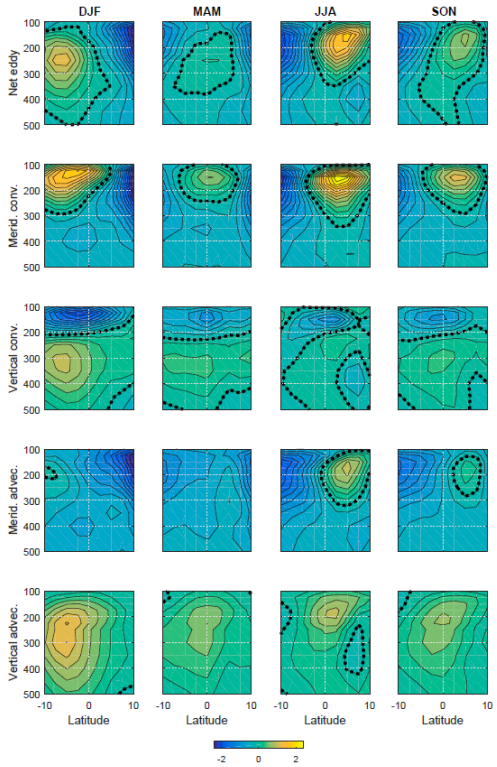
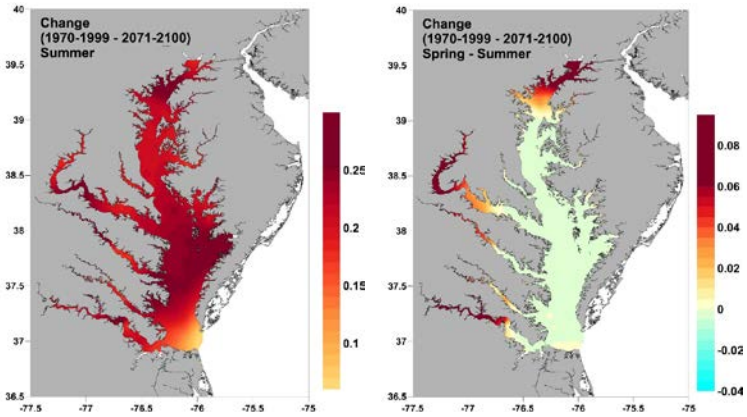
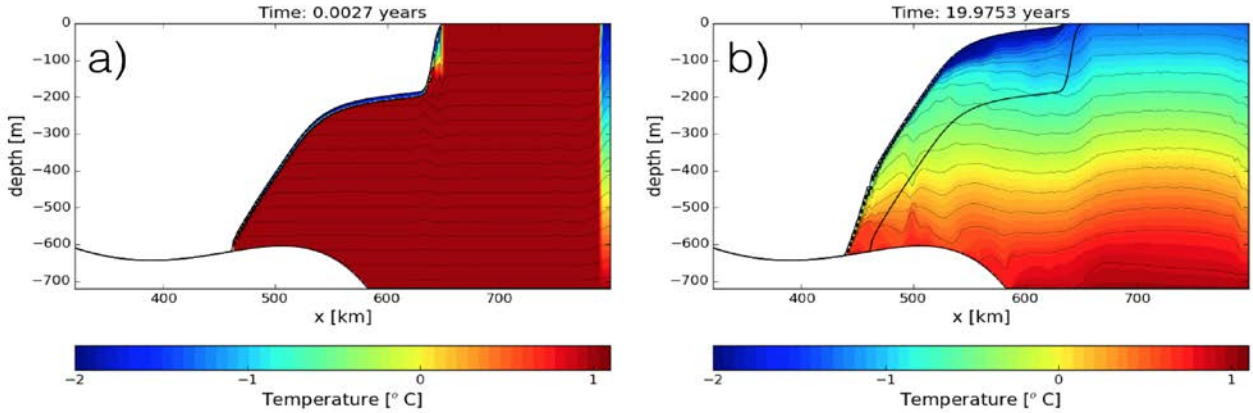


Annual Progress Report
April 1, 2016 – March 31, 2017

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



Jorge L. Sarmiento, Director
Sonya Legg, Associate Director
Cooperative Institute for Climate Science
Princeton University Forrestal Campus
300 Forrestal Road, Sayre Hall
Princeton, New Jersey 08540-6654



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Cooperative Institute for Climate Science
Princeton University

Annual Progress Report under cooperative agreement NA14OAR4320106

For the period April 1, 2016 – March 31, 2017

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.

