempts to understand the overturning circulation in this region. Recent literature has noted a spatial correspondence between the Antarctic sea ice extent and the latitude at which the divide between the upper and the lower overturning cells in the Southern Ocean outcrops at the surface. This has given rise to two hypotheses: firstly, that the sea ice extent controls the location of the latitude dividing the two overturning cells via its effect on surface buoyancy fluxes. Secondly, that the latitude of the overturning divide limits the sea ice extent due to its influence on sea surface temperatures. We tested these hypotheses by running a series of perturbation experiments in a coupled GCM. It was found that no directly causal relationship exists between the Southern Ocean overturning and the Antarctic sea ice extent, but that there are complex interactions between the two. In particular, changes to the overturning circulation may indirectly influence the sea ice extent via modification of the Southern Ocean stratification and upwelling of heat. Perturbations to the sea ice extent, meanwhile, have a highly seasonal influence on surface buoyancy fluxes, whose effect on the overturning is not immediately apparent in the annual average due to the seasonal variation in both the location of these fluxes and the water masses receiving the fluxes.

At present, one of the least understood and most rapidly changing contributions to surface buoyancy fluxes in the Southern Ocean is that from iceberg melt. Due to a lack of observational data, the distribution, trajectories, and melt of icebergs are currently poorly constrained. We plan to analyze acoustic data from Sermilik Fjord in southeastern Greenland to obtain a one-year record of iceberg speed and draft in the fjord. This will be used in conjunction with co-located ocean current and wind velocity data to study the dominant balances controlling iceberg motion. The results from the data analysis will be used to inform laboratory experiments of iceberg melting that seek to guide the improvement of parameterizations of melt flux from icebergs in ocean and climate models. In the context of the currently increasing discharge of icebergs from both poles, accurate modelling of this melt flux and its influence on

surface buoyancy fluxes is an important component of assessing the potential impacts of future climate change on ocean circulation.

References:

Ferrari, R. et. al., 2014. Antarctic Sea Ice Control on Ocean Circulation in Present and Glacial Climates. PNAS, 111(24), pp.8753-8.

Marshall, J. & Speer, K., 2012. Closure of the Meridional Overturning Circulation Through Southern Ocean Upwelling. Nature Geoscience, 5(3), pp.171-180.

Presentations:

A. FitzMaurice, A., K. Morrison, and R. Hallberg: On the Relationship between Antarctic Sea Ice Extent and the Southern Ocean Overturning Circulation. Poster presented at: Physical and Biogeochemical Processes in the Southern Ocean: Observations, State Estimation, and Modeling V. 18th Biennial Ocean Sciences Conference, 2016 Feb 21-26; New Orleans, LA.

Progress Report Title: **Understanding Cloud Processes with an Idealized Model**

Principal Investigator: Michelle Frazer (Princeton Graduate Student)

CICS/GFDL Collaborator: Yi Ming (GFDL), Isaac Held (GFDL), Stephan Fueglistaler (Princeton)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Model Applications

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: My project involves studying moisture effects in an idealized setting (the Held-Suarez dynamical core) in order to isolate the physical mechanisms driving global moisture distribution and ultimately improve the understanding of cloud effects in general circulation models (GCMs).

Methods and Results/Accomplishments:

My research utilizes the idealized Held-Suarez (HS) dynamic core (Held and Suarez 1994) to study moisture and cloud effects. The HS core involves a spherical rotating planet with a dry atmosphere forced by a Newtonian relaxation of temperature toward a prescribed zonally symmetric equilibrium. With the addition of passive water and cloud tracers, the HS core is a unique platform to explore the isolated role of various cloud processes through controlled experiments. I use the HS model with two different moisture representations: a passive water tracer for the base case (after Galewsky, et al. 2005) and a cloud scheme from a comprehensive climate model (as in Zhao, et al. 2009). The base case is a representation of advection-condensation theory: an advected parcel becomes saturated when it enters surface layers (where moisture is replenished by evaporation) and loses moisture through immediate precipitation (no clouds) when 100% relative humidity (RH) is reached. The cloud scheme adds cloud liquid, cloud ice, and cloud amount tracers. Cloud formation and precipitation are influenced by microphysical factors as well as processes such as rain re-evaporation. Sub-grid-scale cloud distribution is a total water-based probability density function.

The HS base case yields a qualitatively realistic RH distribution (outside of the tropics which lack a convection parameterization and the boundary layer which includes artificial evaporation). With the introduction of a cloud scheme, RH in the dry subtopics increases (by a few percent) and RH in the polar upper troposphere decreases (by a few percent). Perturbation experiments suggest that the RH changes due to the cloud scheme are largely caused by two factors. First, rain evaporation and snow sublimation moisten the dry subtropics. Second, the ability of the cloud scheme to allow cloud formation (and hence precipitation) before 100% grid-box RH is reached means that cloud formation in the extratropics reduces the amount of moisture advected poleward along isentropic surfaces.

Perturbation experiments varying the circulation by changing the equilibrium temperature field highlight the importance of circulation in setting RH and cloud amount. Both are tightly connected to changes in the strength of baroclinic eddies as well as the location of the eddy-driven jet stream. Neither RH or cloud amount can be solely explained by temperature changes.

So far, this project has demonstrated the usefulness of the HS core for understanding cloud processes by cleanly isolating key processes. Additionally, the importance of cloud microphysics, cloud formation, RH thresholds, and circulation changes have been highlighted. Going forward, I will further

study the effects of perturbation experiments on RH, clouds, and the hydrological cycle while eventually incorporating a diagnostic radiation code and individual cloud radiative effects in this idealized model.

Outreach Activities: I tutor a high school student bi-weekly through Princeton's PACE Center Community House SAT Prep program.

References:

Held, I. M., and M. J. Suarez, 1994: A proposal for the intercomparison of the dynamical cores of atmospheric general circulation models. Bull. Amer. Meteor. Soc., 75, 1825–1830.

Galewsky, J., A. Sobel, and I. Held, 2005: Diagnosis of subtropical humidity dynamics using tracers of last saturation. J. Atmos. Sci., 62, 3353–3367.

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Publications:

Frazer, M. E., Y. Ming, and I. M. Held. "What Controls the Strength of the Hydrological Cycle and Subtropical Relative Humidity in an Idealized Model?" Poster presentation, Gordon Research Conference (and Gordon Research Seminar) on Radiation & Climate, July 2015.

Frazer, M. E., Y. Ming, and I. M. Held. "What Controls the Strength of the Hydrological Cycle and Subtropical Relative Humidity in an Idealized Model?" Poster presentation, AGU Fall Meeting, December 2015.

Progress Report Title: **Long Term Variability of Planktonic Ecosystems in Earth System Models**

Principal Investigator: Fernando González Taboada (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Charles Stock and John Dunne (GFDL), Andrew Barton (Princeton)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Model Applications

NOAA Goals:
Healthy Oceans Goal: Marine Fisheries, Habitats, and Biodiversity are Sustained within Healthy and Productive Ecosystems

Objectives: Assess the ability of Earth Systems Models (ESM) to reproduce long term variability in planktonic marine ecosystems, with a particular focus on decadal variability, regime shifts, and prospects for marine ecosystem prediction.

Methods and Results/Accomplishments:

We have worked on two main projects within the Marine Ecosystems Tipping Points initiative; (i) an assessment of the ability of Earth System Models (ESMs) to reproduce and predict variability in marine ecosystem dynamics, and (ii) an analysis of the reliability of different wind reanalysis products for ocean model forcing, with an emphasis on coastal upwelling.

The assessment of marine ecosystem variability in ESMs focuses on a novel set of diagnostics targeting the prediction of short term changes in marine Net Primary Production (NPP), from monthly to seasonal scales using statistical methods. The focus on NPP reflects its central role in marine ecosystem functioning and in the global carbon cycle. A first objective consist in mapping and identifying candidate mechanisms generating NPP predictability, in order to identify candidate regions where NPP prediction might potentially lead to an improved management of living marine resources. The approach relied on fitting a set of reduced dimension, linear Dynamic SpatioTemporal Models (rDSTM, Cressie & Wikle 2011) to changes in monthly NPP anomalies derived from 18 years of remote sensing data and from simulations of the Carbon, Ocean Biogeochemistry and Lower Trophics (COBALT) planktonic ecosystem model coupled to GFDL ESM2M (Stock et al. 2014). This assessment revealed that seasonal NPP can be anticipated up to 24 months in advance, especially in subtropical latitudes. Predictability was dominated by the decay of major modes at short lead times, with an important contribution emerging from the prevalence of slow moving modes related to El Niño-Southern Oscillation and the Atlantic multidecadal oscillation. Predictability at longer lead times resulted from interactions reflecting the propagation of major climatic modes. Preliminary results were presented at Ocean Sciences Meeting 2016 and we are currently finishing to draft a manuscript.

The assessment of wind reanalysis products focused on identifying the differences and limitations of candidate datasets for high-resolution retrospective ocean-ice-ecosystem simulations – a key product from the marine ecosystem tipping points initiative. We focused on the representation of wind patterns responsible for nutrient upwelling, a critical determinant of marine ecosystem productivity, and on characterization and detection of potential biases in coastal regions and eastern boundary current regions where models present important sea surface temperature biases (Richter 2015). The results revealed systematic differences between different products, with an increase in quality in recent, higher resolution products that can be compensated to some extent but not substituted by an interpolation scheme ignoring

winds over land. However, biases remain in some regions of particular interest, like the California and the Namibian upwelling regions, which suggest the need of nonlinear adjustments and/or more elaborate interpolations schemes in these areas. We are currently finishing to draft a manuscript.

References:

Brodeau, L., Barnier, B., Treguier, A.M., Penduff, T., and Gulev, S. (2010). An ERA40-based atmospheric forcing for global ocean circulation models. Ocean Modelling 31: 88-104.

Cressie, N. & Wikle, C.K. (2011). Statistics for Spatio-Temporal Data. 1st ed. John Wiley & Sons, Hoboken, NJ, USA.

Fore, A., Stiles, B., Chau, A., Williams, B., Dunbar, R. and Rodriguez, E. 2014. Point-wise wind retrieval and ambiguity removal improvements for the QuikSCAT climatological data set. IEEE Transactions on Geoscience and Remote Sensing 52: 51-59.

Large, W.G. and Yeager, S.G. (2009). The global climatology of an interannually varying air-sea flux data set. Climate Dynamics 33: 341-364.

Richter, I. 2015. Climate model biases in the eastern tropical oceans: causes, impacts and ways forward. Wiley Interdisciplinary Reviews: Climate Change, 6, 345-358.

Stock, C.A., J.P. Dunne and J.G. John. 2014. Global-scale carbon and energy flows through the marine planktonic food web: an analysis with a coupled physical-biological model. Progress in Oceanography 120: 1-28.

Publications:

González Taboada F., Ch. Stock, S. Griffies, J Dunne. (in preparation). Limitations and biases of wind reanalysis products for ocean model forcing.

González Taboada F., A. Barton, Ch. Stock (in preparation). Predictive skill of oceanic net primary production based on a reduced dimension, linear dynamic spatiotemporal model.

Barton, A., F. González Taboada, A. Atkinson, Ch. Stock. (in preparation). Environmental Variability and Plankton Community Dynamics in the English Channel.

González Taboada, F., R. Anadón (in press) Determining the causes behind the collapse of a small pelagic fishery using Bayesian population modeling. Ecological Applications. doi: 10.1890/15-0006.1.

García, F. C., E. García-Martín, F. González Taboada, S. Sal Bregua, P. Serret, Á. López-Urrutia (in press) The allometry of the smallest: superlinear scaling of microbial metabolic rates in the Atlantic Ocean. ISME Journal. doi: 10.1038/ismej.2015.203.

Presentations:

González Taboada, F., A. Barton, Ch. Stock. 2016. Predicting global oceanic NPP with reduced-dimension, linear dynamical spatiotemporal models. Ocean Sciences Meeting, New Orleans, USA. [poster].

Barton, A., F. González Taboada, A. Atkinson, Ch. Stock. 2016. Environmental Variability and Plankton Community Dynamics in the English Channel. Ocean Sciences Meeting, New Orleans, USA. [oral presentation].

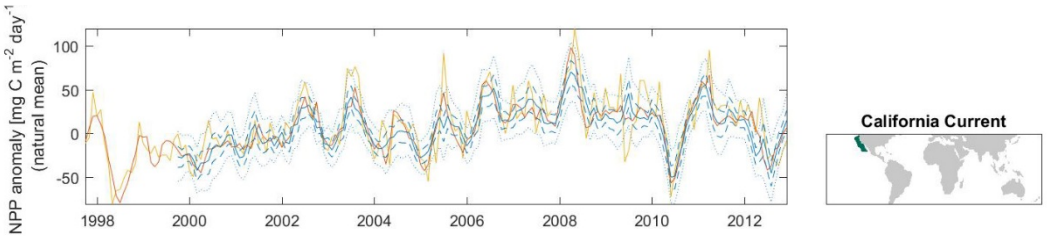

Figure 1. Example model fit of linear rDSTM to monthly NPP anomalies over the California Current Large Marine Ecosystem (Eppley-VGPM, www.science.oregonstate.edu/ocean.productivity). The model assimilates NPP anomalies (yellow) into a smoothed state (orange), which is used to estimate an evolution matrix used to project forward in time the anomalies (blue lines).

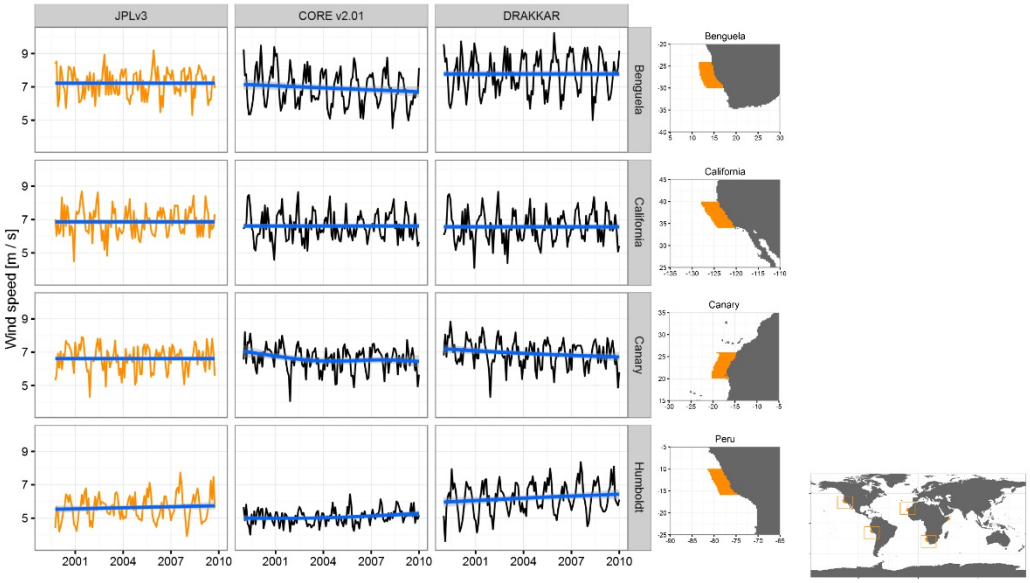

Figure 2. Monthly wind speed magnitude averaged over the main upwelling regions of the world for two of the ocean model forcing reanalysis products analyzed (Brodeau et al. 2010, Large and Yeager 2009) and compared to QuikSCAT data (Jet Propulsion Laboratory, JPL L2B v3 12.5 km; podaac.jpl.nasa.gov/QuikSCAT, Fore et al., 2014).

Progress Report Title: **Subseasonal-to-Seasonal Climate Prediction with a Focus on Drought**

Principal Investigator: Nathaniel Johnson (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Gabriel Vecchi (GFDL), Andrew Wittenberg (GFDL), Sarah Kapnick (GFDL)

Other Participating Researchers: Lakshmi Krishnamurthy (Princeton), Jiaxin Black (Scripps/GFDL), Steven Feldstein (Penn State), Michelle L'Heureux (NOAA CPC), Dan Harnos (NOAA CPC), Steve Baxter (NOAA CPC), Shang-Ping Xie (Scripps), Yu Kosaka (U. Tokyo)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Model Applications

NOAA Goals:
Weather-Ready Nation Goal: Society is Prepared for and Responds to Weather-Related Events (80%)
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts (20%)
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Objectives: The primary objectives of this project are (1) to improve our understanding of subseasonal-to-seasonal climate predictability over North America, with a focus on regional droughts, and (2) to develop improved subseasonal-to-seasonal climate prediction methods.

Methods and Results/Accomplishments:

Over the past year, I have made progress in the theory and application of climate prediction studies, with a focus on drought prediction. I completed a study based on the analysis of observations and climate model simulations, including the GFDL CM2.1, to understand distinct North American impacts of two types of El Niño. This study, which focuses on the subseasonal to seasonal mechanisms and impacts, including temperature, precipitation, and drought, has resulted in a manuscript that is now in press (Johnson and Kosaka 2016).

I also have been investigating sources of North American precipitation biases in GFDL's climate models with the hope that such knowledge can translate into improved understanding of factors influencing North American drought. Specifically, I have examined differences between free-running and flux-adjusted versions of the Forecast-oriented Low Ocean Resolution (FLOR) models in an attempt to decipher why positive precipitation biases over western North America are substantially reduced in the flux-adjusted version. I conducted several experiments with FLOR to diagnose how both North Pacific and North Atlantic sea surface temperature biases are responsible for these differences. This study is nearing completion.

During the year, I also was actively involved in a research-to-operations effort in collaboration with the NOAA Climate Prediction Center (CPC). I worked with CPC scientists to transition a statistical forecast tool based on my previous work (Johnson et al. 2014) into forecast guidance that can be directly applied to operational forecasts. I organized, modified, tested, and transferred my codes to CPC so that the codes could be further modified for operational use. In September of 2015, we successfully transitioned the forecast guidance as a regular input to the operation of CPC's new experimental Week 3-4 temperature and precipitation outlooks (http://www.cpc.ncep.noaa.gov/products/predictions/WK34/), the first NOAA operational product offered for those lead times.

In June 2015, I began supervising a postdoctoral researcher, Dr. Jiaxin Black, in her studies on subseasonal climate predictability. Dr. Black has nearly completed the first project on subseasonal prediction of atmospheric teleconnection, and we plan to submit a manuscript on this work within the next few months.

Outreach Activities: Johnson, N. C. (July 2015). Transitioning research into operations for extended range weather and climate prediction. Presentation for a Penn State University extended range forecast workshop for Pennsylvania middle and high school teachers.

References:

Johnson, N. C., D. C. Collins, S. B. Feldstein, M. L. L'Heureux, and E. E. Riddle, 2014: Skillful wintertime North American temperature forecasts out to four weeks based on the state of ENSO and the MJO. Weather and Forecasting, 29, 23-38.

Publications:

Johnson, N. C., and Y. Kosaka, 2016: The impact of eastern equatorial Pacific convection on the diversity of boreal winter El Niño teleconnection patterns. Climate Dynamics, in press.

Fučkar N. S., V. Guemas, N. C. Johnson, F. Massonnet, and F. J. Doblas-Reyes, 2016: Clusters of interannual sea ice variability in the Northern Hemisphere. Climate Dynamics, in press.

Chang, C.-H., and N. C. Johnson, 2015: The continuum of wintertime Southern Hemisphere atmospheric teleconnection patterns. Journal of Climate, 28, 9507-9529.

Xie, S -P., C. Deser, G. A. Vecchi, M. Collins, T. L. Delworth, A. Hall, E. Hawkins, N. C. Johnson, C. Cassou, A. Giannini and M. Watanabe, 2015: Towards predictive understanding of regional climate change. Nature Climate Change, 5, 921-930.

Horton, D. E., N. C. Johnson, D. Singh, D. L. Swain, B. Rajaratnam, and N. S. Diffenbaugh, 2015: Contribution of changes in atmospheric circulation patterns to extreme temperature trends. Nature, 522, 465-469.

Presentations:

Johnson, N. C. (January 2015). Increasing temperature extremes during the recent global warming hiatus. AMS 95th Annual Conference.

Johnson, N. C. (October 2015). Distinctions in the boreal winter teleconnection patterns between convective and non-convective eastern Pacific El Niño episodes. 40th Annual Climate Diagnostics and Prediction Workshop.

Johnson, N. C. (December 2015). Increasing temperature extremes during the global warming hiatus. 2015 AGU Fall Meeting.

Johnson, N. C. (November 2015). Development of new forecast products for weeks 3-4. NOAA Climate Test Bed Meeting.

Johnson, N. C., Harnos, D. (October 2015). Operational transition of combined ENSO, MJO, and trend influences on temperature and precipitation for Weeks 3-4. Webinar presentation in the NOAA MAPP Webinar series.

Johnson, N. C. (April 2015). The diversity of El Niño teleconnection patterns during boreal winter. Lamont-Doherty Earth Observatory Ocean and Climate Physics Seminar series.

Johnson, N. C., Baxter, S., Feldstein, S., L'Heureux, M., & Xie, S.-P. (February 2015). Beyond week 2: Preliminary work toward generating a North American forecast system for weeks 3-4. Webinar presentation in the NOAA MAPP Webinar series.

Progress Report Title: **Exploring Emission versus Climate Drivers of Tropospheric Ozone Variability and Trends over Northern Mid-Latitudes from Space**

Principal Investigator: Meiyun Lin (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Larry Horowitz (GFDL)

Other Participating Researchers: Owen Cooper (NOAA ESRL)

Award Number: NA14OAR4320106

Task III: Individual Projects

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Model Applications

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: Determine how tropospheric ozone across the northern mid-latitudes has responded to changes in anthropogenic/biomass burning emissions and to changes in dynamic factors associated with interannual to decadal climate variability during the past 30 years.

Methods and Results/Accomplishments:

PI Meiyun Lin has been analyzing a suite of GFDL-AM3 hindcast simulations (1980-2014) designed to isolate the response of ozone to historical changes in human-induced emissions of non-methane ozone precursors from Asia versus North America, stratosphere/troposphere exchange, methane, wildfires and meteorology. These simulations are used to interpret tropospheric ozone observations, particularly with regard to data representativeness and attribution. Highlights are below from a paper published in Geophysical Research Letter [*Lin et al.,* 2015]. We present a 20-year time series of in-situ free tropospheric ozone observations above western North America during springtime and interpret results using the GFDL-AM3 chemistry-climate model hindcast simulations (1980-2014). Revisiting the analysis of *Cooper et al*. [Nature, 2010], we show that sampling biases can substantially influence calculated trends. AM3 co-sampled in space and time with observations reproduces the observed ozone trend (0.65±0.32 ppbv year-1) over 1995-2008 (in simulations either with or without time-varying emissions), whereas AM3 'true median' with continuous temporal and spatial sampling indicates an insignificant trend (0.25±0.32 ppbv year^{-1}). Our analysis provides new insights into the complicated world of ozone pollution trends over the western United States. While rising Asian emissions raises U.S. ozone background, large meteorologically-driven ozone variability and sparse in in-situ sampling can complicate efforts to obtain robust ozone trend estimates. The present-day ozone sampling frequency and distribution does not capture the full interannual and spatial variability of ozone across western North America, especially on time scales as short as 14 years (1995-2008). Accurate detection of changes in springtime ozone means and extremes over the western U.S. will require improvements in the current observation network.

PI Meiyun Lin is also working to understand the roles of emissions, wildfires, and climate variability on U.S. surface ozone trends and extremes over 1980 to 2014. Figures 2 and 3 below are highlights from a manuscript currently in preparation. Observations show that springtime ozone trends at the west coast of North America have leveled off in the 2000s, as illustrated for one site Lassen Volcanic National Park in California (Figure 2). We find that hemispheric pollution transport during spring has

weakened in the 2000s as a result of the negative phase of the Pacific Decadal Oscillation and the poleward shift of the subtropical jet stream (Figure 3). These shifts weaken pollution transport from Asia to the west coast of North America, partially offsetting the effects of rising Asian emissions on ozone flowing into the U.S. west coast. Two manuscripts are currently in preparation to document these results. Over the past year Lin has also received a number of invitations to speak at prestigious meetings (see a list of presentations below).

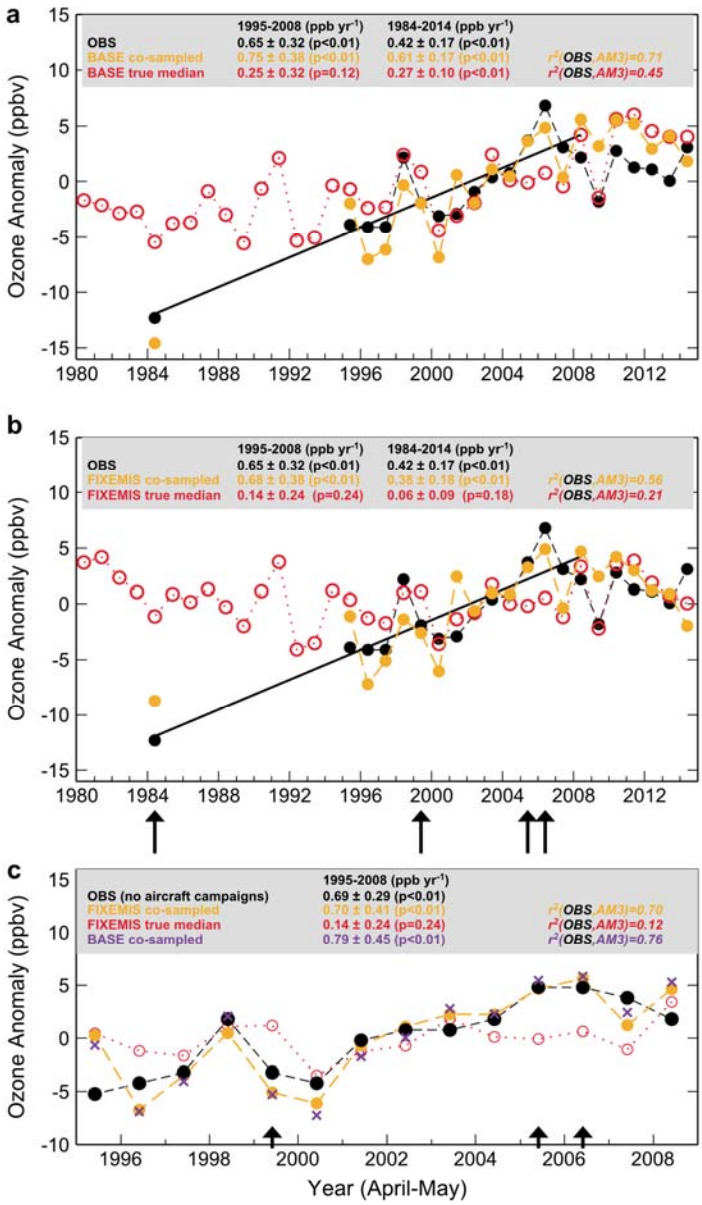


Figure 1. Representativeness of ozone measurements constructed from various platforms. (a) Anomalies (relative to the 1995–2010 mean) in the median values of April–May ozone mixing ratios 3–8 km above western North America for 1980 to 2014: from a composite of available in situ measurements (black), from AM3_BASE cosampled in space and time with observations (orange), and from the model "true median" of continuous daily and spatial sampling over the entire domain (32–50°N, 128–104°W; red). (b) Same as Figure 1a but for AM3_FIXEMIS. (c) For the 1995–2008 period with aircraft campaign data removed. The linear trends, the 95% confidence intervals, *P* values, and correlations (r^2) between observations and simulations are shown. Arrows at the bottom of the graph denote the years when observational estimates of regional median ozone are biased by sampling artifacts (Figure 2).

Figure above is taken from Lin M.Y. et al. (2015, Geophysical Research Letters).

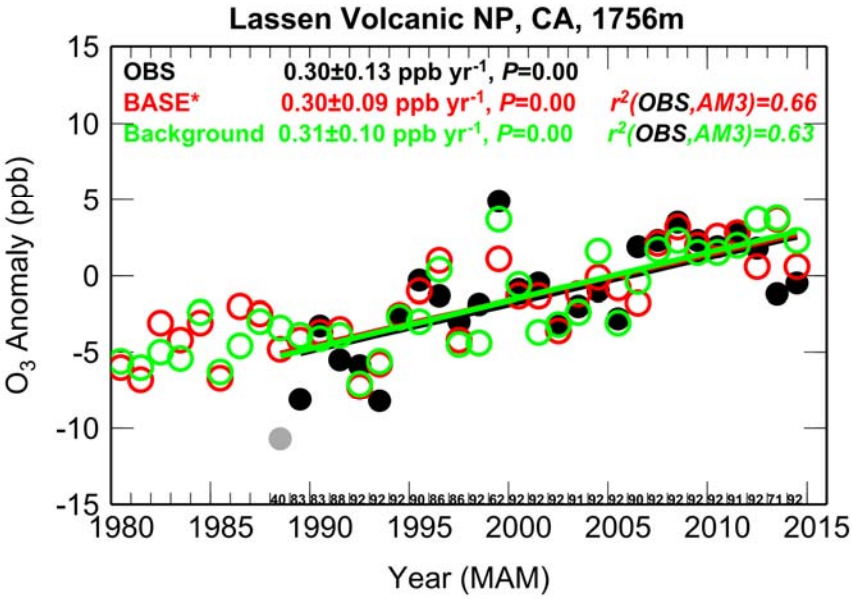


Figure 2: Time series of springtime surface ozone anomalies (relative to the 1995-2010 mean) for 1980 to 2014 at Lassen Volcanic National Park in California as observed (black) and simulated by the GFDL-AM3 BASE simulation (red) and the simulation with North American anthropogenic emissions shut off (green).

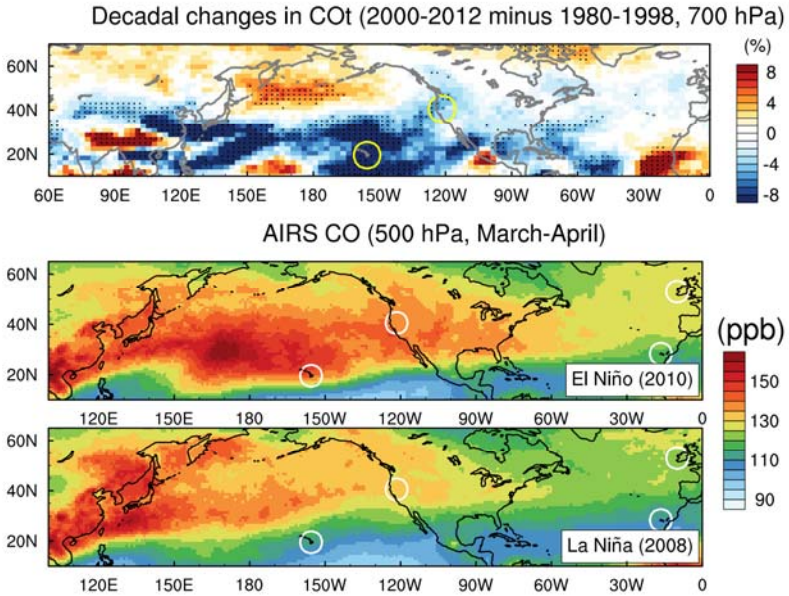


Figure 3. **Weakening of hemispheric pollution transport during March-April in the 2000s** (a) Weakening hemispheric pollution transport in the 2000s as diagnosed by the difference in a CO-like tracer (with constant emissions) from 1980-1998 to 2000-2012, as a result of a shift to the negative phase of the Pacific Decadal Oscillation and the poleward shift of the subtropical jet stream. (b-c) March-April 500-hPa CO mixing ratios measured by NASA AIRS during El Niño (2010) versus La Niña (2011). White circles denote surface sites where observed slow or no growth in ozone during the 2000s is attributed in part to the weakened transport.

Figures above are taken from Lin M.Y. et al. (2016, in prep).

Publications:

Lin, Meiyun, L.W. Horowitz, O.R. Cooper, D. Tarasick, S. Conley, L.T. Iraci, B. Johnson, T. Leblanc, I. Petropavlovskikh, E.L. Yates: Revisiting the evidence of increasing springtime ozone mixing ratios in the free troposphere over western North America, Geophysical Research Letters, 42, doi:10.1002/2015GL065311, 2015.

Lin, Meiyun, et al.: The roles of emissions, wildfires, and climate variability on U.S. surface ozone trends and extremes. To be submitted to Journal of Geophysical Research, 2016.

Presentations:

Oct-7, 2015, IGAC/SPARC Chemistry Climate Model Initiative Workshop, Italy: The Role of Climate, the Stratosphere, and Emissions on US Surface O_3 Trends and Extremes (Invited).

Sep-18, 2015, CARB/UC Davis Meteorology And Climate - Modeling for Air Quality (MAC-MAQ) Conference: Detecting changes in US background ozone means and extremes amidst climate variability (Invited).

Aug-20, 2015, Western States Air Resources Council. Key drivers of western US surface ozone means and extremes: Climate variability, stratospheric intrusions, and Asian pollution (Invited seminar).

May-11, 2015, HTAP: Modeling Air Quality from the Global to Local Scales, NCAR: Establishing process-oriented constrains on global models for ozone source attribution: Lessons from GFDL AM3.

May-13, 2015, Western Regional Air Partnership (WRAP), NCAR: Key drivers of western US surface ozone variability over recent decades: Stratospheric intrusions, Asian pollution, and Climate variability (Invited).

Apr-21, 2015, NASA AIRS Science Team Meeting, JPL, Pasadena: Challenges in quantifying sources and variability of lower tropospheric ozone over western N. America: Perspectives from satellites and models (Invited keynote speaker).

Apr-2, 2015, Transboundary Ozone Pollution Conference, California: Quantifying Asian influence on Western U.S. surface ozone exceedances and long-term trends (Invited).

Progress Report Title: **Dynamics of Transient Baroclinic Eddies in the Atmosphere of Mars**

Principal Investigator: Todd Mooring (Princeton Graduate Student)

CICS/GFDL Collaborators: Isaac Held and R. John Wilson (GFDL)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Model Applications

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: Enhance understanding of the transient baroclinic waves in the Martian atmosphere via diagnosis of reanalysis data and simulations with an idealized general circulation model

Methods and Results/Accomplishments:

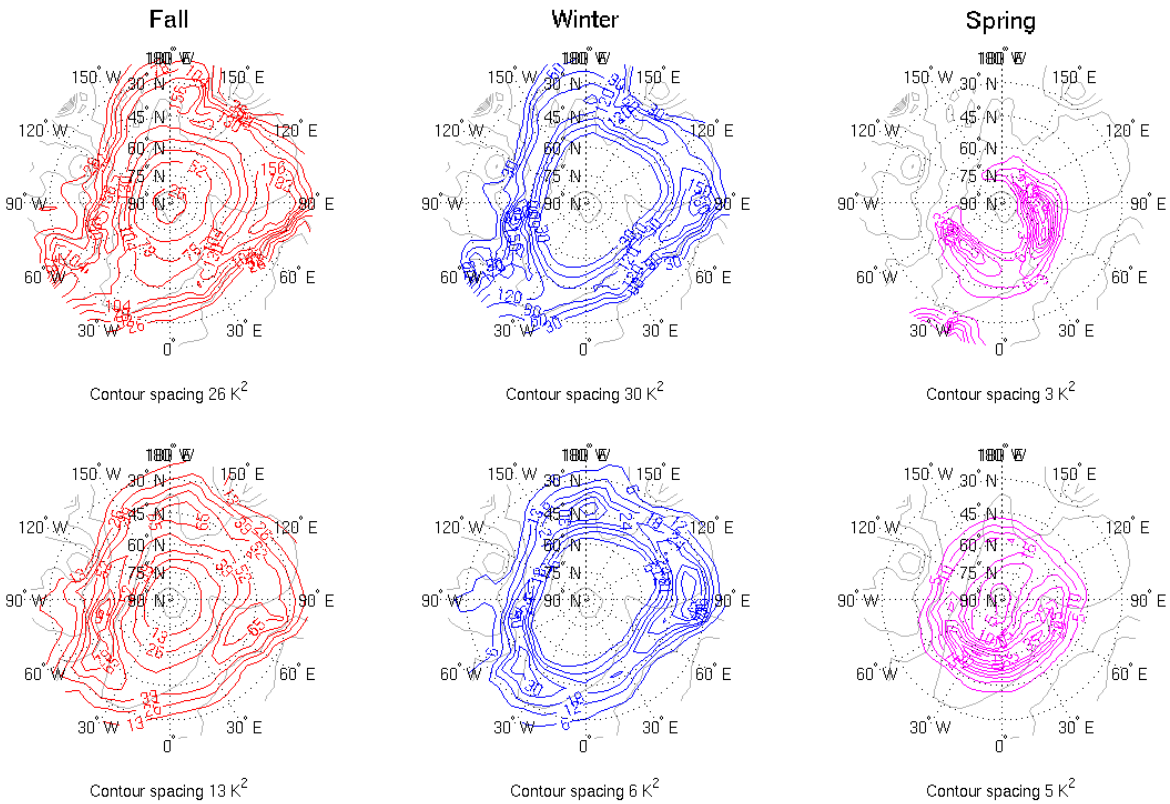
My PhD work focuses on extratropical transient eddies in the Martian atmosphere. I have approached this topic from two directions: improving our observational characterization of the transient eddies by examining them in a reanalysis dataset and performing idealized GCM simulations to better understand the fundamental atmospheric dynamics underlying their observed behaviors. The first paper from this investigation, a diagnosis of the eddies as represented in the MACDA Mars reanalysis (Montabone et al. 2014), came out last year (Mooring and Wilson 2015).

More recent and ongoing work uses an idealized GCM to explore the relationship between the time mean flow and the transient eddies in an idealized GCM with Newtonian relaxation thermal forcing. I apply the methodology of Chang (2006), iteratively constructing the radiative-convective equilibrium temperature field used to force the model so that the model's three-dimensional time mean temperature distribution is essentially prescribed.

This modeling technique is being used to address three specific questions about the dynamics of the Martian transient eddies: 1) To what extent can the seasonal cycle of transient eddy properties be accounted for in terms of the changing mean flow and the very simple physics (Newtonian relaxation plus Rayleigh surface friction) of the idealized GCM? 2) Is a bias in the eddy wavenumber spectrum (towards zonal wavenumber 2) of the GFDL full-physics Mars GCM the result of deficiencies in that model's mean flow? 3) Why are the transient eddies in the Martian atmosphere sometimes so regular, producing almost sinusoidal surface weather variability? Two hypotheses have existed for decades (Leovy 1979, Barnes 1986), but have never been meaningfully compared.

Preliminary results indicate that the idealized GCM can indeed capture aspects of the seasonally-varying spatial distribution of transient eddy activity on Mars (see figure), and that the GFDL Mars GCM wavenumber bias is indeed linked to the mean flow. The investigation of Martian wave regularity is expected to yield increased knowledge of why the atmospheric dynamics of Earth and Mars differ.

Outreach Activities: Outreach activities conducted this year include participation in the Princeton University ReMatch undergraduate research mentoring program, which involved attending four dinner or meet-and-greet events to talk to underclassmen about my work and research opportunities in atmospheric and oceanic sciences. I also volunteered at the Monmouth Junction (N. J.) PTO Science Fair, listening to elementary school students (and parents) explain their science fair projects and asking questions.



The idealized GCM described above has some capacity to reproduce the northern hemisphere seasonal cycle of squared eddy temperature (T'^2) on $\sigma = 0.9$ seen in the MACDA Mars reanalysis. The upper panels of the figure are from three idealized GCM simulations with mean temperature distributions based on various seasonal segments of the reanalysis, while lower panels are the actual reanalysis T'^2 fields. The spatial structures of the eddy activity in the idealized GCM are moderately realistic but their amplitudes are not. The model seems to do less well simulating eddy meridional winds (v'^2) and shortening the radiative damping time can result in the virtual elimination of springtime eddies.

References:

Barnes, J. R. (1986), Finite-amplitude behavior of a single baroclinic wave with multiple vertical modes: effects of thermal damping, J. Atmos. Sci., 43 (1), 58-71.

Chang, E. K. M. (2006), An idealized nonlinear model of the Northern Hemisphere winter storm tracks, J. Atmos. Sci., 63 (7), 1818-1839, doi:10.1175/JAS3726.1.

Leovy, C. B. (1979), Martian meteorology, Ann. Rev. Astron. Astrophys., 17, 387-413.

Montabone, L., Marsh, K., Lewis, S. R., Read, P. L., Smith, M. D., Holmes, J., Spiga, A., Lowe, D. and Pamment, A. (2014), The Mars Analysis Correction Data Assimilation (MACDA) Dataset V1.0, Geosci. Data J., 1 (2), 129–139. doi:10.1002/gdj3.13.

Publications:

Mooring, T. A. and R. J. Wilson (2015), Transient eddies in the MACDA Mars reanalysis, Geophys. Res. Planets., 120 (10), 1671-1696, doi:10.1002/2015JE004824.