Bring Your Young Scientist to Work Day 2016

On Thursday, April 28, 2016 the GFDL Employee's Association (GFDLEA) hosted "Bring Your Young Scientist to Work Day" at GFDL, a day of discovery and exploration at a premier NOAA research laboratory. Twenty-two children of employees, their friends and relatives attended the event designed to help spark interest in the field of climate science by exposing them to the scientists and lab employees who carry out important work and research in their community.

Bring Your Scientist Work Day Participants
(Credit: Will Cooke)

Age appropriate talks covered a wide range of topics including: air pollution and climate; hurricanes and climate; ocean acidification; the climate of Mars; climate modeling; and AMOC and the future of world climate. Among the speakers were: Kirsten Findell (GFDL), Yi Ming (AOS/GFDL), Hannah Zanowski (CICS), John Dunne (GFDL), Tim Marchok (GFDL), Todd Mooring (CICS), Desiree Tommasi (CICS), Whit Anderson (GFDL), Andrew Shao (CICS), Shannon Rees (Engility), and Tom Delworth (AOS/GFDL).

CICS Researcher Hannah Zanowski talked about her personal experience "amongst the bergs" aboard the German Research Icebreaker *Polarstern* and led a hands-on activity based on the behavior of the meltwater from dyed ice cubes to demonstrate how both temperature and salinity determine the density of seawater. Desiree Tommasi, a CICS scientist, conducted "The Phytoplankton Race," an interactive activity that explored buoyancy, the role of phytoplankton in ecosystems, how phytoplankton acquire energy, and the adaptations they have to remain close to the surface to acquire energy from sunlight.

Shannon Rees, a programming scientist in GFDL's Weather and Climate Dynamics Group, explored the science behind clouds with her "Clouds in a Jar" experiment, an apparent crowd favorite, according to GFDLEA President Rich Gudgel.

In addition to the talks and interactive activities, the children explored the Lab and its technology, including the computing facility, on a walking tour led by GFDL scientists, enjoyed a courtyard cookout, and earned "Certificates of Attendance" which were presented to them by Whit Anderson, acting deputy director of GFDL, all the while acquiring awareness of GFDL's mission and career opportunities in the STEM fields – science, technology, engineering and math.

CICS Research Internships

CICS research internships are a new program initiated in 2016, designed to broaden participation in climate and earth system science. The program matched undergraduate and graduate students from diverse backgrounds with hosts at GFDL to work on a focused scientific problem while gaining exposure to the full range of GFDL scientific activities. Applicants were recruited by advertising in a wide range of venues, including through the Institute for Broadening Participation, and by targeted mailings to minority serving institutions and contacts through the NOAA Education Partnership Program. From the approximately 100 applications received, a total of 8 candidates were selected for CICS funding, comprising 6 undergraduates and 2 graduate students. The interns spent 8-10 weeks in Princeton, advised by GFDL hosts, and assisted by AOS graduate student and/or postdoctoral associate mentors. Each intern received a stipend and reimbursement for travel to and from their home institution, ensuring that the internship would be accessible to students from a wide range of backgrounds and institutions. The students' experience was enhanced by seminars, tutorials and workshops, including a tutorial on Python, and a discussion on applying to graduate school. The summer research period concluded with a 12-minute presentation to the GFDL community. Students, home institutions, and titles of research presentations are listed below.