Progress Report Title: **Projecting Anadromous Fish Habitat in the Northeastern United States Using Downscaled Climate Models**

Principal Investigator: Barbara Muhling (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Charles Stock (GFDL), Keith Dixon (GFDL), Desiree Tommasi (Princeton)

Other Participating Researchers: Vincent Saba (NMFS), Carlos Gaitan (University of Oklahoma)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Model Applications

NOAA Goals:
Healthy Oceans Goal: Marine Fisheries, Habitats, and Biodiversity are Sustained within Healthy and Productive Ecosystems (50%)
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts (50%)

Objectives: To apply a range of statistical downscaling techniques to northeast US estuarine and nearshore environments, and to use these to project future habitat for diadromous fishes and habitats.

Methods and Results/Accomplishments:

The first objective of this project was to build models to predict estuarine dynamics using only the atmospheric variables (air temperature, precipitation) available from general circulation models (GCMs). An estuarine water temperature model was built using a non-linear lagged air temperature relationship, and verified using >25 years of *in situ* measurements. A water balance model using Hamon evapotranspiration was then applied to the Susquehanna River watershed, which supplies ~50% of freshwater inflow to Chesapeake Bay. Historical monthly river discharge (1970-2006) was well correlated with model predictions (R^2=0.8), with good bias characteristics once a correction for wind-induced snow under-catch was incorporated (**Fig. 1**).

Air temperature over Chesapeake Bay, and air temperature and precipitation over the Susquehanna watershed, were then downscaled using five different techniques: bias correction quantile mapping (BCQM), change factor quantile mapping (CFQM), equidistant quantile mapping (EDQM), cumulative distribution function transform (CDFt), and a modified delta method. Projections from the IPSL-CM5A-LR GCM under RCP8.5 were selected for the initial test case. Results showed that future modeled estuarine water temperatures from the downscaled methods were cooler in spring, but warmer in summer than the GCM, with substantial (~2°C) model spread at high temperatures (**Fig. 2**). Similarly, the downscaled methods projected lower future catchment precipitation and higher air temperatures than the GCM, resulting in lower calculated Susquehanna River streamflow through 2100.

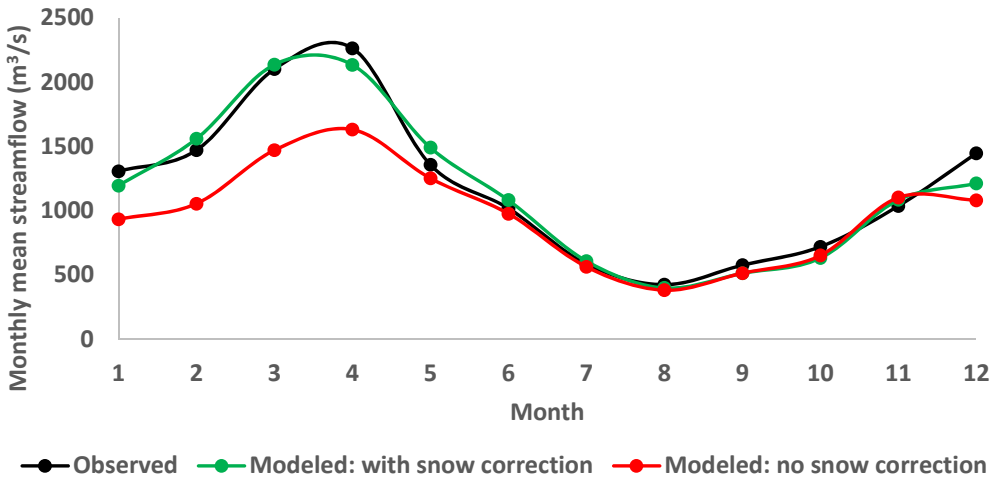


Fig 1: Mean monthly Susquehanna River streamflow at Conowingo Dam 1970-2006. Observations are shown in black, results from a water balance model are shown with (green) and without (red) a correction for wind-induced snow under-catch.

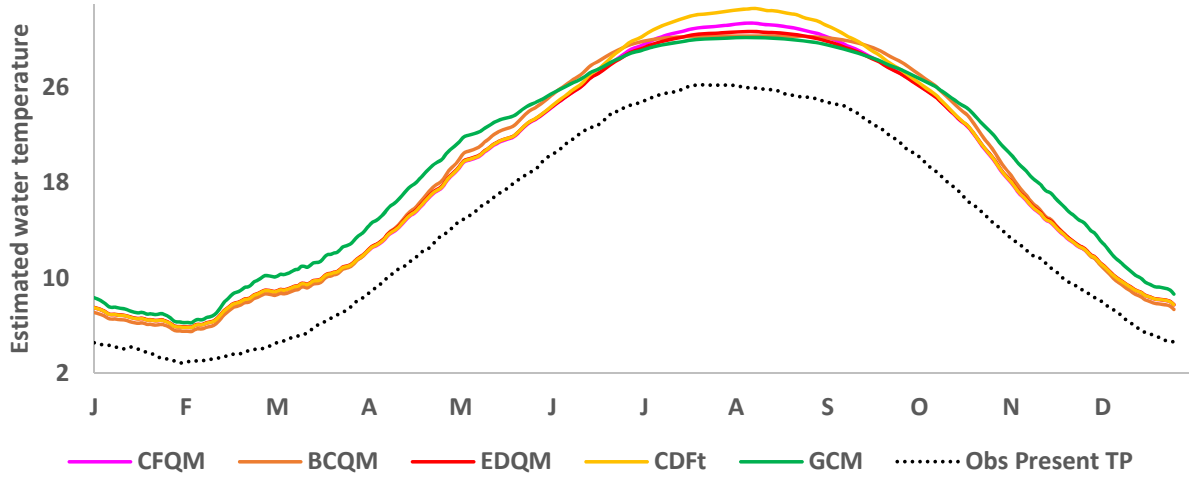


Figure 2: Modeled seasonal cycle of surface water temperature in the upper Chesapeake Bay from five different statistical downscaling methods applied to the IPSL-CM5A-LR GCM under RCP8.5, for years 2070-2100. The present day (1985-2015) mean at the Thomas Point buoy is shown in black.

In order to relate these environmental drivers to anadromous fish habitat, statistical models were developed to predict temperature and salinity at the surface and near-bottom across the Chesapeake Bay and major tributaries. Boosted regression tree and generalized additive models were constructed using historical conductivity-temperature-depth (CTD) cast data. Example predictions for bottom salinity are shown in **Figure 3**. Ongoing work will apply downscaled projections to new and existing models of distribution, recruitment and phenology for diadromous fishes and habitats.

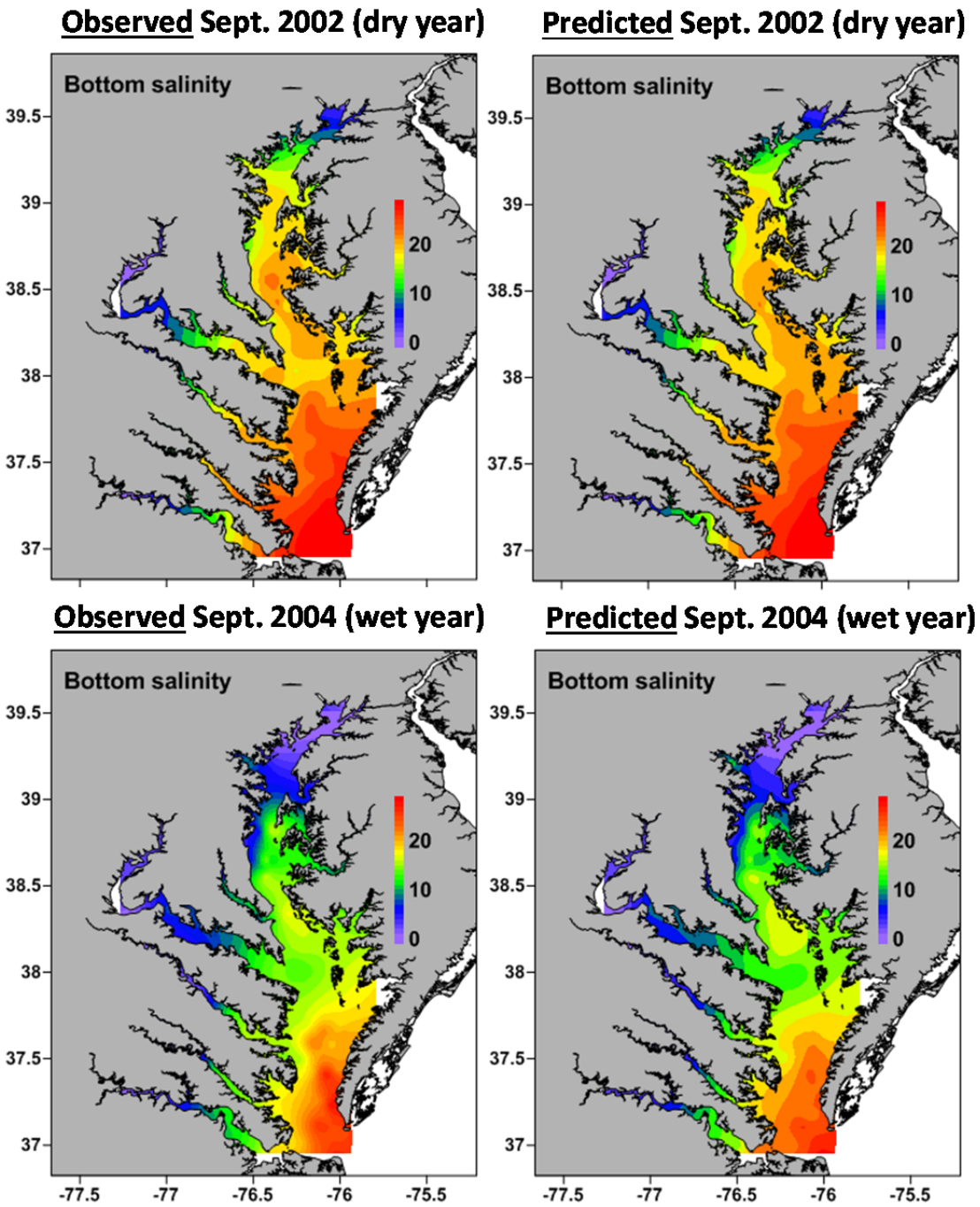


Figure 3: Observed and predicted bottom salinity in the Chesapeake Bay and major tributaries for a dry September (2002: top), and a wet September (2004: bottom). Predictions were derived from boosted regression tree models trained on historical CTD cast data (Chesapeake Bay Program).

Publications:

Lowerre-Barbieri, S., DeCelles, G., Pepin, P., Catalan, I.A., Karnauskas, M., Muhling, B.A., Erisman, B., Cadrin, S., Alós, J., Ospina-Alvarez, A., Stachura, M.M., Tringali, M., Burnsed, S.W., Paris, C.B. (submitted) Reproductive resilience: a paradigm shift in understanding spawner and recruit processes in exploited marine fishes. Fish and Fisheries, March 2016

Domingues, R., Goni, G., Bringas, F., Muhling, B.A., Lindo-Atichati, D., Walter, J., Variability of preferred environmental conditions for Atlantic bluefin tuna (*Thunnus thynnus*) larvae in the Gulf of Mexico. Fisheries Oceanography, 5(3), 320-336, doi:10.1111/fog.12152.

Muhling, B.A., Lindegren, M., Worsoe Clausen, L., Hobday, A.J., Lehodey, P. (in press) Impacts of climate change on pelagic fish and fisheries. Book chapter in Phillips, B., Perez, M. (eds) The Impacts of Climate Change on Fisheries and Aquaculture. Wiley.

Liu, Y., Lee, S.K., Enfield, D.B., Muhling, B.A., Lamkin, J.T., Muller-Karger, F.E., Roffer, M.A. "Past and future climate variability in the Intra-Americas Sea and its impact on the marine ecosystem and fisheries", U.S. CLIVAR Variations Newsletter Winter 2016.

Presentations:

Muhling, B.A., Gaitan, C., Tommasi, D., Saba, V., Stock, C., Dixon, K. "Downscaling climate models for ecological forecasting in northeast U.S. estuaries", STAC workshop: "The Development of Climate Projections for Use in Chesapeake Bay Program Assessments", Annapolis, Maryland, March 2016.

Muhling, B.A., Gaitan, C., Tommasi, D., Saba, V., Stock, C., Dixon, K. "Climate change, estuaries and anadromous fish habitat in the northeastern United States: models, downscaling and uncertainty", Ocean Sciences Meeting, New Orleans, Louisiana, February 2016.

Muhling, B.A., Tommasi, D., Saba, V., Stock, C., Gaitan, C., Dixon, K. Latour, R. et al. "Fish habitat, estuaries and climate change in the northeast US: models, downscaling and uncertainty", Rutgers Fishbaste seminar series, November 2015.

Lee, S.K., Liu, Y., Muhling, B.A. "Potential Impact of climate change and variability on the Intra-Americas Sea (IAS)", NOAA Climate variability and fisheries workshop: Setting research priorities for the Gulf of Mexico, South Atlantic, and Caribbean regions, St Petersburg, Florida, October 2015.

Muhling, B.A., Tommasi, D., Stock, C., Lamkin, J., Roffer, M., Nero, R., Domingues, R., Walter, J. "Towards spatial management of bluefin tuna in the Gulf of Mexico", Application of seasonal to decadal scale climate forecasts for marine resource management workshop, Princeton, New Jersey, June 2015.

Muhling, B.A., Gaitan, C., Tommasi, D., Saba, V., Stock, C., Dixon, K., "Statistical Downscaling for Estuaries and Nearshore Environments", NOAA Ecological Forecasting meeting, Silver Spring, Maryland, May 2015.

Progress Report Title: **Impact of ENSO on East Asian Precipitation**

Principal Investigator: Ching Ho Justin Ng (Princeton Graduate Student)

CICS/GFDL Collaborator: Gabriel Vecchi (GFDL)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Model Applications

NOAA Goals:
Weather-Ready Nation Goal: Society is Prepared for and Responds to Weather-Related Events

Objectives: To identify the impact of ENSO phenomenon on precipitation in East Asia, to improve predictability of extreme rainfall during future (extreme) El Nino events

Methods and Results/Accomplishments:

Precipitation observations from multiple datasets are studied and correlated with sea-surface temperatures in the Nino3.4 region. It is shown that in some particular regions in East Asia (not everywhere), rainfall increases during both El Nino and La Nina phases compared to the ENSO-Neutral state. I also demonstrated that in this region, the response of precipitation to ENSO is statistically robust.

Then this result is compared with nudged-SST model runs of FLOR and HiFLOR, which show similar responses of rainfall. Then, hypotheses leading to these changes in rainfall are proposed, and I am currently testing these hypotheses using models. Also, I am trying to relate this result back to the broader context of climate predictability, and preliminary studies show that this non-linearity is not seen in control runs of a few hundred years. Thus, it is possible that in longer timescales, other climate variability processes such as the PDO and AMO might play a role in the response of precipitation.

References:

Delworth et al (2006, 2012), Vecchi et al (2014) - CM2.1, FLOR, FLOR-FA, HiFLOR Model Runs.

Progress Report Title: **Preparation GFDL Curator Infrastructure for CMIP6**

Principal Investigator: Serguei Nikonov (Princeton Earth System Modeler)

CICS/GFDL Collaborator: V. Balaji (Princeton), Amy Langenhorst (GFDL), Aparna Radhakrishnan (GFDL/HPTi)

Other Participating Researchers: Hans Valhenkamp (UCAR)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Model Applications

***NOAA Goals*:**
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: Full revision and update of all components of the GFDL Curator infrastructure for running the CMIP6 project. CMIP6 has new experiments organizations (MIPs) and model data output, vast amount of simulations, and output fields. These aspects should be considered and be capable to process by Curator.

Methods and Results/Accomplishments:

The CMIP6 project is expected to be of one order of magnitude bigger than CMIP5. It includes diversity of simulations and enormous output amount. It means we are closer and closer to computer resources limits which are currently at GFDL's disposal. In such critical situations, the role of their accurate estimation is very important. To fulfill an assessment of computer resources and space needed, the Data Requests documents gathered from all participating MIPs and compiled together by BADC were used. Based on experiment design presented there, the GFDL CMIP6 data floating model was built. It produces estimations numbers and will allow us to make high level planning CMIP6 preparation in GFDL.

Another type of activity providing CMIP6 infrastructure preparedness was a revision and redesign of all necessary components of the Curator system - metadata database, XML/DB mapper, publishing tools and web interfaces (MDBI and data search/download website). In the course of reviewing Curator software, there were about 70 tasks for upgrade and improvement planned. Most of them are implemented and are launched to Operations.

The important part of GFDL data serving is participating in a multi-institutional international project called the Earth System Grid Federation (ESGF). GFDL Data Portal became a tier 1 Node in the Federation. There were fulfilled efforts for upgrading the software package and keeping it in good shape for serving several projects, the biggest of which is CMIP5. Continual participation in ESGF conferences and discussions in various working teams (publishing, installation, computation) allowed us to meet GFDL's specific needs and needs for CMIP6 in the ESGF development process.

Presentations:

GFDL workflow for massive data publishing. A. Radhakrishnan, S. Nikonov, V. Balaji, E. Mason. Princeton-Industry Symposium on High Performance Computing. May 11, 2015. Princeton, NJ.

CMIP6 Publication Workflow at GFDL. S. Nikonov, V. Balaji, E. Mason, A. Radhakrishnan. 5th GO-ESSP Workshop. Feb 23-26, 2015. Abington, UK.

Progress Report Title: **Climate Implications of the Heterogeneity of Anthropogenic Aerosol Forcing**

Principal Investigator: Geeta Persad (Princeton Graduate Student)

CICS/GFDL Collaborator: Yi Ming, V. Ramaswamy, Paul Ginoux, Tom Delworth, David Paynter, and Vaishali Naik (GFDL)

Other Participating Researchers: Michael Oppenheimer (Princeton)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Model Applications

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: The objective of the projects listed here is to better understand the role of anthropogenic aerosols in the climate system, particularly how the vertical and horizontal structure of aerosol radiative forcing influences its climate impact at regional and global scales.

Methods and Results/Accomplishments:

A paper, "Spatially Similar Surface Energy Flux Perturbations due to Greenhouse Gases and Aerosols," was reviewed and is shortly to be resubmitted at *Nature Communications.* The degree of difference between spatial patterns of climate change due to heterogeneous aerosol forcing versus homogeneous greenhouse gas forcing deeply impacts the detection, attribution, and prediction of regional climate change. This paper addresses a gap in current understanding of these two forcings' response pattern development, using historical forcing simulations in the Geophysical Fluid Dynamics Laboratory's (GFDL) AM2.1 Atmospheric General Circulation Model (AGCM). The results indicate that fast atmospheric and land-surface processes alone substantially homogenize the global pattern of surface energy flux response to heterogeneous aerosol forcing.

A second paper, "Competing Atmospheric- and Surface-Driven Impacts of Absorbing Aerosols on the East Asian Summertime Climate," is currently in preparation for submission to the *Journal of Geophysical Research* with the coauthorship of David Paynter, Yi Ming, and V. Ramaswamy. We construct a set of novel idealized forcing simulations in the GFDL AM3 AGCM to decompose the radiative effects of regional anthropogenic aerosol emissions into their surface and atmospheric forcing of East Asian summertime climate. Aerosols' surface and atmospheric effects counteract each other regionally—atmospheric heating enhances summer monsoon circulation, while surface dimming suppresses it—but absorbing aerosols' combined effects reduce summer monsoon rainfall. This paper constitutes the first such vertical decomposition of aerosols' impacts in this high-emissions region and elucidates the monsoonal response to aerosols' surface versus atmospheric forcing. This work was presented at the 2015 Gordon Research Seminar and Conference in Radiation and Climate and at the 2015 American Geophysical Union Fall Meeting.

I also participated in an organizational capacity in the above conferences. I served as the Chair of the 2015 Gordon Research Seminar in Radiation and Climate in July 2015 and as a Discussion Leader in the associate Conference. I also co-chaired and co-convened a session at the 2015 American Geophysical

Union Fall Meeting, entitled "Climate Change is a Cross-Disciplinary Challenge: Disciplinary Advances in an Accessible Framework."

A third paper, "Trade and the Future of China's Black Carbon Emissions," is in preparation for submission to *Climatic Change* with the coauthorship of Vaishali Naik and Michael Oppenheimer. Future aerosol emissions patterns will affect the distribution of regional climate impacts. This paper interrogates how international trade affects existing assumptions about East Asia's future black carbon aerosol emissions, using integrated assessment modeling, emissions and economic data, and AM3 simulations. Exports emerge as a uniquely large and potentially growing source of Chinese black carbon emissions that may counteract projected emissions reductions, with substantial climate and health consequences. The findings encourage greater emissions projection sophistication and illustrate how societal decisions may influence future aerosol forcing heterogeneity.

These and earlier materials are included in my PhD dissertation, titled "Climate Implications of the Horizontal and Vertical Heterogeneity of Anthropogenic Aerosol Forcing". That work will be defended in a Final Public Oral examination on May 9th, and is anticipated to be published in dissertation form on May 17th and to lead to conferral of my doctoral degree from the Program in Atmospheric and Oceanic Sciences on May 31st, 2016. This work has also been presented in invited lectures at the Carnegie Institution for Science's Department of Global Ecology and in the University of Texas at Austin's Climate Forum.

Outreach Activities: Mentor, Youth Careers in Science Program, *California Academy of Sciences* (February 2016): workshop on climate science and careers in climate science with underrepresented students from San Francisco Area high schools. Expert Scientist, 2015 Climate Game Jam, *California Academy of Sciences* (December 2015): advisory scientist for nationwide game development competition focused on climate science; resulting games to be used in middle school science curricula nationwide.

Publications:

Persad, G. G., Y. Ming, and V. Ramaswamy, 2016: Spatially Similar Surface Energy Flux Perturbations due to Greenhouse Gases and Aerosols. Nature Communications (Submitted).

Persad, G. G., D. Paynter, Y. Ming, and V. Ramaswamy, 2016: Competing Atmospheric- and Surface-Driven Impacts of Absorbing Aerosols on the East Asian Summertime Climate. In preparation for submission to JGR-Atmospheres.

Persad, G. G., V. Naik, and M. Oppenheimer, 2016: Trade and the Future of China's Black Carbon Emissions. In preparation for submission to Climatic Change.

Presentations:

Persad, G., D. Paynter, V. Naik, Y. Ming, M. Oppenheimer and V. Ramaswamy, 2016: Climate Implications of the Heterogeneity of Anthropogenic Aerosol Forcing. Invited lecture. Carnegie Institution for Science, Department of Global Ecology Seminar. Stanford, CA.

Persad, G., 2015: Black Carbon Aerosol: The Hare to Carbon Dioxide's Tortoise. Invited lecture. University of Texas at Austin Climate Forum. Austin, TX.

Persad, G., D. Paynter, Y. Ming, and V. Ramaswamy, 2015: Competing Atmosphere- and Surface-Driven Impacts of Aerosol Absorption on the East Asian Summer Monsoon. American Geophysical Union Fall Meeting, San Francisco, CA.

Persad, G., D. Paynter, Y. Ming, and V. Ramaswamy, 2015: The Regional Climate Response to Absorption-Driven Solar Dimming over East Asia. Gordon Research Conference on Radiation and Climate. Waterville, ME.

Progress Report Title: **Interactions between Cloud-Radiative Effects and the Large-Scale Circulation**

Principal Investigator: Max Popp (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Isaac Held (GFDL), Levi Silvers (Princeton)

Other Participating Researchers: Ming Zhao (UCAR)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Model Applications

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: The goal of our research is to improve the understanding of the interaction between cloud-radiative effects and the large-scale circulation.

Methods and Results/Accomplishments

The project started in July 2015. We have since developed the tools necessary to study cloud-radiative effects. These include the ability of the atmospheric circulation model AM4 to turn off the interaction of the radiative shortwave and longwave fluxes with clouds as well as the cloud induced radiative heating rates, and the implementation of special output for the task at hand. Furthermore, we have set up an aqua-planet version (an idealized fully water covered world) of AM4 that facilitates the investigation of the interaction between large-scale circulation and cloud-radiative effects.

We have chosen to start our research by tackling the so-called double-ITCZ problem. Simulations on aqua-planets with prescribed sea-surface temperatures often exhibit two distinct ITCZs off the equator. Several mechanisms which contribute to this effect have been proposed, but there is still a lack of coherent theory. Especially the influence of cloud-radiative effects on the ITCZ position has received little attention. Understanding the influence of cloud radiative effects on the position of the ITCZ is not only of academic interests, since climate models have a tendency of producing two ITCZ too frequently and too pronounced especially in the eastern Pacific (e.g. Lin 2007, Li and Xie 2014).

Our aqua-planet simulations with prescribed sea-surface temperatures suggest that cloud-radiative effects have a large influence on the tropical circulation. There is a double ITCZ in the control simulation and in the simulations with both longwave and shortwave cloud-radiative effects turned off (Fig. 1). However, the ITCZs in the simulations without cloud-radiative effects is further away from the equator than in the control simulations. A detailed analysis reveals that it is exclusively the longwave cloud-radiative effect which pulls the two ITCZs equator-wards, whereas the shortwave cloud-radiative effect pulls the two ITCZs pole-wards. When only longwave cloud-radiative effects are turned on, the two ITCZs merge into a single ITCZ at the equator. Overall the influence of the longwave cloud-radiative effect on the position of the ITCZs is larger than that of the shortwave cloud-radiative effect.

We are currently investigating the mechanisms which drive the changes in the position in ITCZs in the different simulations, with the aim of preparing a publication.

References:

Lin, J. L., 2007: The double-ITCZ problem in IPCC AR4 coupled GCMs: Ocean–atmosphere feedback analysis. J. Climate, 20,4497–4525.

Li G. and S.-P. Xie, 2014: Tropical Biases in CMIP5 Multimodel Ensemble: The Excessive Equatorial Pacific Cold Tongue and Double ITCZ Problems. J. Climate, 27, 1765–1780.

Publications:

Max Popp and Levi Silvers, Double and single ITCZs with and without clouds, EGU General Assembly 2016, Vienna, Austria.

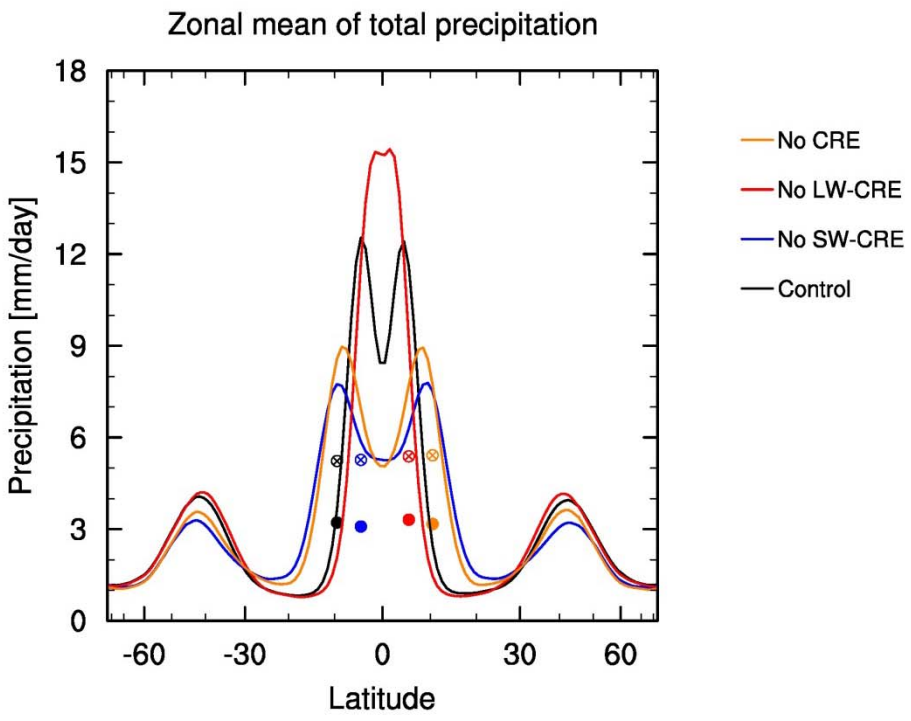


Fig. 1: Zonal and temporal mean of precipitation for the different aqua-planet experiments with and without cloud-radiative effects (CRE) in the longwave (LW) and the shortwave (SW). The filled circles denote the global mean for each experiment and the crossed circles denote the tropical means from 20 S to 20 N. Temporal means are taken over five years. The horizontal axis is scaled with the sine of latitude.

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: Charles Stock (GFDL)

Other Participating Researchers: Sarah Schlunegger (Princeton), Thomas Frölicher (ETH, Switzerland)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: David Legler (CPO)

Theme: Earth System Model Applications

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: The purpose of this work is to use models to aid in the detection of carbon uptake and acidification rates for the ocean, and to relate this to ocean ecosystem health.

Methods and Results/Accomplishments:

Work over the last year has primarily focused on application of the Large Initial Condition Ensemble suite of runs conducted with GFDL's Earth system model ESM2M. The first result of this work was published in 2015 (Rodgers et al., 2015), with a second work having been submitted (Frölicher et al., 2016). These studies address the timescales over which anthropogenic changes in ecosystem stressors can be expected to emerge above the natural background variability.

Newer work with the ensemble runs has focused on the emergence timescales for anthropogenic carbon uptake by the ocean. In collaboration with Sarah Schlunegger (PhD student of Jorge Sarmiento at Princeton University) and Jorge Sarmiento at Princeton, work is underway to test the hypothesis that natural decadal variability in the overturning strength of the shallow overturning structures of the Pacific basin play a first-order role in sustaining observed natural decadal variability of the ocean carbon cycle.

Work has also been conducted on quantifying the rate and patterns of re-emergence of anthropogenic carbon from the ocean interior to the ocean mixed layer. A suite of Lagrangian and Eulerian diagnostics are under development to identify the pathways of re-emergence through the ocean's overturning structure. This has resulted in the publication of Nakano et al. (2015). Although the long-term goals of this work are oriented towards understanding impacts for acidification and climate-carbon feedbacks under climate change, the work to date has focused on applications to ocean carbon cycle models that have been forced with reanalysis fluxes.

Outreach Activities: Two summer undergraduate interns were hosted last summer, Maricela Coronado (Princeton U., funded by PEI) and Alicia Menendez (Stanford University, funded independently through a fellowship from Stanford).

Publications:

Frölicher, T.L., K.B. Rodgers, C. Stock, and W.W.L. Cheung (2016), Sources of uncertainties in 21st century projections of potential ocean ecosystem stressors, under revisions at Global Biogeochemical Cycles.

Rodgers, K.B., J. Lin, and T.L. Frölicher (2015), Emergence of multiple ecosystem drivers in a large ensemble suite with an Earth System Model, Biogeosciences, 12, 3301-3320.

Nakano, H., M. Ishii, K.B. Rodgers, H. Tsujino, and G. Yamanaka (2015), Anthropogenic CO_2 uptake, transport, storage, and dynamical controls in the ocean imposed by the meridional overturning circulation: a modeling study, Global Biogeochemical Cycles, 29, doi:1002/2015GB005128.

Rödenbeck, C., D.C.E. Bakker, N. Gruber, Y. Iida, A.R. Jacobson, S. Jones, P. Landschützer, N. Metzl, S. Nakaoka, A. Olsen, G.-H. Park, P. Peylin, K.B. Rodgers, T.P. Sasse, U. Schuster, J.D. Shutler, V. Valsala, R. Wanninkhof, and J. Zeng (2015), Data-based estimates of the ocean carbon sink variability – first results of the Surface Ocean pCO_2 Mapping intercomparison (SOCOM), Biogeosciences, 12, 7251-7278.

Progress Report Title: **Climate Impacts of the Atlantic Multidecadal Variability**

Principal Investigator: Yohan Ruprich-Robert (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Tom Delworth (GFDL)

Other Participating Researchers: Rym Msadek (CNRS-CERFACS)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Model Applications

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: The main goal of this postdoctoral research is to improve our knowledge of the North Atlantic decadal variability (principally of the Atlantic Multidecadal Variability), both in terms of physical mechanisms and climate impacts.

Methods and Results:

We estimate the climate impacts of the observed AMV using the GFDL-CM2.1, GFDL-FLOR, and NCAR-CESM1 climate models by restoring the model North Atlantic Sea Surface Temperatures (SSTs) to anomalies corresponding to the observed AMV. By perturbing only the North Atlantic sector of the coupled models, our set-up allows to estimate and isolate the full climate response to the observed AMV forcing. The mean response has been documented in an article under revision in Journal of Climate (Ruprich-Robert et al.). Our main results are: 1) During boreal summer (JJAS) the AMV warming leads to a weakening of the Walker circulation that generates precipitation anomalies all around the tropical belt and strengthen the monsoon activity over Asia and Africa. It also leads to reduced rainfall over the western part of US and over South Europe. 2) During boreal winter (DJFM) the AMV warming leads to the formation of a negative phase of the Interdecadal Pacific Oscillation (IPO; Fig. 1). This response comes from a modification of the Walker circulation occurring during JJAS that leads during DJFM to the development of La Niña-like conditions through processes that are proper to the Pacific internal variability (including Bjerkness feedback). 3) Over the North Atlantic/European region, the subpolar part of the AMV leads during DJFM to a negative phase of the North Atlantic Oscillation that is reinforced by direct atmospheric teleconnections from the tropical North Atlantic. However, this response is modified in CM2.1 by the remote impacts of the tropical part of the AMV on the Pacific and ultimately projects on a negative phase of the East Atlantic Pattern. 4) The signal-to-noise ratio of the simulated AMV impacts during DJFM suggests only weak predictability over land in the extratropics. However, this ratio indicates high predictability over the North Pacific, Mexico and South Asia. Over the North Pacific, our experiment results suggest that climate shift similar or stronger than this observed in 1976-77 has about 40% chance to happen following a transition of the AMV from its positive to its negative phase.

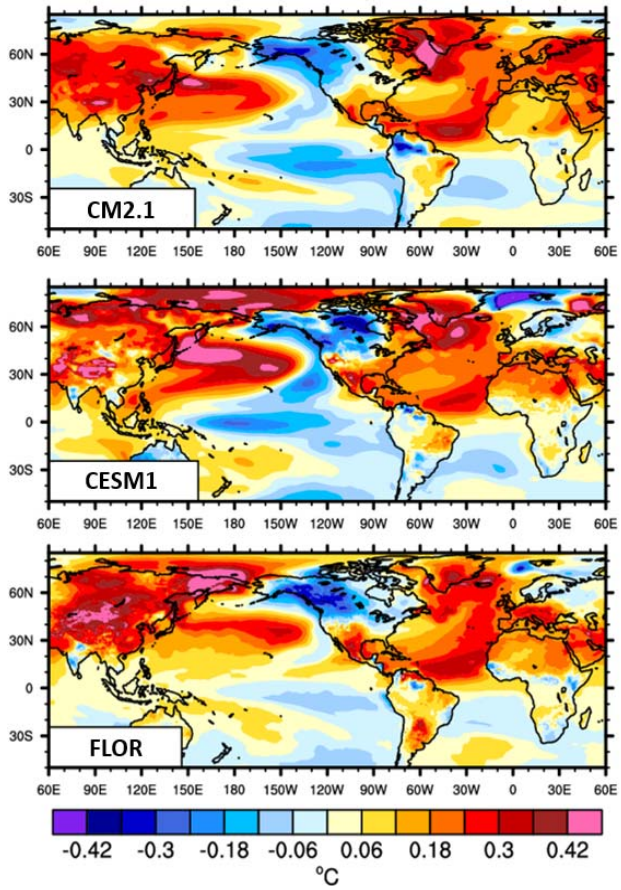


Fig. 1: Mean state difference in terms of boreal winter 2 meter air temperature between the positive and the negative phases of the observed AMV as estimated by idealized experiments performed with the (*top*) GFDL-CM2.1, (*middle*) NCAR-CESM1, and (*bottom*) GFDL-FLOR coupled models.

Our results hence stress the importance played by the North Atlantic Ocean variability associated with the AMV on driving changes at global scale, especially Pacific Ocean variations at decadal timescale. In this study, we specifically focused and quantified the climate impacts associated to the internal component of the AMV, which has been shown to be predictable to some extent on multiannual timescale. Our results are therefore encouraging for the prospect of getting skillful decadal predictions over region outside of the North Atlantic through the impacts of the AMV. Our experimental protocol has been recently adopted by the Decadal Climate Prediction Project of WCRP for idealized experiments as part of CMIP6.

We are currently pursuing our works on the AMV impacts, but we focus on weather extreme. We investigate the impacts of the AMV on the occurrence of heat waves and cold spell as well as on the occurrence of drought. For the extratropical atmosphere, we use a weather regime approach, focusing more specifically on the realism of the frequency of occurrence of blocking and NAO events and on their modulations by the AMV. For the tropics, we investigate cyclones distributions.

Publications:

Ruprich-Robert Y., Msadek R., Castruccio F., Yeager S., Delworth T., and Danabasoglu G. (under revision in Journal of Climate) Assessing the climate impacts of the observed Atlantic Multidecadal Variability using the GFDL CM2.1 and NCAR CESM1 global coupled models.

Ruprich-Robert Y., Msadek R. and Delworth T. (in preparation) Extreme conditions over Europe and North America: role of the Atlantic Multidecadal Variability.

Presentations:

Ruprich-Robert Y., Msadek R., Delworth T., Castruccio F., Yeager S., Danabasoglu G. (talk) Extremes conditions over North America: the role of the Atlantic Multidecadal Variability, Ocean Sciences 2016, February 2016, New Orleans (LA).

Ruprich-Robert Y., Msadek R., Delworth T., Castruccio F., Yeager S., Danabasoglu G. (talk) Pacific impacts of the Atlantic Multidecadal Variability, Rapid - US AMOC International meeting, July 2015, Bristol (UK).

Ruprich-Robert Y., Msadek R., Delworth T., Castruccio F., Yeager S., Danabasoglu G. (talk) Pacific impacts of the Atlantic Multidecadal Variability, IUGG General Assembly, June 2015, Prague (Czech Republic).

Ruprich-Robert Y., Msadek R., Delworth T. (talk) Climate impacts of the Atlantic Multidecadal Variability: an experimental protocol, AGCI workshop on Decadal Climate prediction, June 2015, Aspen (CO).

Progress Report Title: **On the Seasonal Cycle of Arctic Haze**

Principal Investigator: Zhaoyi Shen (Princeton Graduate Student)

CICS/GFDL Collaborator: Yi Ming, Larry Horowitz, Isaac Held, and V. Ramaswamy (GFDL)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Model Applications

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: To apply an atmospheric general circulation model to analyze factors controlling the seasonal cycle of Arctic haze with a focus on black carbon

Methods and Results/Accomplishments:

There is a wide debate on what causes the seasonality of Arctic haze, with peak concentrations in winter but pristine conditions in summer (Quinn et al., 2007). A dynamically oriented view holds that the more vigorous large-scale circulation during wintertime facilitated the long-range transport of mid-latitude pollutants to the Arctic. A competing theory is that Arctic haze occurs in winter, since snow is less efficient than rain in scavenging aerosols. This study applies an atmospheric general circulation model (GFDL AM3) and proposes a theoretical framework to compare the roles of circulation and wet removal in controlling the seasonal cycle of Arctic black carbon (BC).

We find that the eddy-driven BC transport varies little throughout the year. The seasonal cycle of Arctic BC is attributed mostly to wet removal, which is linked directly to the hydrophilic fraction of BC and the wet deposition efficiency of hydrophilic BC. Specifically, a confluence of low hydrophilic fraction and wet deposition efficiency gives rise to the wintertime peak of BC. Both factors can be tied to the nature of the aging process and microphysical properties of aerosols. The transition to low BC in summer results from a gradual increase in the wet deposition efficiency, while the return of BC in late fall can be explained by a sharp decrease in the hydrophilic fraction. The results may have important implications for understanding the natural variations and secular trends of Arctic aerosols and their climate effects.

References:

Quinn, P. K., G. Shaw, E. Andrews, E. G. Dutton, T. Ruoho-Airola, and S. L. Gong (2007), Arctic haze: current trends and knowledge gaps, Tellus B, 59 (1), 99–114, doi:10.1111/j.1600-0889.2006.00238.x.

Publications:

Factors controlling the seasonal cycle of Arctic black carbon, Poster. AGU 2015 Fall Meeting, San Francisco, CA. (12/2015)

Factors controlling the seasonal cycle of Arctic black carbon, Poster. Gordon Research Conference on Radiation and Climate. Waterville, ME. (7/2015)

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

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

CICS/GFDL Collaborator: Gabriel Vecchi, Thomas Delworth, Paul Ginoux, and Thomas Knutson (GFDL)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Model Applications

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

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 cyclones

Methods and Results/Accomplishments:

North Africa, and in particular the Sahara desert, is the largest contributor to global, aerosolized mineral dust in the world (Ginoux et al., 2012). Dust emissions from North Africa have a significant interannual scale of variability with a nearly 5x increase from the late 1960s to the mid-1980s (Ridley et al., 2014). In addition, Saharan-borne dust is commonly not of a single, homogeneous composition, but is instead a combination of a multitude of regional mineral deposits (Caquineau et al., 2002). The choice of mineralogy dataset has been shown to considerably affect the interactions with radiation (Sokolik and Toon, 1999). The scattering and absorptive properties of dust lead to interactions with both the shortwave and longwave spectrums which in combination lead to a redistribution of radiative heating in the atmospheric column and in turn influence the climate (Miller et al., 2014). Such climatologically important changes could further modulate the impact of dust on tropical cyclone frequency.