2016 CICS Summer Interns: (Back Row L to R) Aria Alexander, Claire Miles, Miguel Moravec, Leonardo Rodriguez (Front Row L to R) Maryam Abdi-Oskouei, Alyssa Stansfield, Alice Nadeau, Maria Pulido-Velosa, Ariek Norford

Maryam Abdi-Oskouei, University of Iowa: Methane in the GFDL atmospheric chemistry model.
Aria Alexander, Princeton University: Diurnal precipitation in Ohio.
Claire Miles, Stanford University: Changes in climate extremes under global warming.
Miguel Moravec, Vanderbilt University: Automatic analysis scripts for the North American Multi-Model Ensemble.

Alice Nadeau, University of Minnesota: Assessing ocean biogeochemical stocks and fluxes in GFDL's ESMs.
Ariek Norford, Franklin and Marshall College: Assessing GFDL model fidelity with a suite of satellite constraints on ocean ecosystems and biogeochemistry.
Maria Pulido-Velosa, Florida International University: Benchmarking ocean biogeochemical fields in GFDL's ESMs.
Alyssa Stansfield, Rutgers University: The impact of ENSO on the extreme winter weather over North America in GFDL's FLOR model.

CW2017: The Fourth Workshop on Coupling Technologies for Earth System Models

The Fourth Workshop on Coupling Technologies for Earth System Models (CW2017) was held from March 20-22, 2017 at the Princeton Center for Theoretical Science on the campus of Princeton University, with 60 people in attendance. The workshop, organized by CICS Scientist, V. Balaji, head of the Modeling System Group at GFDL, aimed to bring together leading researchers and practitioners in the field of coupling infrastructure for Earth System models. This workshop is the fourth in a series, the first being held at CERFACS in December 2010, the second at NCAR in February 2013, and the third in Manchester in April 2015.

The workshop was organized around three key themes: Coupling technologies; Use of coupling technologies in ESMs and performance, and Science of coupling and coupling strategies. Topics relevant to the workshop included, but were not limited to: Development and use of coupling technologies for Earth System Models; Performance considerations of couplers; New developments in existing coupling infrastructure; Couplers, metadata and workflows; Coupling frameworks in the broader geosciences; and Science of coupling (interpolation methods, convergence, stability).

CICS Scientist Olga Sergienko, an AOS research glaciologist, and Robert Hallberg, a GFDL oceanographer, presented the keynote address "The numerical stability of ice/ocean coupling, introducing interactive ice sheets into coupled models, and implications for coupler design." Given that combining different component models together into a viable coupled system is a complicated exercise in balancing competing considerations arising from practical software design, navigating interpersonal relationships, and dynamical system stability analysis, the pair concluded that recognizing these valid but sometimes contradictory considerations is important as the modeling community strives to maximize their collective scientific productivity through intelligent coupler design.

This workshop was sponsored by IS-ENES2 and the Princeton University Cooperative Institute for Climate Science (CICS).

Fall Model Hierarchies Workshop

A "Model Hierarchies Workshop" was held from November 2–4, 2016 in McDonnell Hall on Main Campus. The workshop, co-sponsored by CICS, addressed the key challenge of how to make the hierarchy of models more effective, so that climate scientists may readily isolate observed behavior of a complex model in a simpler one, and represent findings from idealized model in General Circulation Models (GCMs). The event was attended by about 150 participants from relevant communities within the climate science/modeling field. Participants represented a range of perspectives and included research projects in themes spanning tropical convection, stratosphere-troposphere interactions, coupled problems involving oceans and ecosystems, and the general area of climate sensitivities and feedbacks. The meeting was held in conjunction with the 20th Session of the World Climate Research Programme Working Group on Coupled Modeling (WGCM-20), which ran from October 31 – November 2, 2016.

Model Hierarchies Workshop Welcome –
CICS Scientist V. Balaji

The workshop featured AOS Faculty Member Isaac Held and Tim Palmer (University of Oxford) giving a talk on "Debating model hierarchies," and seven additional invited speakers including, Bjorn Stevens (Max Planck Institute), Masaki Satoh (Tokyo University), Michela Biasutti (Columbia University), Alan Plumb (Massachusetts Institute of Technology), Amy Clement (University of Miami), Mick Follows (Massachusetts Institute of Technology), and Marika Holland (NCAR). The event included approximately 30 talks and featured 60 posters; 30% of the accepted abstracts came from women and about 45% from early-career scientists, both numbers above the norm for an open workshop of this kind.