We use the Geophysical Fluid Dynamics Laboratory (GFDL) Coupled Model CM2.5 Forecast-oriented Low Ocean Resolution version (CM2.5-FLOR) (Vecchi et al., 2014) to calculate the effect of perturbations to the atmospheric aerosol burden of dust under various optical regimes. The first regime is derived from a combination of the observations of Volz (1973) and Patterson et al. (1977). The remaining optical regimes are calculated using Mie theory with the refractive indicies given by Balkanski et al. (2007). In addition, we create two other artificial optical regimes by increasing the amount of shortwave scattering of the most scattering case. Using the model's six-hourly output, we track simulated tropical cyclones (TCs) with the method described by Zhao et al. (2009). We use the same prescribed climatological annual cycles of monthly, global mineral dust aerosol burden as in Figure 2 of Strong et al. (2015). The model is initialized in a spun-up state for each of the 6 optical regimes using the base dust climatology and run for 300 years. Using the climate state at years 100 and 200 as initialization, we create two perturbation simulations for each optical regime where we keep the optical properties the same, but change the annual dust climatology to the reduced state. Each of these perturbations is allowed to run for 100 years in parallel to their respective control simulations. We calculate the impact of dust by aligning and then subtracting the perturbation simulations from their respective control simulations.

The results show considerable sensitivity to various optical properties. Saharan dust causes a unanimous decrease in tropical cyclone activity across the North Atlantic with the strongest changes in

the most absorbing and scattering cases. There are also anomalous changes in the West Pacific and Indian Oceans which are large in absolute magnitude, but small in percent difference. Depending on the optical properties of the dust, the model idealized simulations explain between none and half of the observed change in Atlantic hurricane changes between the late 1960's and the mid-1980's. Relating modeled changes in tropical cyclone track density to common cyclogenesis parameters across the globe does not provide a clear-cut solution. However, comparisons of North Atlantic Accumulated Cyclone Energy (ACE) with top of atmosphere (ToA) radiative anomalies over the Main Development Region (MDR) produces a monotonic relationship.

We similarly compare the mean states of each optical regime and find that the differences due to changes in dust optical properties can be regionally larger than those due directly to changes in dust amount. They also have a global extent, with a pronounced tropical influence. As the dust becomes increasingly more scattering, there is a large feedback onto the North Atlantic Oscillation which in turn impacts the Atlantic Meridional Overturning Circulation. The mechanisms by which the North Atlantic Oscillation are affected are currently being explored.

Outreach Activities: Co-supervision of undergraduate intern in summer of 2015

References:

Balkanski, Y., M. Schulz, T. Claquin, and S. Guibert, 2007: Reevaluation of mineral aerosol radiative forcings suggest a better agreement with satellite and AERONET data. Atmos. Chem. Phys., 7, 81-95, doi:10.5194/acp-7-81-2007.

Caquineau, S., A. Gaudichet, L. Gomes, and M. Legrand, 2002: Mineralogy of Saharan dust transported over northwestern tropical Atlantic Ocean in relation to source regions. J. Geophys. Res., 107(D154251), 14 pp., doi:10.1029/2000JD000247.

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.

Miller, R. L., P. Knippertz, C. P. Garcia-Pando, J. P. Perlwitz, and I. Tegen, 2014: Impact of dust radiative forcing upon climate. Mineral dust: A key player in the Earth system, P. Knippertz, and J.-B. W. Stuut, Eds., Springer Netherlands, 327-357, doi:10.1007/978-94-017-8978-3_13.

Patterson, E. M., D. A. Fillette, and B. H. Stockton, 1977: Complex index of refraction between 300 and 700 nm for Saharan aerosols. J. Geophys. Res., 82 (21), 3153-3160, doi:10.1029/JC082i021p03153.

Ridley, D. A., C. L. Heald, and J. M. Prospero, 2014: What controls the recent changes in African mineral dust aerosol across the Atlantic? Atmos. Chem. Phys. Discuss., 14, 3583-3627, doi:10.5194/acpd-14-3583-2014.

Sokolik, I. N., and O. B. Toon, 1999: Incorporation of mineralogical composition into models of the radiative properties of mineral aerosol from UV to IR wavelengths. J. Geophys. Res., 104 (D8), 9423-9444, doi:10.1029/1998JD200048.

Strong, J. D. O., G. A. Vecchi, and P. Ginoux, 2015: The response of the tropical Atlantic and West African climate to Saharan dust in a fully coupled GCM. J. Climate, 28, 7071-7092, doi:10.1175/JCLI-D-14-00797.1.

Vecchi, G. A., and Coauthors, 2014: On the seasonal forecasting of regional tropical cyclone activity. J. Climate, 27, 7994-8016, doi:10.1175/JCLI-D-14-00158.1.

Volz, D. E., 1973: Infrared optical constants of ammonium sulfate, Sahara dust, volcanic pumice, and flyash. App. Optics, 12 (3), 564-568, doi:10.1364/AO.12.000564.

Zhao, M., I. M. Held, S.-J. Lin, and G. A. Vecchi, 2009: Simulations of global hurricane climatology, interannual variability, and response to global warming using a 50-km resolution GCM. J. Climate, 22, 6653-6678, doi:10.1175/2009JCLI3049.1.

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.

Strong, J. D. O., G. A. Vecchi, and P. Ginoux, 2015: The response of the Tropical Atlantic and West African climate to Saharan dust in a fully coupled GCM. J. Climate, 28, 7071-7092, doi:10.1175/JCLI-D-14-00797.1.

Strong, J. D. O., G. A. Vecchi, and P. A. Ginoux, 2015: The effect of Saharan dust on North Atlantic hydroclimate and tropical cyclones in a high-resolution GCM. Proceedings, AGU Fall Meeting, San Francisco, CA.

Strong, J. D. O., G. A. Vecchi, 2016: The climatological effect of Saharan dust on global tropical cyclones in a fully coupled GCM. Proceedings, 32nd Conf. on Hurricanes and Tropical Meteorology, San Jose, PR, Amer. Meteor. Soc.

Progress Report Title: **Application of Seasonal to Decadal Climate Predictions for Marine Resource Management**

Principal Investigator: Desiree Tommasi (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Charles Stock and Gabriel Vecchi (GFDL)

Other Participating Researchers: Mike Alexander (ESRL), Kathy Pegion (George Mason University), Nick Bond (University of Washington – JISAO), Yan Xue (NOAA CPC), Trond Kristiansen (Institute of Marine Research, Bergen, Norway), Rick Methot (NOAA Fisheries), David Checkley (Scripps Institution of Oceanography)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Model Applications

NOAA Goals:
Healthy Oceans Goal: Marine Fisheries, Habitats, and Biodiversity are Sustained within Healthy and Productive Ecosystems

Objectives: 1) Assess utility of seasonal to decadal climate predictions to improve management of living marine resources (LMRs) in a dynamic environment, and 2) develop proof of concept applications on how climate forecast information can be integrated into current fisheries management decision frameworks to better respond to climate-driven changes in the dynamics of LMRs.

Methods and Results/Accomplishments:

Populations of small pelagic fish are strongly influenced by climate variability. The inability of managers to anticipate environment-driven fluctuations in stock productivity can lead to overfishing and stock collapses. We demonstrated that NOAA's Geophysical Fluid Dynamics Laboratory (GFDL CM 2.5-FLOR) and the National Center for Environmental Prediction (NCEP CFSv2) climate forecast systems allow for skillful sea surface temperature (SST) anomaly predictions at a seasonal scale over many coastal ecosystems (Stock et al. 2015), raising the possibility for broad incorporation of future environmental information for improved management of living marine resources in a dynamic environment.

Indeed, using the case study of Pacific sardine (*Sardinops sagax caerulea*), we showed for the first time that these seasonal climate forecasts make fisheries management more effective. SST is a robust indicator of environmental factors influencing Pacific sardine productivity and past SST variability is presently incorporated in the harvest guideline for this stock. The value of SST anomaly predictions to management was quantified under four harvest guidelines differing in their level of integration of SST data and predictions. The harvest guideline that incorporated stock biomass forecasts informed by skillful SST predictions led to increases in stock biomass and yield, and reductions in the probability of yield and biomass falling below socioeconomic or ecologically acceptable levels. However, to mitigate the risk of collapse in the event of an erroneous forecast, it was important to combine such forecast-informed harvest controls with additional harvest restrictions at low biomass. This analysis highlighted the utility of skillful seasonal climate predictions to more dynamically adjust fishing pressure to the current productivity state of a fish population, leading to more effective catch targets. This work has now been submitted for publication.

Finally, we organized a workshop on the Application of Seasonal to Decadal Climate Predictions for Marine Resource Management at Princeton University on June 3-5 2015. The workshop brought together 60 fisheries and climate scientists from academia and government research institutions to allow for a holistic examination of the challenges associated with the application of seasonal scale forecasts in a fisheries management context and how to meet them. D. Tommasi is currently leading a review paper on this topic to be submitted in 2016. Additionally, the workshop provided a forum to discuss potential proof of concept applications of seasonal and decadal scale climate forecast systems in a marine resource management context. Currently, we are assessing decadal SST anomaly forecast skill in coastal systems, and will be determining their utility to the management of Atlantic cod (*Gadus morhua*). Also, following a paper elucidating environment-freshwater survival links for river herring (*Alosa pseudoharengus* and *A. aestivalis*) (Tommasi et al., 2015), the use of seasonal forecasts of air temperature and precipitation to proactively manage river herring spawning habitat will be explored.

Outreach Activities: Co-supervised a Princeton University Junior Independent Research Project and a Princeton University Senior Thesis Project (in collaboration with Rebecca Asch).

Publications:

Stock, C. A., Pegion, K., Vecchi, G. A., Alexander, M.A., Tommasi, D., Bond, N. A., Fratantoni, P., Gudgel, R., Kristiansen, T., O'Brien, T., Xue, Y., Yang, X. (2015). Seasonal sea surface temperature anomaly prediction for coastal ecosystems**.** Progress in Oceanography, 137: 219-236.

Tommasi, D., Nye, J. A., Stock, C.A., Hare, J. A., Alexander, M., Drew, K. (2015). Effect of Environmental Conditions on Juvenile Recruitment of Alewife (Alosa pseudoharengus) and Blueback Herring (A. aestivalis) in Freshwater: A Coastwide Perspective. Canadian Journal of Fisheries and Aquatic Sciences, 72: 1037-1047.

Kearney, K., Tommasi, D., Stock, C. A. (2015). Simulated ecosystem response to volcanic iron fertilization in the subarctic Pacific Ocean. Fisheries Oceanography, 24: 395-413.

Friedland, K. D., Leaf, R.T., Kane, J., Tommasi, D., Asch, R. G., Rebuck, N., Ji, R., Large, S. I., Stock, C. A., Saba, V. S. (2015). Spring bloom dynamics and zooplankton biomass response on the US Northeast Continental Shelf. Continental Shelf Research, 102: 47-61.

Presentations:

Tommasi, D., Stock. C., Pegion, K., Vecchi, G., Methot, R.D., Alexander, M., and Checkley, D. (2016). Assessing the Utility of Seasonal SST Forecasts to the Fisheries Management Process. Oral Presentation at the 2016 ASLO Ocean Sciences Meeting in New Orleans, LA, USA.

Tommasi, D., Stock. C. (2015). Incorporating seasonal climate forecasts in a harvest control rule for Pacific sardine. Oral Presentation at the 144^{5h} Annual Meeting of the American Fisheries Society in Portland, OR, USA.

Tommasi, D., Stock. C. (2015). Incorporating seasonal climate forecasts in a harvest control rule for Pacific sardine. Oral Presentation at the Marine Ecosystem Analysis and Prediction Workshop in Dalhousie University, Halifax, Nova Scotia, Canada.

Progress Report Title: **Extreme Weather in High-Resolution Global Coupled Models**

Principal Investigator: Karin van der Wiel (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Gabriel Vecchi and Sarah Kapnick (GFDL)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Model Applications

NOAA Goals:
Weather-Ready Nation Goal: Society is Prepared for and Responds to Weather-Related Events

Objectives: To investigate the representation of extreme weather events in high-resolution global climate models and to investigate how these might change in response to CO2 forcing

Methods and Results/Accomplishments:

Since arriving in October 2015, I have worked on a project on daily precipitation extremes over the contiguous US. I have found that the newly developed high-resolution GFDL FLOR and HiFLOR models improve the quality of simulated precipitation extremes over the contiguous US compared to lower resolution models (e.g. CM2.1 and LOAR). This improvement includes the annual and seasonal mean pattern, the distribution of precipitation and the intensity and seasonality of extreme events (see figure below). Furthermore, I have found that the 1-year and 5-year returning event is projected to increase in precipitation intensity in response to doubled atmospheric CO2 concentrations. However, the spatial pattern of change is strongly dependent on model resolution.

Outreach Activities: I volunteer as a scientist in the 'Letters to a Pre-Scientist' program (more details at www.prescientist.org).

Publications:

Van der Wiel, K, SB Kapnick, GA Vecchi, et al.: The resolution dependence of US precipitation extremes in response to CO2 forcing. In preparation for Journal of Climate.

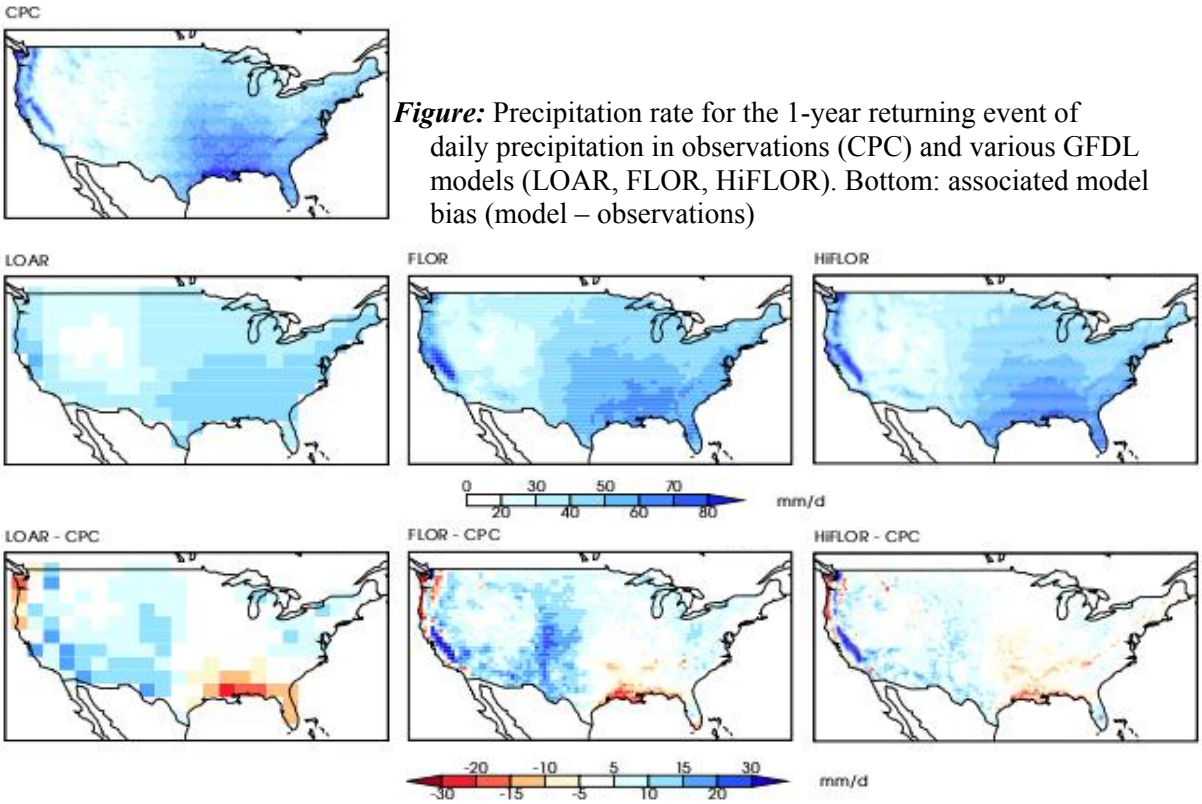


Figure: Precipitation rate for the 1-year returning event of daily precipitation in observations (CPC) and various GFDL models (LOAR, FLOR, HiFLOR). Bottom: associated model bias (model – observations)

Progress Report Title: **Examining Climate Impacts of Antarctic Open-Ocean Polynyas**

Principal Investigator: Hannah Zanowski (Princeton Graduate Student)

CICS/GFDL Collaborator: Robert Hallberg (GFDL), Jorge Sarmiento (Princeton)

Award Number: NA14OAR4320106

Task III: Individual Projects

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Model Applications

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: We explore how polynya signals reach the deep and abyssal oceans in a coupled climate model, with an emphasis on understanding the timescales on which various dynamical effects (waves and advection) act.

Methods and Results/Accomplishments:

To study polynya signals, we regularly force large polynyas in the Weddell Sea every 29 years in GFDL CM2G. Polynyas are created by periodically increasing the diapycnal diffusivity in a region of the Weddell Sea. This causes strong vertical mixing to occur. Each polynya is accompanied by a dye tracer that is used to study its advective signal. The isopycnal ocean component of CM2G (GOLD; Adcroft and Hallberg 2006) is particularly useful for studying wave propagation. As in Zanowski et al. 2015, we have created a composite of the polynyas (Fig.1; we have 33 so far) in order to determine the most robust aspects of the polynya signal spreading. We hope to force at least 50 polynyas during the simulation so that it will be easier to determine whether or not weaker, nonlocal signals are statistically significant.

In the model deep ocean (below 3900 m), advective signals take decades to centuries to reach the Northern Hemisphere (Fig. 2). This seems quite fast compared to the millennial overturning circulation timescale, but it is still quite slow compared to wave propagation from the polynyas. Topographic, planetary, and Kelvin waves are responsible for this fast response in the deep ocean. These waves can propagate ~10,000 km on the order of 20-30 years. The wave propagation manifests itself as temperature (and other property) anomalies on isobaths (Fig. 3a). Interestingly, but perhaps not surprisingly, in this model we have found a strong connection between the Weddell Sea polynya signals and changes in the North Atlantic (Fig. 3b). So far, analysis of the North Atlantic signals (not shown) indicates that the polynyas cause an adjustment to the Atlantic Meridional Overturning Circulation (AMOC) due to their increase in Antarctic Bottom Water (AABW) formation. Also, at this point it is unclear whether or not there is an atmospheric teleconnection between the forced Weddell Sea polynyas and the North Atlantic changes, but preliminary analyses of North Atlantic surface air temperature and sea level pressure do not seem to support this.

Outreach Activities: Exhibitor, PPPL Young Women's Conference in Science, Technology, Engineering, and Mathematics (March 2016); Invited Lecturer, ENV 316: Climate Science and Communication, Princeton University (February 2016); Climate science and oceanography exhibitor, Melvin H. Kreps Middle School "Staycation," (June 2015); Exhibitor, Ocean Fun Days, (May 2015); Panelist, Annual New York City Girls Computer Science and Engineering Conference (November 2015); Princeton Prison Teaching Initiative (2015-2016)

References:

Adcroft, A., and R. Hallberg, 2006: On methods for solving the oceanic equations of motion in generalized vertical coordinates. Ocean Modell., 11, 224-233, doi: 10.1016/j.ocemod.2004.12.007.

Zanowski, H., R. Hallberg, and J.L. Sarmiento, 2015: Abyssal ocean warming and salinification after Weddell Polynyas in the GFDL CM2G coupled climate model. J. Phys. Oceanogr., 45, 2755-2772, doi: 10.1175/JPO-D-15-1509.1.

Publications:

Zanowski, H., R. Hallberg, and J.L. Sarmiento, 2015: Abyssal ocean warming and salinification after Weddell Polynyas in the GFDL CM2G coupled climate model. J. Phys. Oceanogr., 45, 2755-2772, doi: 10.1175/JPO-D-15-1509.1.

Zanowski, H., R. Hallberg, and J.L. Sarmiento: A tale of two timescales: Weddell polynya pathways in the global abyssal oceans. Poster session to be presented at: Physical and Biogeochemical Processes in the Southern Ocean: Observations, State Estimation, and Modeling V. 18th Biennial Ocean Sciences Conference, 2016 Feb 21-26; New Orleans, LA.