Lead Organizer V. Balaji, a CICS scientist, noted that the side discussions around the talks, over meals, and during breaks gave rise to a number of possible future collaborations. One concrete example is the RCEMIP, the "radiative-convective equilibrium model intercomparison project," a collaboration between one of the field's luminaries, Masaki Satoh, and one of its rising stars, Allison Wing, spurred by a conversation over coffee. This project will assemble models of various levels of complexity, and workshop organizers expect many "hierarchical" findings to emerge. In addition to fostering communication and collaboration between relevant communities, an anticipated outcome of the workshop is a paper intended for a broad audience around the theme of model hierarchies.

Co-sponsors of the event included the World Climate Research Programme under the auspices of the WCRP Grand Challenge on Clouds, Circulation, and Climate Sensitivity and the Working Group on Coupled Models, with the facilities provided by Princeton University and technical support provided by the Institut Pierre Simon Laplace (IPSL).

Modeling a Living Planet: A Symposium in Honor of Jorge Sarmiento

Friends and colleagues of CICS Director Jorge Sarmiento, the George J. Magee Professor of Geoscience and Geological Engineering, Professor of Geosciences, convened a symposium in his honor from March 14-15, 2016. The symposium was held in the Frick Chemistry Lab/Taylor Auditorium on Princeton University's Main Campus.

The symposium celebrating the research of Jorge L. Sarmiento, "Modeling a Living Planet," highlighted Sarmiento's groundbreaking work in ocean biogeochemistry as well as new research directions inspired by his scientific curiosity. Weaving together ocean circulation, the global carbon cycle, ocean elemental cycling, and ocean biogeography, through the consideration of the range of physical and temporal scales, the program covered interactions among the physical, geochemical, and biological aspects of the climate system.

Over the course of the two days, invited talks provided a broad context for panel discussions and poster sessions that addressed five topics related to Sarmiento's major research interests: Ocean ventilation – From the North Atlantic to the Southern Ocean; Dance of the elements – What chemistry tells us about life on earth; Life *in silico* – How we are doing at modeling changing ocean ecosystems; The breath of life – A changing carbon cycle; and Climate Policy: Impacts and mitigation.

The Symposium honored Sarmiento's scientific contributions in these areas as well as his contributions to graduate and postdoctoral education. Valued colleagues shared their expertise; among them former mentor Wally Broecker, Sarmiento's Ph.D. adviser at Columbia University, former AOS Senior Scientist Kirk Bryan, his postdoc adviser, and Niki Gruber, a former postdoc with whom he coauthored the textbook *Ocean Biogeochemical Cycles* (2006). Sessions were facilitated by former and current Sarmiento Group members. Presenters included leading researchers from around the globe, many of *whom* are former Ph.D. students *or* postdoctoral researchers who were mentored by him during his more than 35 years on the AOS faculty.

Sarmiento's research interests include the global carbon cycle, the use of chemical tracers to study ocean circulation, and the impact of climate change on ocean biology and biogeochemistry. Many of his scientific contributions have been on the role of the Southern Ocean in determining the air-sea balance of carbon dioxide during glacial and interglacial climate change, oceanic uptake of anthropogenic carbon and its sensitivity to climate change, and the resupply of nutrients to the upper ocean north of 30°S. He has served as the Director of the Southern Ocean Carbon and Climate Observations and Modeling program (SOCCOM), since the initiative's launch in 2014. In addition to SOCCOM Director, he has held and currently holds various prominent posts. He has served as the Director of the Cooperative Institute for Climate Science (CICS), since its inception in 2003, and served as director of the AOS Program from 1980-1990 and from 2006-2015.

The symposium was presented with support from the Program in Atmospheric and Oceanic Sciences (AOS), the Cooperative Institute for Climate Science (CICS), the Department of Geosciences, and Princeton University's Office of the Dean of the Faculty.