Zanowski, H., R. Hallberg, and J.L. Sarmiento, 2016: Weddell polynya pathways in the global abyssal oceans (In prep).

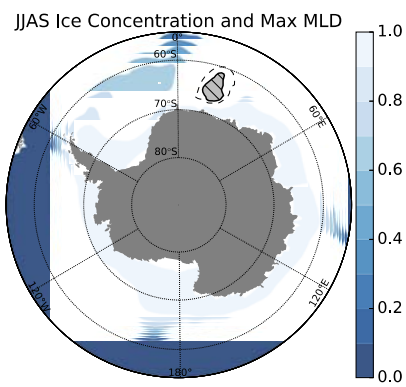


Figure 1. Composite winter (JJAS) sea ice concentration (color) and maximum mixed layer depth contours at 1000 m (dashed) and 2000 m (solid).

Figure 2. Year 100 composite tracer concentration at 4200 m. Years are relative to Year 0, the start year of the polynyas. The tracer value is set to 1.0 in the mixed layer only during the times when the polynyas are forced. Thin gray lines indicate bathymetric contours at 2000 m, 3000 m, and 4000 m. Note the pseudo-logarithmic color scale.

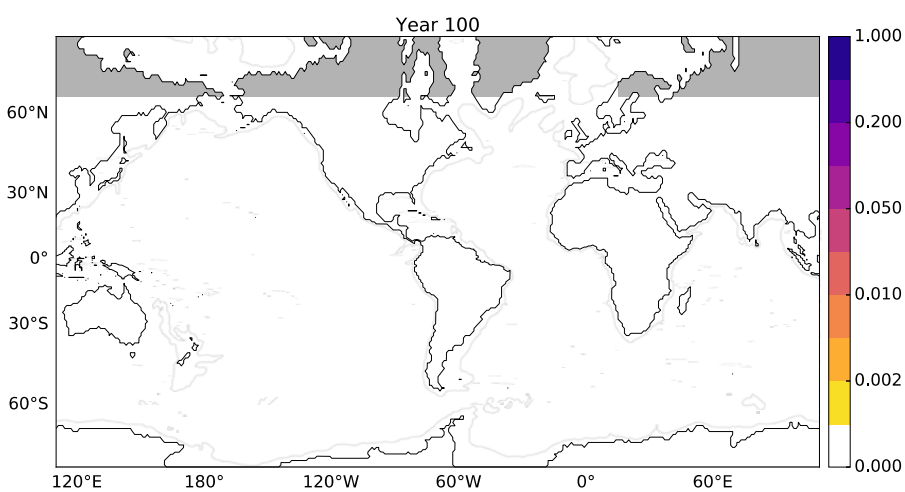
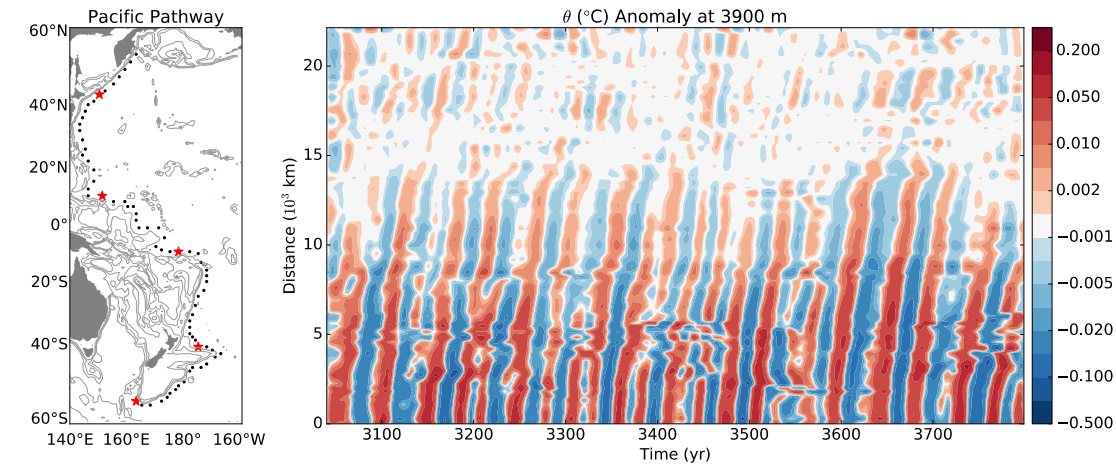
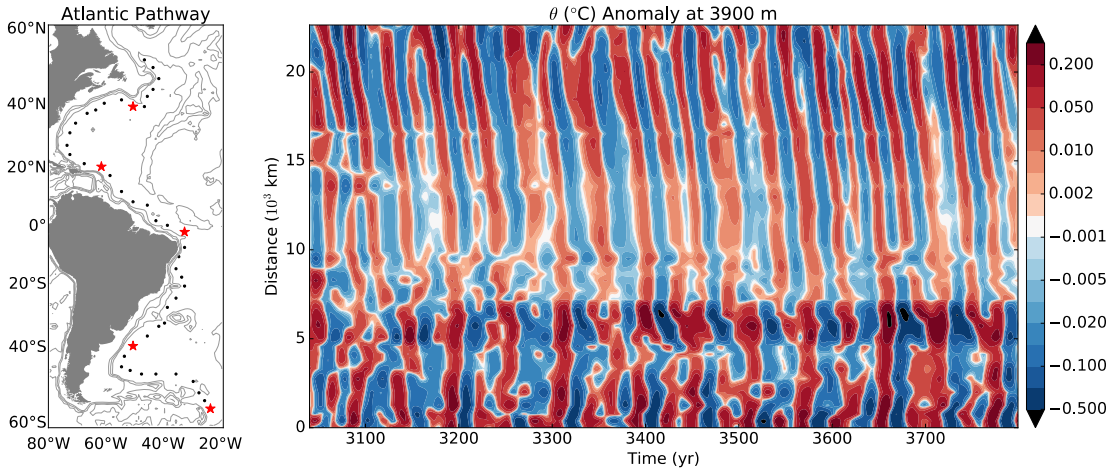


Figure 3. Bandpass filtered θ (˚C) anomalies at 3900 m along western boundaries in the a) Pacific, and b) Atlantic. Red stars on each map correspond to labeled distances on anomaly plots. Distance increases northward. Note the pseudo-logarithmic color scale.

a)



b)



Progress Report Title: **Detection, Attribution and Projection of Regional Rainfall Changes on (Multi-) Decadal Time Scales**

Principal Investigator: Honghai Zhang (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Tom Delworth (GFDL)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Model Applications

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: This projection is to investigate the physical mechanisms underlying observed regional (multi-) decadal rainfall changes and, based on the findings, to project future long-term rainfall changes.

Methods and Results/Accomplishments:

The project initially focused on the Southeastern South America (SESA, 25S~40S,45W~65W), where observed summertime rainfall has exhibited a long-term positive trend during the past century and a contrasting decadal decline during the current century. To understand these regional low-frequency rainfall changes, we made use of a suite of attribution simulations performed with a pair of GFDL high-resolution climate models (CM2.5 and flux-adjusted FLOR).

The observed low-frequency SESA summertime rainfall changes are attributed to both radiative forcing and internal variability. In GFDL models, radiative forcing explains about 30% of the 20th-century SESA summertime moistening trend, most of which is due to the increasing greenhouse gases that drives tropical expansion and the consequent poleward shift of Hadley subtropical dry branch away from the SESA (thus more rainfall). Besides a weak contribution from ozone depletion that is possibly underestimated by GFDL models compared to other climate models, the rest of the 20th-century moistening trend is attributed to internal climate variability, likely the tropical SST variability associated with the PDO and AMO. The decadal rainfall decline observed during the current century is largely (~60%) caused by the recent strengthening of the tropical Pacific trade winds (via atmospheric teleconnection), which is likely related with the internal Pacific decadal variability. This result suggests that the recent SESA rainfall decline is temporary and the moistening trend will resume in response to both the continued emission of greenhouse gases and a return of the tropical Pacific to its normal state.

Indeed, the models project a positive rainfall trend that will be dominant towards the end of the current century in response to both a medium and a high-end emission scenario of future changes of radiative forcing (RCP4.5 and 8.5, see figure below). These projected future rainfall changes will expose new challenges for the long-term development of regional agriculture and socioeconomics.

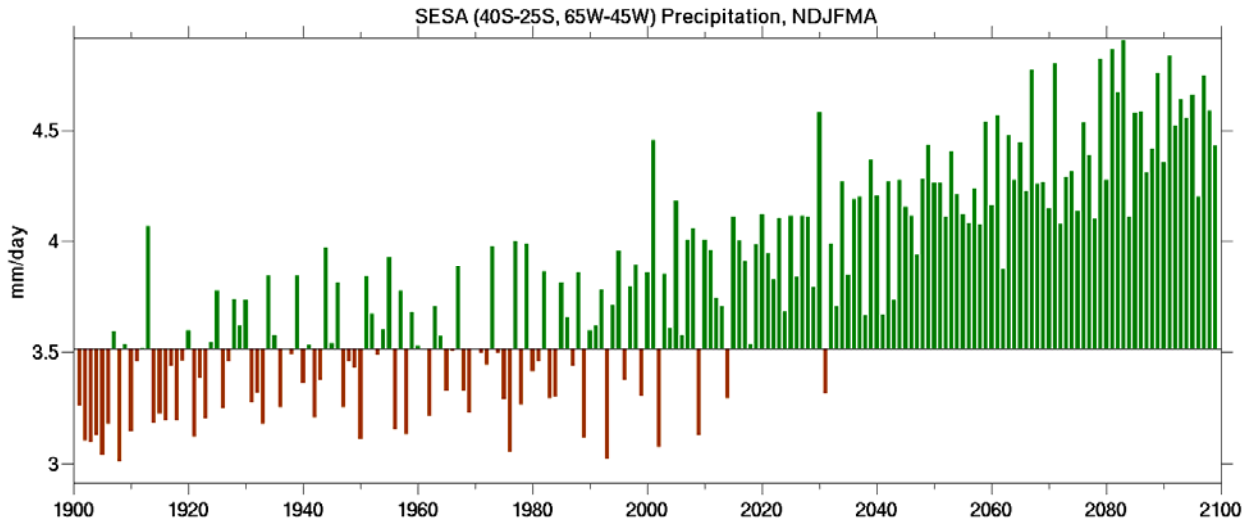


Figure. Simulated summertime (NDJFMA) precipitation changes in the SESA in CM2.5 (5-member ensemble mean) in response to observed estimates of radiative forcing during 20th century and the RCP8.5 emission scenario during the 21st century.

Publications:

Zhang, H., T. Delworth, F. Zeng, G. Vecchi, K. Paffendorf and L. Jia., 2016: Detection, Attribution and Projection of Regional Rainfall Changes On (Multi-) Decadal Time Scales: A Focus on Southeastern South America, to be submitted (in internal review).

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

Principal Investigator: Liping Zhang (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Tom Delworth and Fanrong Zeng (GFDL)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Model Applications

NOAA Goals:
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: To understand the Pacific decadal Oscillation response to climate change; to examine the Antarctic Bottom water characteristics during the Southern Ocean internal cycle; to access the decadal prediction skill of Southern Ocean SST and its associated climate impacts

Methods and Results/Accomplishments:

The impact of climate change on the Pacific decadal oscillation (PDO) is studied using GFDL fully coupled climate model. The model results show that the PDO has a similar spatial pattern in altered climates, but its amplitude and time scale of variability change in response to global warming or cooling. In response to global warming (cooling) the PDO amplitude is significantly reduced (increased), with a maximum decrease over the Kuroshio-Oyashio-Extension (KOE) region. In a warmer (cold) climate the PDO timescale becomes shorter (longer). Physically, global warming (cooling) enhances (weakens) ocean stratification. The increased (decreased) ocean stratification acts to increase (reduce) the phase speed of internal Rossby waves, thereby altering the timescale of the simulated PDO.

The impact of Antarctic bottom water (AABW) on the Weddell Gyre and its northward propagation characteristics are investigated in GFDL model. The response of the Weddell Gyre to AABW changes is primarily attributed to interactions between the AABW outflow and ocean topography, instead of the surface wind stress curl and freshwater anomalies. The slow advection by deep ocean currents determines the AABW propagation speed south of 35°S. North of 35°S the propagation speed is determined both by advection in the deep western boundary current and through Kelvin waves.

By examining initialized decadal hindcasts made with the GFDL coupled model, it is found the internal Southern Ocean (SO) SST has great potentials to be predicted several years in advance. The success of hindcast prediction, especially the cooling trend appeared in observation, is largely due to the correct initialization of weak Antarctic bottom water formation. The surface wind anomaly over the SO, partly influenced by the North Atlantic SST that has high predictability, produces anomalous latent heat loss and northward Ekman transport, which finally improves prediction skill of SO SST. The GFDL CM2.1 hindcasts also predict significant changes in Antarctic sea ice and surface air temperature associated with the recent SO shifts, which generally agree with the observed changes.

Publications:

Liping Zhang and Tom Delworth, 2015: Analysis of the Characteristics and Mechanisms of the Pacific Decadal Oscillation in a Suite of Coupled Models from the Geophysical Fluid Dynamics Laboratory. Journal of climate, 28, 7678-7701.

Liping Zhang and Tom Delworth, 2015: Simulated response of the Pacific decadal oscillation to climate change. (Journal of climate, finish first revision).

Liping Zhang, Tom Delworth and Fanrong Zeng, 2016: The impact of multidecadal Atlantic meridional overturning circulation variations on the Southern Ocean. (Climate Dynamics, finish first revision).

Liping Zhang and Tom Delworth, 2016: Impact of the Antarctic bottom water on the Weddell Gyre and its northward propagation characteristics in GFDL model. (Submitted to JGR-ocean)

Liping Zhang et al, 2016: Assessing decadal-scale climate prediction in the Southern Ocean. (To be submitted to GRL).

Tom Delworth, Fanrong Zeng, Gabe Vecchi, Xiaosong Yang, Liping Zhang and Rong Zhang, 2016: The North Atlantic Oscillation as a driver of Northern Hemisphere rapid climate change. (Nature Geoscience, finish first revision).

Presentations:

Liping Zhang and Tom Delworth. "Simulated response of the Pacific decadal oscillation to climate change." Oral presentation, 2015 JOINT ASSEMBLY meeting, Canada, May 2015.

Liping Zhang, Tom Delworth and Fanrong Zeng. "The impact of multidecadal Atlantic meridional overturning circulation variations on the Southern Ocean." Poster presentation, AGU fall meeting, December 2015.

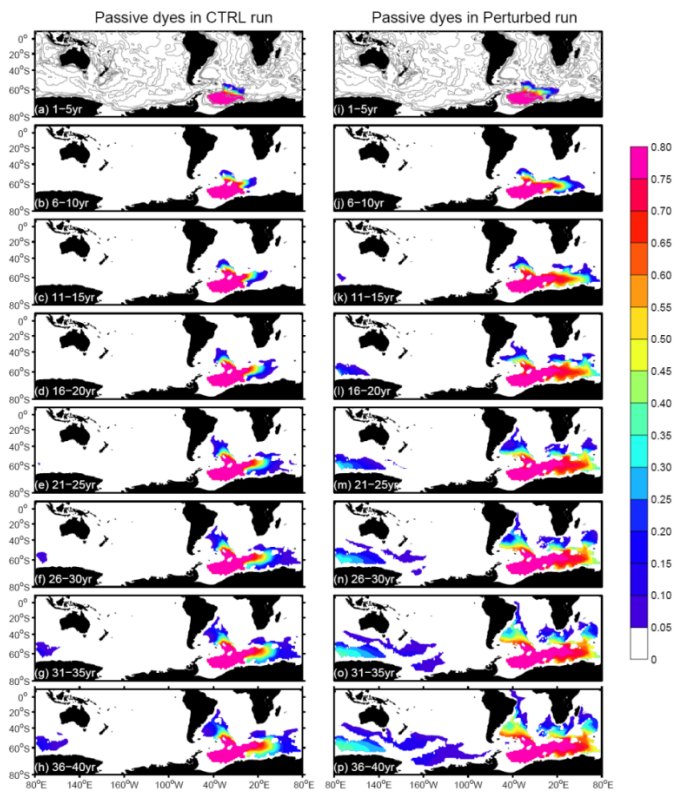


Figure 1: Time evolution of passive dyes in the fully coupled control run (left panels) and perturbed positive salinity experiment (right panels). Unit is 1.

	JI Lead Author		NOAA Lead Author		Other Lead Author	
	FY15	FY16	FY15	FY16	FY 15	FY16
Peer-reviewed	22	31	7	1	27	51
Non Peer-reviewed	60*	102*	1*	2*	2*	24*
Chapters in books		1				1
Ph.D. Thesis	2	3				

**Including Presentations*

2015-2016 Peer-Reviewed Publications

- Alford, M.H., T. Peacock, J.A. MacKinnon, J.D. Nash, M.C. Buijsman, L.R. Centurioni, S.-Y. Chao, M.-H. Chang, D.M. Farmer, O.B. Fringer, K.-H. Fu, P. Gallacher, H.C. Graber, K.R. Helfrich, S. Jachec, C. Jackson, J.M. Klymak, D.S. Ko, S. Jan, T.M.S. Johnston, S. Legg, I.-H. Lee, R.-C. Lien, M.J. Mercier, J.N. Moum, R. Musgrave, J.-H. Park, A.I. Pickering, R. Pinkel, L.R. Rainville, S. Ramp, D.R. Rudnick, S. Sarkar, A. Scotti, H.L. Simmons, L.C. St Laurent, K. Venayagamoorthy, Y.-H. Wang, J. Wang, Y.J. Yang, T. Paluszkiewicz, T.Y. Tang, 2015: The formation and fate of internal waves in the South China Sea. Nature v521, doi:10.1038/nature14399.

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2015-2016 Non Peer-Reviewed Publications/Presentations

- Alvarado, M., J. Mao, and coauthors (2015) : Advancing atmospheric chemistry through the use of satellite observations from the cross-track infrared sounder (CrIS), Report of the CrIS Atmospheric Chemistry Data User's workshop, NOAA Program Office, doi:10.7289/V50V89SS.

- Bakker, D., A. Olsen, K. O'Brien, M. Hoppema, R. Key, S. Lauvset, A. Kozyr, Y. Nojiri, B. Pfeil, C. Rödenbeck, U. Schuster, B. Tilbrook, R. Wanninkhof, A. Watson, and all international SOCAT and GLODAP2 contributors, Global synthesis products enable quantification of the ocean carbon sink and ocean acidification, Model data fusion workshop, Paris, France Apr. 20-21, 2015.

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- Bakker, D., A. Olsen, S. Hankin, M. Hoppema, R. Key, P. Landschützer, S. Lauvset, A. Kozyr, Y. Nojiri, B. Pfeil, C. Rödenbeck, U. Schuster, B. Tilbrook, R. Wanninkhof, Andrew Watson, et al., Global synthesis products enable quantification of the ocean carbon sink and ocean acidification, invited talk, Challenger Conference for Marine Science, Brussels, Sept. 11, 2014.

- Barton, A.D. (2015). Toward a global plankton trait database. Invited oral presentation at the EMODnet Biology Workshop, Heraklion, Greece, June 9-10.

- Barton, A.D., González-Taboada, F., Atkinson, A., and C.A. Stock, (2016). Environmental variability and plankton population dynamics in the English Channel. Oral presentation at the Ocean Sciences Meeting, New Orleans, LA, February 22-26.

- Barton, A.D., González-Taboada, F., Atkinson, A., and C.A. Stock, (2015). Drivers of regime shifts in marine plankton communities. Poster presented at the "Trait-based Approaches to Ocean Life" workshop, Waterville Valley, NH, October 5-8.

- Barton, A.D., Ward, B.A., Williams, R.G., and M.J. Follows (2015). The roles of turbulence and zooplankton grazing in shaping phytoplankton community structure and carbon export. Invited oral presentation at the ASLO Aquatic Sciences Meeting, Granada, Spain, February 22-27.

- Chai, J., M. Jansen and G. K. Vallis, 2015, Zonostrophic Turbulence in Two-layer Quasi-geotrophic Model. Presented at the American Geophysical Union Fall Annual Meeting.

- Chaney, N., (2015), Field-scale land surface modeling over continental extents: Applications in satellite remote sensing of soil moisture, Abstract H43H-1622 presented at 2052 Fall Meeting, AGU, San Francisco, Calif., 14-18 Dec.

- Choi, Kityan, El Nino-Southern Oscillation: Asymmetry, nonlinear atmospheric response and the role of mean climate by Choi, Kit Yan, Ph.D. Thesis, Princeton University, 2015.

- Clark, S. K., Ming, Y., and Held, I. M. "Climate Impacts of Inter-hemispherically Asymmetric Radiative Forcing." AGU Fall Meeting, San Francisco, CA, December 2015. Poster Presentation.

- Clark, S. K., Ming, Y., and Held, I. M. "Climate Impacts of Inter-hemispherically Asymmetric Radiative Forcing." Gordon Research Conference, Lewiston, ME, July 2015. Poster Presentation.

- Deroubaix et al., Global Natural and Anthropogenic Dust Modeling, American Meteorological Society conference, New Orleans, LA, January 2016.

- Diggs, S., A. Kozyr, C. Berys-Gonzalez, Barna, R. Key, J. Kappa, Lee, Hu, Roxanne, Sharon, J. Swift, CTD/Hydrographic/Carbon/Tracer Data Management for US and International GO-SHIP and Related Programs, Global Ocean Data Analysis Version 2 (GLODAPv2), Ocean Sciences Meeting, New Orleans, LA, Feb. 2016.

- FitzMaurice, A., K. Morrison, and R. Hallberg: On the Relationship between Antarctic Sea Ice Extent and the Southern Ocean Overturning Circulation. Poster presented at: Physical and Biogeochemical Processes in the Southern Ocean: Observations, State Estimation, and Modeling V. 18th Biennial Ocean Sciences Conference, 2016 Feb 21-26; New Orleans, LA.

- Frazer, M. E., Y. Ming, and I. M. Held. "What Controls the Strength of the Hydrological Cycle and Subtropical Relative Humidity in an Idealized Model?" Poster presentation, Gordon Research Conference (and Gordon Research Seminar) on Radiation & Climate, July 2015.

- Frazer, M. E., Y. Ming, and I. M. Held. "What Controls the Strength of the Hydrological Cycle and Subtropical Relative Humidity in an Idealized Model?" Poster presentation, AGU Fall Meeting, December 2015.

- González Taboada, F., A. Barton, Ch. Stock. 2016. Predicting global oceanic NPP with reduced-dimension, linear dynamical spatiotemporal models. Ocean Sciences Meeting, New Orleans, USA. [poster].

- Haseloff, M., Schoof, C., Gagliardini, O. (2015): Modelling the migration of ice stream margins, WAIS Workshop, Sept. 16-19, 2015, Loveland, CO, USA.

- Haseloff, M., Schoof, C., Gagliardini, O. (2015): The influence of subtemperate sliding on the formation of temperate ice in ice stream margins and their migration, AGU fall meeting, Dec. 14-18, 2015, San Francisco, CA, USA.

- Hill, Spencer, Towards constraining future rainfall in the Sahel using the moist static energy budget. Oral. AGU 2015 Fall Meeting, San Francisco, CA, December 14, 2015.

- Hill, Spencer, Towards constraining Sahel rainfall responses to global mean temperature changes. Invited oral. Linde Center for Global Environmental Science Monsoons: Past, Present and Future workshop, California Institute of Technology, Pasadena, CA, May 21, 2015.

- Hindmarsh R. C. A., O. V. Sergienko and T. T. Creyts (2015). Diagnostics of basal conditions – the formation of the extensive zones of surface ribs in ice sheets and streams. EGU General Assembly, Vienna, Austria, 12-17 April, 2015.

- Jia, Liwei, Dec. 2015, American Geophysical Union Fall Meeting, San Francisco: The Role of Radiative Forcing, Sea Surface Temperature, Atmospheric and Land Initial Conditions to U.S. Summer Warming Episodes (poster).

- Jia, Liwei, May 2015, American Geophysical Union Joint Assembly, Montreal, Canada: Skillful Seasonal Prediction of Temperature and Precipitation over Land in a new GFDL High Resolution Climate Model.

- Jia, Liwei, Sep. 2015, Workshop on using and interpreting climate information from NOAA/GFDL models for epidemiological studies in Africa and Asia, Princeton University: Improved Seasonal Prediction of Temperature and Precipitation over Land in a High-resolution GFDL Climate Model.

- Johnson, N. C. (April 2015). The diversity of El Niño teleconnection patterns during boreal winter. Lamont-Doherty Earth Observatory Ocean and Climate Physics Seminar series.

- Johnson, N. C. (December 2015). Increasing temperature extremes during the global warming hiatus. 2015 AGU Fall Meeting.

- Johnson, N. C. (January 2015). Increasing temperature extremes during the recent global warming hiatus. AMS 95th Annual Conference.

- Johnson, N. C. (November 2015). Development of new forecast products for weeks 3-4. NOAA Climate Test Bed Meeting.

- Johnson, N. C. (October 2015). Distinctions in the boreal winter teleconnection patterns between convective and non-convective eastern Pacific El Niño episodes. 40th Annual Climate Diagnostics and Prediction Workshop.

- Johnson, N. C., Baxter, S., Feldstein, S., L'Heureux, M., & Xie, S.-P. (February 2015). Beyond week 2: Preliminary work toward generating a North American forecast system for weeks 3-4. Webinar presentation in the NOAA MAPP Webinar series.

- Johnson, N. C., Harnos, D. (October 2015). Operational transition of combined ENSO, MJO, and trend influences on temperature and precipitation for Weeks 3-4. Webinar presentation in the NOAA MAPP Webinar series.

- Juckes, M., V. Eyring, K. Taylor, V. Balaji, and R. Stouffer, 2015: The CMIP6 data request: the next generation climate archive. EGU General Assembly Conference Abstracts, volume 17, 13112.

- Kam, Jonghun, Attribution assessment for recent climate extremes: Record annual-mean warmth during 2014 and the 2011-14 California drought, Invited Talk at Earth System Research Laboratory/NOAA, Feb. 9th, Boulder, CO.

- Key, R.M., A. Olsen, S. van Heuven, M. Hoppema, M. Ishii, E. Jeansson, S. Jutterström, A. Kozyr, S.K. Lauvset, X. Lin, B. Pfeil, C. Schirnick, R. Steinfeldt, T. Suzuki, T. Tanhua, A. Velo, GLODAPv2: A decade in the making, Carbochange final meeting, Bergen, Norway, Jan. 19-22, 2015.

- Key, R.M., GLODAPv2: A New Biogeochemical Ocean Data Product, Texas A&M Univ., invited seminar, Dec. 7, 2015.

- Key, R.M., The status of open ocean carbon measurements and data, GEOCARBON Meeting, Paris, France, Nov. 19, 2014.

- Laufkötter, C., C. A. Stock, J.P. Dunne, "The Role of Temperature and Oxygen for the Remineralization of Sinking Organic Matter", Ocean Sciences 2016, New Orleans (oral).

- Laufkötter, C., J. P. Dunne, N. Gruber and M. Vogt, "Drivers of future changes in export production – a model comparison," 3rd Climate Change Symposium, Santos, Brazil (poster).

- Lauvset, S.K., A. Olsen, R. M. Key, X. Lin, T. Tanhua, M. Hoppema, S. Jutterström, R. Steinfeldt, E. Jeansson, S. van Heuven, M. Ishii, T. Suzuki, A. Velo, C. Schirnick, A. Kozyr, and B. Pfeil, GLODAPv2 – A new and updated global ocean carbon data product, IMBER Newsletter, 2014.

- Lauvset, S.K., A. Olsen, R.M. Key, X. Lin, T. Tanhua, M. Hoppema, S. Jutterstrom, R. Steinfeldt, E. Jeansson, S. van Heuven, M. Ishii, T. Suzuki, A. Velo, A. Kozyr, B. Pfeil, and C. Schirnick, Evaluation of global pH and $CaCO_3$ saturation state from WOCE to CLIVAR, IMBER meeting, Bergen, Norway, June 24-27, 2014.

- Lee, M., NEIR (National Institute of Environmental Research), Studies on Impact Assessment of Climate Change on Water Quality in a Regional Scale using a Land Surface Model (Ⅱ), Incheon, South Korea, 2015.

- Lee, M., Shevliakova, E., Malyshev, S., Milly, P.C.D., Jaffe, P. Stock, C. Climatic Variability and Extremes, Interacting with Nitrogen Storage, Amplify Risks of Coastal Eutrophication, Ocean Sciences Meeting, New Orleans, Louisiana, USA, 2016.

- Lee, S.K., Liu, Y., Muhling, B.A. "Potential Impact of climate change and variability on the Intra-Americas Sea (IAS)", NOAA Climate variability and fisheries workshop: Setting research priorities for the Gulf of Mexico, South Atlantic, and Caribbean regions, St Petersburg, Florida, October 2015.

- Legg, S., A. Melet, and R. Hallberg, Impacts of spatial distribution of parameterized local and remote tidal mixing on large-scale ocean circulation and climate. Ocean Sciences meeting 2016.

- Li, D., R. Zhang, and T.R. Knutson, Comparison of Low-Frequency Variability of Summer Arctic Sea Ice in Three Coupled Climate Models, AGU Fall Meeting. San Francisco, CA, December, 2015.

- Lin, Meiyun, Apr-2, 2015, Transboundary Ozone Pollution Conference, California: Quantifying Asian influence on Western U.S. surface ozone exceedances and long-term trends (Invited).

- Lin, Meiyun, Apr-21, 2015, NASA AIRS Science Team Meeting, JPL, Pasadena: Challenges in quantifying sources and variability of lower tropospheric ozone over western N. America: Perspectives from satellites and models (Invited keynote speaker).

- Lin, Meiyun, Aug-20, 2015, Western States Air Resources Council. Key drivers of western US surface ozone means and extremes: Climate variability, stratospheric intrusions, and Asian pollution (Invited seminar).

- Lin, Meiyun, May-11, 2015, HTAP: Modeling Air Quality from the Global to Local Scales, NCAR: Establishing process-oriented constrains on global models for ozone source attribution: Lessons from GFDL AM3.

- Lin, Meiyun, May-13, 2015, Western Regional Air Partnership (WRAP), NCAR: Key drivers of western US surface ozone variability over recent decades: Stratospheric intrusions, Asian pollution, and Climate variability (Invited).

- Lin, Meiyun, Oct-7, 2015, IGAC/SPARC Chemistry Climate Model Initiative Workshop, Italy: The Role of Climate, the Stratosphere, and Emissions on US Surface O_3 Trends and Extremes (Invited).

- Lin, Meiyun, Sep-18, 2015, CARB/UC Davis Meteorology And Climate - Modeling for Air Quality (MAC-MAQ) Conference: Detecting changes in US background ozone means and extremes amidst climate variability (Invited).

- Liu, Y., Lee, S.K., Enfield, D.B., Muhling, B.A., Lamkin, J.T., Muller-Karger, F.E., Roffer, M.A. "Past and future climate variability in the Intra-Americas Sea and its impact on the marine ecosystem and fisheries", U.S. CLIVAR Variations Newsletter Winter 2016.

- Mao, J. (Invited) ACS spring meeting, symposium "Transformations of Matter in the Troposphere", Denver, CO (03/2015) Observational constraints on isoprene oxidation over Southeast US.

- Mao, J. (Invited) NOAA Earth System Research Levorotary, Boulder, CO (01/2015) Oxidation of biogenic volatile organic compounds over Southeast US: a modeling perspective.

- Mao, J. (Invited) University of Alaska Fairbanks (04/2016) Radical chemistry in the troposphere: from air quality to climate change.

- Mao, J. (Invited) University of California Riverside (02/2015) Radical chemistry in the troposphere: from air quality to climate change.

- Mao, J. (Invited) University of California Riverside (03/2016) Radical chemistry in the troposphere: from air quality to climate change.

- Mao, J. (Invited) University of Houston (03/2016) Radical chemistry in the troposphere: from air quality to climate change.

- Mao, J. (Keynote Speaker) Nitrate Radicals and Biogenic Volatile Organic Compounds (VOCs): Oxidation, Mechanisms and Organic Aerosol, Georgia Institute of Technology, Atlanta, GA (06/2015) Organic nitrates and ozone over the Southeast US.

- Mao, J. AGU Fall meeting, San Francisco, CA, USA (12/2015) Development of a coupled biogenic emission module in an earth system model.

- Mao, J. GEIA meeting, Beijing, China (11/2015) Development of a coupled biogenic emission module in an earth system model.

- Mao, J., A.M. Carlton, L. W. Horowitz and coauthors, "Southeast Atmosphere Studies Workshop 2015", IGAC Newsletter, 2015.

- Mater, B., R. Hallberg, S. Legg, A. Adcroft, and J. Nycander, Representing the propagation and far-field dissipation of internal tides in a global climate model. Ocean Sciences meeting 2016.

- Mauzerall, DL, Nitrogen, Ozone and Water: Key Factors Impacting Sustainable Intensification of Crop Production, Food Security Group seminar, Stanford University, February 22, 2016.

- Mauzerall, DL, X Zhang, EA Davidson, TD Searchinger, P Dumas, Y Shen, Managing Nitrogen for Sustainable Development, EMBO conference, Nitrogen Nutrition of Plants, Montpellier, France, August 2016.

- McNichol, A.P., R.M. Key, K. von Reden, K. Elder, Understanding the Changing Global Distribution of Radiocarbon: What are we learning from the WOCE and CLIVAR Repeat Hydrography Result, Ocean Sciences Meeting, New Orleans, LA, Feb. 2016.

- Melet, A, Hallberg, R.W., S. Legg, M. Nikurashin and K. Polzin ; Climatic impacts of parameterized internal-wave driven mixing, Ocean Sciences meeting 2016.

- Muhling, B.A., Gaitan, C., Tommasi, D., Saba, V., Stock, C., Dixon, K. "Downscaling climate models for ecological forecasting in northeast U.S. estuaries", STAC workshop: "The Development of Climate Projections for Use in Chesapeake Bay Program Assessments", Annapolis, Maryland, March 2016.

- Muhling, B.A., Gaitan, C., Tommasi, D., Saba, V., Stock, C., Dixon, K. "Climate change, estuaries and anadromous fish habitat in the northeastern United States: models, downscaling and uncertainty", Ocean Sciences Meeting, New Orleans, Louisiana, February 2016.

- Muhling, B.A., Gaitan, C., Tommasi, D., Saba, V., Stock, C., Dixon, K., "Statistical Downscaling for Estuaries and Nearshore Environments", NOAA Ecological Forecasting meeting, Silver Spring, Maryland, May 2015.

- Muhling, B.A., Tommasi, D., Saba, V., Stock, C., Gaitan, C., Dixon, K. Latour, R. et al. "Fish habitat, estuaries and climate change in the northeast US: models, downscaling and uncertainty", Rutgers Fishbaste seminar series, November 2015.

- Muhling, B.A., Tommasi, D., Stock, C., Lamkin, J., Roffer, M., Nero, R., Domingues, R., Walter, J. "Towards spatial management of bluefin tuna in the Gulf of Mexico", Application of seasonal to decadal scale climate forecasts for marine resource management workshop, Princeton, New Jersey, June 2015.

- Nazarian, R. and S. Legg, Internal wave scattering in continental slope canyons: a parameter space study. Ocean sciences meeting 2016.

- Nazarian, R., and S. Legg, February 24, 2016: Internal Wave Scattering in Continental Slope Canyons: A Parameter Space Study. American Geophysical Union. 2016 Ocean Sciences Meeting.

- Nazarian, R., and S. Legg, June 16, 2015: A Parameter Space Study of Internal Wave Dynamics in Continental Slope Canyons. American Meteorological Society. Atmospheric and Oceanic Fluid Dynamics Conference.

- Nikonov, S., Balaji, V., Mason, E., Radhakrishnan, A., CMIP6 Publication Workflow at GFDL. 5th GO-ESSP Workshop. Feb 23-26, 2015. Abington, UK.

- Olsen, A., R.M. Key, S. Lauvset, X. Lin, T. Tanhua, M. Hoppema, S. Jutterström, R. Steinfeldt, E. Jeansson, S. van Heuven, M. Ishii, T. Suzuki, A.Velo, A. Kozyr, B. Pfeil, Global Ocean Data Analysis Project Version 2 (GLODAPv2), Ocean Sciences Mtg, Honolulu, Hawaii, Feb. 23-28, 2014.

- Olsen, A., R.M. Key, S.K. Lauvset, S. van Heuven, X. Lin, T. Tanhua, M. Hoppema, S. Jutterstrom, R. Steinfeldt, E. Jeansson, M. Ishii, T. Suzuki, A. Velo, A. Kozyr, B. Pfeil, C. Schirnick, Presenting GLODAPv2: Ocean biogeochemical time trends and future plans, IMBER meeting, Bergen, Norway, June 24-27, 2014.

- Olsen, Are, Robert M Key, Steven van Heuven, Siv K Lauvset, Anton Velo, Xiaohua Lin, Carsten Schirnick, Alexander Kozyr, Toste S Tanhua, Mario Hoppema, Sara Jutterstrom, Reiner Steinfeldt, Emil Jeansson, Masao Ishii, F.F. F Pérez and Toru Suzuki, Global Ocean Data Analysis Version 2 (GLODAPv2), Ocean Sciences Meeting, New Orleans, LA, Feb. 2016.

- Paulot, F., Dry deposition of nitrogen: impact of climate and land-use change, CCMI Meeting, Rome (2015).

- Paulot, F., Global oceanic emission of ammonia: Constraints from seawater and atmospheric observations, OCB Meeting, Woods Hole (July 2015).

- Paulot, F., Sensitivity of nitrate aerosols to ammonia emissions and to nitrate chemistry: Implications for present and future nitrate optical depth, AEROCOM meeting, Rome (2015).

- Persad, G., 2015: Black Carbon Aerosol: The Hare to Carbon Dioxide's Tortoise. Invited lecture. University of Texas at Austin Climate Forum. Austin, TX.

- Persad, G., D. Paynter, V. Naik, Y. Ming, M. Oppenheimer and V. Ramaswamy, 2016: Climate Implications of the Heterogeneity of Anthropogenic Aerosol Forcing. Invited lecture. Carnegie Institution for Science, Department of Global Ecology Seminar. Stanford, CA.

- Persad, G., D. Paynter, Y. Ming, and V. Ramaswamy, 2015: Competing Atmosphere- and Surface-Driven Impacts of Aerosol Absorption on the East Asian Summer Monsoon. American Geophysical Union Fall Meeting, San Francisco, CA.

- Persad, G., D. Paynter, Y. Ming, and V. Ramaswamy, 2015: The Regional Climate Response to Absorption-Driven Solar Dimming over East Asia. Gordon Research Conference on Radiation and Climate. Waterville, ME.

- Popp, Max and Levi Silvers, Double and single ITCZs with and without clouds, EGU General Assembly 2016, Vienna, Austria.

- Radhakrishnan, A., Nikonov, S., Balaji, V., Mason, E., GFDL workflow for massive data publishing. Princeton-Industry Symposium on High Performance Computing. May 11, 2015. Princeton, NJ.

- Ray, S., and A. T. Wittenberg, 2015: Climatological heat budget of the equatorial Pacific upper ocean in the GFDL FLOR global coupled GCM. NCEP Climate Diagnostic Workshop. October, 2015, Denver, USA.

- Ray, S., and A. T. Wittenberg, 2016: The Equatorial Pacific Warm Pool Mixed Layer Heat Budget. AGU Ocean Sciences Meeting, February, 2016, New Orleans, USA.

- Ruprich-Robert Y., Msadek R., Delworth T. (talk) Climate impacts of the Atlantic Multidecadal Variability: an experimental protocol, AGCI workshop on Decadal Climate prediction, June 2015, Aspen (CO).

- Ruprich-Robert Y., Msadek R., Delworth T., Castruccio F., Yeager S., Danabasoglu G. (talk) Extremes conditions over North America: the role of the Atlantic Multidecadal Variability, Ocean Sciences 2016, February 2016, New-Orleans (LA).

- Ruprich-Robert Y., Msadek R., Delworth T., Castruccio F., Yeager S., Danabasoglu G. (talk) Pacific impacts of the Atlantic Multidecadal Variability, Rapid - US AMOC International meeting, July 2015, Bristol (UK).

- Ruprich-Robert Y., Msadek R., Delworth T., Castruccio F., Yeager S., Danabasoglu G. (talk) Pacific impacts of the Atlantic Multidecadal Variability, IUGG General Assembly, June 2015, Prague (Czech Republic).

- Schuller, D., L. Talley, H. Zanowski, R. Key, K. Johnson and E. Boss, Hydrographic data facility serves the GO-SHIP and Argo communities, GAIC Conference, Galway, Ireland, Sept. 14-18, 2015.

- Schuller, Daniel, Lynne Talley1, Susan Becker, Robert Key, Ken Johnson, Emmanuel Boss, SIO'S Oceanographic Data Facility: Providing high quality nutrient and oxygen data for the GO-SHIP and Argo communities, CLIVAR meeting, Qingdao, China, Sep. 18-25, 2016.