Ocean Fun Days 2016

CICS, AOS, and GFDL researchers lent their expertise at the thirteenth annual celebration of Ocean Fun Days at the Jersey Shore. The free, two-day event, whose goal is to promote the wise use of New Jersey's marine and coastal resources, was held on Saturday, May 21st at Island Beach State Park and May 22nd at the New Jersey Sea Grant Consortium (NJSGC) on Sandy Hook.

Left to Right: CICS Researchers Honghai Zhang and Todd Mooring and CICS Director Sonya Legg

The education-oriented event is sponsored by the NJSGC in coordination with the state Department of Environmental Protection and is held annually. CICS Associate Director Sonya Legg and fellow researchers Jasmin John (GFDL), Todd Mooring (CICS), Tom Robinson (Engility), and Honghai Zhang (CICS) oversaw the experiments which included "ocean acidification in a cup," "iceberg melting," and "taste the difference between the bay and the ocean." They joined marine scientists and environmentalists from around the state in offering learning and hands-on activities focused on our marine and coastal environment.

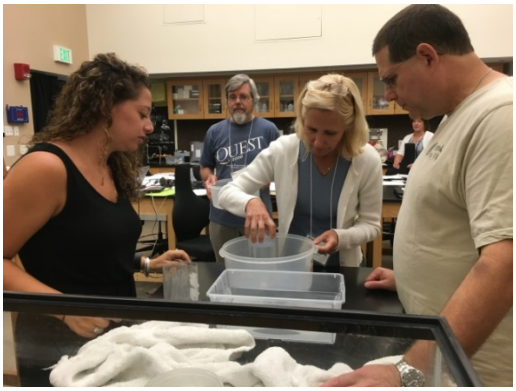
With a record number of exhibitors, the event also offered eco-tours of the island, a host of hands-on activities, educational displays, a variety of classes, and exhibits that celebrate the natural wonders of the Jersey Shore. Eco-friendly activities included coastal crafts, fiddler crab races, eco-tours, workshops, using seins to net fish and other aquatic life, an energy scavenger hunt, games and prizes, youth fishing clinics, Beachcombing 101, face painting, and sea-creature touch tanks and exhibits. In addition to all the booths and exhibits, the NJSGC headquarters location, in the historic Fort Hancock section of Sandy Hook, also included guides tours of many of Sandy Hook's historic sites and an open house at the NOAA/James J. Howard Science Laboratory.

Ocean Fun Days is presented by founding sponsor New Jersey Natural Gas, in partnership with New Jersey Sea Grant Consortium, Asbury Park Press, New Jersey Department of Environmental Protection, New Jersey Division of Parks and Forestry and the National Oceanic and Atmospheric Administration.

Summer Institute in Weather and Climate

In July of 2016, the Cooperative Institute in Climate Science (CICS) co-sponsored a weeklong summer institute in weather and climate for 11 teachers of grades 3-8, hosted by the University's Program in Teacher Preparation. The program, whose formal name is Questioning Underlies Effective Science Teaching (QUEST), is designed to enhance teachers' content knowledge and their skills through hands-on experiments and discussion, emphasizing self-directed investigation rather than textbook learning.

Led by Steve Carson, a middle school teacher and former researcher at the Geophysical Fluid Dynamics Laboratory (GFDL), teachers worked together to better understand the Coriolis Effect. Using water bottles placed atop of a turntable modeling Earth's rotation, teachers used their prediction skills to determine how water would flow from holes in the bottles based on the direction the turntable was spinning. Other experiments focused on air pressure, temperature, the seasons, the greenhouse effect, humidity, clouds, wind and storms.



Under the guidance of Instructor Steve Carson, QUEST participants conduct an experiment demonstrating the Coriolis Effect.

According to Anne Catena, program associate and director of professional development initiatives in Princeton's Program in Teacher preparation, participating teachers learned about the work of researchers and how to translate it for their classrooms, in line with the Next Generation Science Standards being implemented in New Jersey schools this fall. Developed by states, the standards set new expectations for what students should know and be able to do, and are designed to improve science education for all students.

Participants get hands-on experience in QUEST Classroom.