- Sergienko O., M. Harrison, R. Hallberg and A. Adcroft (2015). Strong effects of thermodynamic ice-shelf/ocean interactions in a global sea-ice-ocean isopycnal model. IGS Symposium on Contemporary Ice-Sheet Dynamics: ocean interaction, meltwater and non-linear effects. Cambridge, UK, 16-21 August, 2015.

- Shen, Z., Factors controlling the seasonal cycle of Arctic black carbon, Poster. AGU 2015 Fall Meeting, San Francisco, CA. (12/2015).

- Shen, Z., Factors controlling the seasonal cycle of Arctic black carbon, Poster. Gordon Research Conference on Radiation and Climate. Waterville, ME. (7/2015).

- Silvers, L.G., B. Stevens, C. Hohenegger, and M. Giorgetta, 2015: Bridging the Gap Between GCMs and CRMs: A Look at Equilibrium Climate Sensitivity. GFDL Seminar, January 2015.

- Silvers, L.G., B. Stevens, T. Mauritsen, and M. Giorgetta, 2015: Parameterized Radiative Convective Equilibrium Across a Range of Domains: A Unifying Tool for General Circulation Models and High Resolution Models. GFDL Poster Expo January 2016.

- Silvers, L.G., B. Stevens, T. Mauritsen, and M. Giorgetta, 2015: Parameterized Radiative Convective Equilibrium Across a Range of Domains: A Unifying Tool for General Circulation Models and High Resolution Models. AGU, December 2015.

- Strong, J. D. O., G. A. Vecchi, 2016: The climatological effect of Saharan dust on global tropical cyclones in a fully coupled GCM. Proceedings, 32nd Conf. on Hurricanes and Tropical Meteorology, San Jose, PR, Amer. Meteor. Soc.

- Strong, J. D. O., G. A. Vecchi, and P. A. Ginoux, 2015: The effect of Saharan dust on North Atlantic hydroclimate and tropical cyclones in a high-resolution GCM. Proceedings, AGU Fall Meeting, San Francisco, CA.

- 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.

- Sulman, B.N., E. R. Brzostek, and R. P. Phillips: Modeling plant N acquisition and soil biogeochemical feedbacks in a temperate forest (oral presentation). Ecological Society of America Annual Meeting, Baltimore, MD, Aug 2015.

- Sulman, B.N., L. Nave, C. Treat, Y. He, and C. Koven: Controls on vertical soil carbon distributions in the continental United States: Applications for model evaluation (invited oral presentation). American Geophysical Union 2015 Fall Meeting, San Francisco, CA, Dec 2015.

- Sulman, B.N., R. P. Phillips, E. Shevliakova, A. C. Oishi, and S. Pacala: Root exudation, priming, and protection: Advanced soil carbon processes in a global model (poster presentation). North American Carbon Program PI meeting, Washington, DC, Jan 2015.

- Sulman, B.N., R. P. Phillips, E. Shevliakova, E. R. Brzostek, and S. W. Pacala: Microbes, minerals, and roots in a soil organic matter model at local to global scales (invited poster presentation). INTERFACE RCN 2016 workshop: Integrating models and experiments to explore climate feedbacks in a managed and warming world, St. Pete Beach, FL, Jan 2016.

- Tanhua, Toste, Robert M. Key, Ann McNichol, Carbon isotopes in the Mediterranean Sea, CIESM (The Mediterranean Science Commission) Congress, Kiel, Germany, Sep. 2016.

- Tanhua, Toste, S. van Heuven, A. Olsen, S. Lauvset, A. Velo, R. Key, M. Hoppema, T. Suzuki, Comparability of oceanic nutrient data: Results from the secondary QC of GLODAPv2 nutrient data, CLIVAR meeting, Qingdao, China, Sep. 18-25, 2016.

- Tian, Di, Eric F. Wood, Gabriel Vecchi, Liwei Jia, and Ming Pan 2015, Surface Water and Energy Budgets for sub-Saharan Africa in GFDL coupled climate models. Presented at 2015 AGU Fall meeting, San Francisco, CA.

- Tommasi, D., Stock. C. (2015). Incorporating seasonal climate forecasts in a harvest control rule for Pacific sardine. Oral Presentation at the 144^{5h} Annual Meeting of the American Fisheries Society in Portland, OR, USA.

- Tommasi, D., Stock. C. (2015). Incorporating seasonal climate forecasts in a harvest control rule for Pacific sardine. Oral Presentation at the Marine Ecosystem Analysis and Prediction Workshop in Dalhousie University, Halifax, Nova Scotia, Canada.

- Tommasi, D., Stock. C., Pegion, K., Vecchi, G., Methot, R.D., Alexander, M., and Checkley, D. (2016). Assessing the Utility of Seasonal SST Forecasts to the Fisheries Management Process. Oral Presentation at the 2016 ASLO Ocean Sciences Meeting in New Orleans, LA, USA.

- Van Oostende N, Dunne JP, Fawcett SE, Ward BB (2015) Phytoplankton succession explains size-partitioning of new production following upwelling-induced blooms (poster). Ocean Carbon Biogeochemistry, "Trait-based Approaches to Ocean Life" workshop, Waterville (NH), 5-8 October 2015.

- Wanders, N. and E.F. Wood Assessment of (sub-) seasonal prediction skill using a canonical event analysis, Presented at 2015 AGU Fall meeting, San Francisco, CA.

- Williams, D. N., M. Lautenschlager, V. Balaji, L. Cinquini, C. DeLuca, S. Denvil, D. Duffy, B. Evans, R. Ferraro, M. Juckes, and C. Trenham, 2015b: Strategic Roadmap for the Earth System Grid Federation. Big Data (Big Data), 2015 IEEE International Conference on, 2182--2190.

- Yi, P., S. Legg, and R. Nazarian, February 24, 2016: A Process Study of Tidal Mixing Over Rough Topography. American Geophysical Union. 2016 Ocean Sciences Meeting.

- Yi, Y., S. Legg and R. Nazarian, Tidal mixing over rough topography: sensitivity to topographic length scale and steepness. Ocean sciences meeting 2016.

- Zanowski, H., R. Hallberg, and J.L. Sarmiento: A tale of two timescales: Weddell polynya pathways in the global abyssal oceans. Poster session to be presented at: Physical and Biogeochemical Processes in the Southern Ocean: Observations, State Estimation, and Modeling V. 18th Biennial Ocean Sciences Conference, 2016 Feb 21-26; New Orleans, LA.

- Zhang, Liping and Tom Delworth. “Simulated response of the Pacific decadal oscillation to climate change.” Oral presentation, 2015 JOINT ASSEMBLY meeting, Canada, May 2015.

- Zhang, Liping, Tom Delworth and Fanrong Zeng. “The impact of multidecadal Atlantic meridional overturning circulation variations on the Southern Ocean.” Poster presentation, AGU fall meeting, December 2015.

- Zhang, X., DL Mauzerall, EA Davidson, Managing Nitrogen Managing Nitrogen for Sustainable Intensification of Crop Production, The Second International Conference on Global Food Security, Ithaca, NY, USA, Oct. 13, 2015.

2015-2016 Book Chapters

- DelSole, Timothy, Michael K. Tippett and Liwei Jia, 2015: Multi-year Prediction and Predictability, World Scientific Series on Weather and Climate, Climate Change: Multidecadal and Beyond, Chapter 14, pp 219-233, 2015.

- Muhling, B.A., Lindegren, M., Worsoe Clausen, L., Hobday, A.J., Lehodey, P. (in press) Impacts of climate change on pelagic fish and fisheries. Book chapter in Phillips, B., Perez, M. (eds) The Impacts of Climate Change on Fisheries and Aquaculture. Wiley.

2015-2016 Ph.D. Theses

- Choi, Kityan, August 2015. El Niño-Southern Oscillation: Asymmetry, Nonlinear Atmospheric Response and the Role of Mean Climate, Ph.D. thesis, Princeton University.

- Goldman, Johanna, February 2016. Environmental Factors Influencing Phytoplankton Productivity in the Context of Climate Change, Ph.D. thesis, Princeton University.

- Wang, He, January 2016. Large Scale Impacts of Subarctic Channel Flows and Deep Water Formation in Climate Models, Ph.D. thesis, Princeton University.

ADMINISTRATIVE STAFF

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Task I: Administrative Activities and Outreach Supported Personnel

Name	**Rank**
Shaun Howe	Summer Intern
Eliot Feibush	Visualization/Computational Scientist
Sarmiento, Jorge L.	CICS Director
Legg, Sonya	CICS Associate Director
Laura Rossi	CICS Administrator

Departures - Task II and Task III

Elena Shevliakova – 9/21/15: NOAA/GFDL

Dan Li – 12/31/15: Boston University – Assistant Professor

Benjamin Mater – 12/31/15: Alden Research Laboratories, CO., Sr. Engineer

Elena Shevliakova – 9/21/15: NOAA/GFDL

Xiaohua Lin – 1/5/16: N/A

Ph.D. Defenses

Student: Kityan Choi – August 2015

Advisor: Gabriel Vecchi

Dissertation: El Niño-Southern Oscillation: Asymmetry, nonlinear atmospheric response and the role of mean climate

Current Affiliation: Enthought, UK

Student: He Wang – January 2016

Advisor: Sonya Legg

Dissertation: Large Scale Impacts of Subarctic Channel Flows and Deep Water Formation in Climate Models

Current Affiliation: University of California San Diego, Scripps Institute of Oceanography

Student: Johanna Goldman – February 2016

Advisor: Francois Morel

Dissertation: Environmental Factors Influencing Phytoplankton Productivity in the Context of Climate Change

Current Affiliation: University of Washington

Task II: Cooperative Research Projects and Education Supported Personnel

Name	**Rank**	**Host**
Adcroft, Alistair	Research Oceanographer	GFDL Director
Anber, Usama	Postdoctoral Research Associate	Lin, SJ/Harris, Lucas
Balaji, V.	Sr. Professional Specialist	GFDL Director
Baldwin, Jane	Graduate Student	Vecchi, Gabriel
Barton, Andrew	Associate Research Scholar	Stock, Charlie/Dunne, John
Bushuk, Mitch	Postdoctoral Research Associate	Vecchi, Gabriel
Chai, Junyi	Graduate Student	Held, Isaac/Vallis, Geoff
Chang, Chiung-Yin (Jenny)	Graduate Student	Held, Isaac
Chaney, Nathaniel	Postdoctoral Research Associate	Shevliakova, Elena
Chen, Xi	Postdoctoral Research Associate	Lin, SJ
Choi, Kityan	Graduate Student	Vecchi, Gabriel
Clark, Spencer	Graduate Student	Ming, Yi
Deroubaix, Adrien	Postdoctoral Research Associate	Ginoux, Paul
FitzMaurice, Anna	Graduate Student	Hallberg, Robert
Frazer, Michelle	Graduate Student	Ming, Yi
Gonzalez-Taboada, Fernando	Postdoctoral Research Associate	Stock, Charlie/Dunne, John
Haseloff, Marianne	Postdoctoral Research Associate	Sergienko, Olga
He, Jie	Postdoctoral Research Associate	Vecchi, Gabriel
Hill, Spencer	Graduate Student	Ming, Yi
Hsieh, Tsung-Lin	Graduate Student	Garner, Steve
Jia, Liwei	Associate Research Scholar	Vecchi, Gabriel
Johnson, Nathaniel	Associate Research Scholar	Vecchi, G./Wittenberg, A.
Kam, Jonghun	Postdoctoral Research Associate	Vecchi, G./Knutson, Tom
Laufkotter, Charlotte	Postdoctoral Research Associate	Stock, Charlie/Dunne, John
Lee, Minjin	Postdoctoral Research Associate	Stock, C./Shevliakova, E.
Legg, Sonya	Senior Research Oceanographer	GFDL Director
Li, Dan	Postdoctoral Research Associate	Shevliakova, E/Milly, Chris
Li, Dawei	Postdoctoral Research Associate	Zhang, Rong/Knutson, Tom
Lin, Pu	Postdoctoral Research Associate	Ming, Yi
Lutsko, Nicholas	Graduate Student	Held, Isaac
Malyshev, Sergey	Professional Specialist	Pacala, Steve
Mao, Jingqiu	Associate Research Scholar	Horowitz, Larry
Marques, Gustavo	Postdoctoral Research Associate	Hallberg, Robert
Mater, Benjamin	Postdoctoral Research Associate	Hallberg, R./Legg, Sonya
Mooring, Todd	Graduate Student	Held, Isaac
Muhling, Barbara	Associate Research Scholar	Saba, Vince/Stock, Charlie
Nazarian, Robert	Graduate Student	Legg, Sonya
Nikonov, Sergey	Professional Specialist	Balaji, V.

Task II: Cooperative Research Projects and Education Supported Personnel CONTINUED

Name	**Rank**	**Host**
Ng, Ching Ho (Justin)	Graduate Student	Vecchi, Gabriel
Orlanski, Isidoro	Sr. Research Meteorologist	GFDL Director
Paulot, Fabien	Associate Research Scholar	Horowitz, Larry
Perez Garcia-Pando, Carlos	Associate Research Scientist *Columbia University (subaward)*	Ginoux, Paul
Persad, Geeta	Graduate Student	Ramaswamy, V.
Popp, Max	Postdoctoral Research Associate	Held, Isaac
Pu, Bing	Postdoctoral Research Associate	Ginoux, Paul
Ray, Sulagna	Associate Research Scholar	Wittenberg, Andrew
Ruprich-Robert, Yohan	Postdoctoral Research Associate	Delworth, Tom
Sergienko, Olga	Research Glaciologist	Hallberg, Robert
Shen, Zhaoyi	Graduate Student	Horowtiz, Larry
Shevliakova, Elena	Professional Specialist	Pacala, Steve
Silvers, Levi	Associate Research Scholar	Ming, Yi
Strong, Jeffrey	Graduate Student	Vecchi, Gabriel
Sulman, Benjamin	Associate Research Scholar	Shevliakova, Elena
Tommasi, Desiree	Associate Research Scholar	Stock, Charlie
van der Wiel, Karin	Postdoctoral Research Associate	Vecchi, Gabriel
Ward, Daniel	Postdoctoral Research Associate	Dunne, J./Shevliakova, E.
Zhang, Honghai	Postdoctoral Research Associate	Delworth, Tom
Zhang, Liping	Postdoctoral Research Associate	Delworth, Tom
Zhou, Linjiong	Postdoctoral Research Associate	Lin, SJ/Harris, Lucas

Task II: Cooperative Research Projects Supported Personnel – RECENT HIRES (no reports)

Bhatia, Kieran	Postdoctoral Research Associate	Vecchi, Gabriel
Jones, Alexander	Postdoctoral Research Associate	Ramaswamy, V./Paynter, D.
Krishnamurthy, Lakshmi	Associate Research Scholar	Vecchi, Gabriel
Reichl, Brandon	Postdoctoral Research Associate	Griffies, S./Shevliakova, E.
Shao, Andrew	Postdoctoral Research Associate	Hallberg, Robert
van Huijgevoort, Marjolein	Postdoctoral Research Associate	Shevliakova, Elena
Wolovick, Michael	Postdoctoral Research Associate	Sergienko, Olga

Task III: Individual Research Projects Supported Personnel

Name	**Rank**	**Advisor**
Chavas, Daniel	Postdoctoral Research Associate	Lin, Ning
Fueglistaler, Stephan	Professor	--
Goldman, Johanna	Graduate Student	Morel, Francois
Harig, Christopher	Associate Research Scholar	Simons, Fredrik
Hatzikyriakou, Adam	Graduate Student	Lin, Ning
Jing, Renzhi	Graduate Student	Lin, Ning
Key, Robert M.	Research Oceanographer	Sarmiento, Jorge
Lin, Meiyun	Associate Research Scholar	Horowitz, Larry
Lin, Xiaohua	Research Assistant	Key, Robert
Rodgers, Keith	Research Oceanographer	Sarmiento, Jorge
Tian, Di	Postdoctoral Research Associate	Wood, Eric
VanOostende, Nicholas	Associate Research Scholar	Ward, Bess
Young, Jodi	Postdoctoral Research Associate	Morel, Francois
Zanowski, Hannah	Graduate Student	Sarmiento, Jorge
Zhang, Xin	Postdoctoral Research Associate	Mauzerall, Denise

Personnel				
Category	Number	B.S.	M.S.	Ph.D.
Faculty	2	-	-	2
Research Scientist	7	-	-	7
Visiting Scientist	-	-	-	-
Postdoctoral Research Associate	26	-	-	26
Professional Technical Staff	5	-	1	4
Associate Research Scholar	16	-	-	16
Administrative	1	-	-	-
Total (≥ 50% support)	**43**		**1**	**42**
Undergraduates	1	-	-	-
Graduate Students	20	2	15	2
Employees that receive < 50% NOAA funding (not including graduate students)	14	-	-	14
Located at the Lab (include name of lab)	GFDL-50	-	8	42
Obtained NOAA employment within the last year	1	-	-	-

CICS FY'16 List of Awards for Institutional Award NA14OAR4320106

Amount	PI	Project Title
$ 4,247[*7]	Jorge L. Sarmiento	CICS-YR 6 (Administration-Task I) *GFDL/V. Ramaswamy*
$ 40,746[*8]	Keith Rodgers	Using Models to improve our ability to monitor ocean uptake of anthropogenic carbon (Task III) *CPO-David Legler*
$4,402,447[*9]	Jorge L. Sarmiento	CICS-YR 7 (Research/Education-Task II) *GFDL/V. Ramaswamy*
$ 99,749[*9]	Enrique Curchitser	Climate Downscaling for California Current Marine Ecosystem Impacts - *Rutgers University Subaward* *GFDL/V. Ramaswamy*
$ 53,364[*9]	Mark Zondlo	Reactive nitrogen biogeochemical cycling in the GFDL ESMs: Advancing understanding of the atmosphere-land Interactions under changing climate and land *GFDL/V. Ramaswamy*
$ 578,501[*9]	Jorge L. Sarmiento	CICS-YR 7 (Research/Education-Task III) *GFDL/V. Ramaswamy*
$ 77,829[*10]	Jorge L. Sarmiento	CICS-YR 7 (Administration – Task I) *GFDL/V. Ramaswamy*
$ 73,182[*11]	Jorge L. Sarmiento	CICS-YR 7 (Research/Education-Task II) *GFDL/V. Ramaswamy*
$ 56,758[*11]	Carlos Perez Garcia-Pando	CICS-YR 7 (Research/Education-Task II) *Columbia University Subaward* *GFDL/V. Ramaswamy*
$ 5,847[*12]	Jorge L. Sarmiento	CICS-YR 7 (Administration – Task I) *GFDL/V. Ramaswamy*
$ 100,096[*13]	Jorge L. Sarmiento	CICS-YR 7 (Administration – Task I) *GFDL/V. Ramaswamy*
$ 9,539[*14]	Jorge L. Sarmiento	CICS-YR 7 (Administration – Task I) *GFDL/V. Ramaswamy*
$ 122,175[*15]	Jorge L. Sarmiento	CICS-YR 7 (Research/Education-Task II) *GFDL/V. Ramaswamy*
$ 68,626[*15]	Meiyun Lin	Exploring emission versus climate drivers of tropospheric ozone variability and trends over northern midlatitudes *(Task III) ERSL/NASA-Owen Copper*

CICS FY'16 List of Awards for Institutional Award NA14OAR4320106

Amendment No./PI	Amount	Project Title
Amendment #7 PI: Jorge L. Sarmiento	$ 4,247	Cooperative Institute for Climate Science – Task I
Amendment #8 PI: Keith Rodgers	$ 40,746	Using Models to Improve our Ability to Monitor Ocean Uptake of Anthropogenic Carbon
Amendment #9 PI: Jorge L. Sarmiento	$5,134,061	Cooperative Institute for Climate Science – Year 7
Amendment #10 PI: Jorge L. Sarmiento	$ 77,829	Cooperative Institute for Climate Science – Task I
Amendment #11 PI: Jorge L. Sarmiento	$ 129,940	Cooperative Institute for Climate Science – Year 7
Amendment #12 PI: Jorge L. Sarmiento	$ 5,847	Cooperative Institute for Climate Science – Task I
Amendment #13 PI: Jorge L. Sarmiento	$ 100,096	Cooperative Institute for Climate Science – Task I
Amendment #14 PI: Jorge L. Sarmiento	$ 9,539	Cooperative Institute for Climate Science – Task I
Amendment #15 PI: Jorge L. Sarmiento	$ 190,801	Cooperative Institute for Climate Science – Year 7