The teachers planned Next Generation Science Standards aligned lessons and engaged in practices such as developing and using models, analyzing and interpreting data, and asking questions and defining problems. New skills, enhanced content knowledge, and hands-on explorations with fellow teachers enable QUEST participants to return to their classrooms with renewed enthusiasm for science instruction. The weather and climate track, which was co-facilitated by Martha Friend, Princeton Township Public Schools, and Donna Stumm, Flemington Raritan School District, drew teachers from eight New Jersey school districts: Hillsborough, Montgomery, North Hanover, Northern Burlington, Somerset Hills and West Windsor-Plainsboro.

In addition to CICS, co-sponsors of the event include the National Science Foundation (NSF) and the Program in Teacher Preparation.

The institute took place July 15-20, 2016.

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:

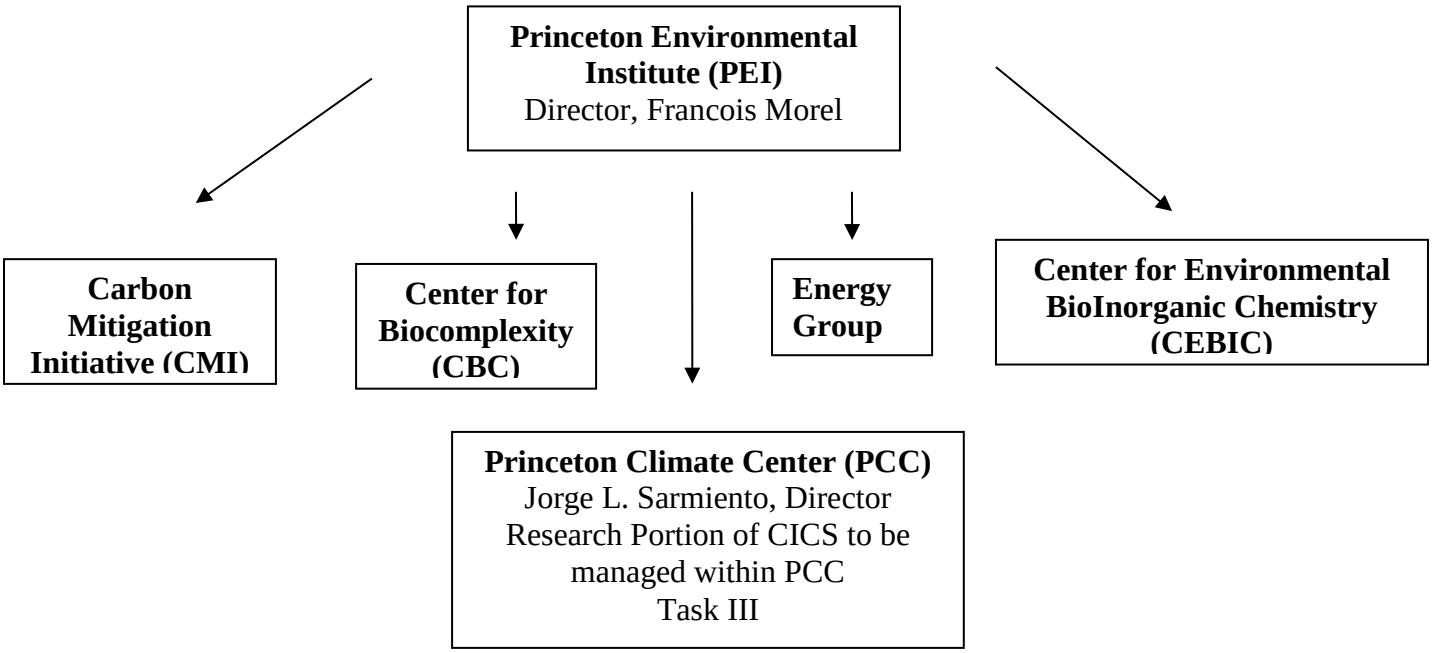
I. Administrative Activities including outreach efforts are carried out jointly by the AOS Program and Princeton Environmental Institute (PEI).

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.

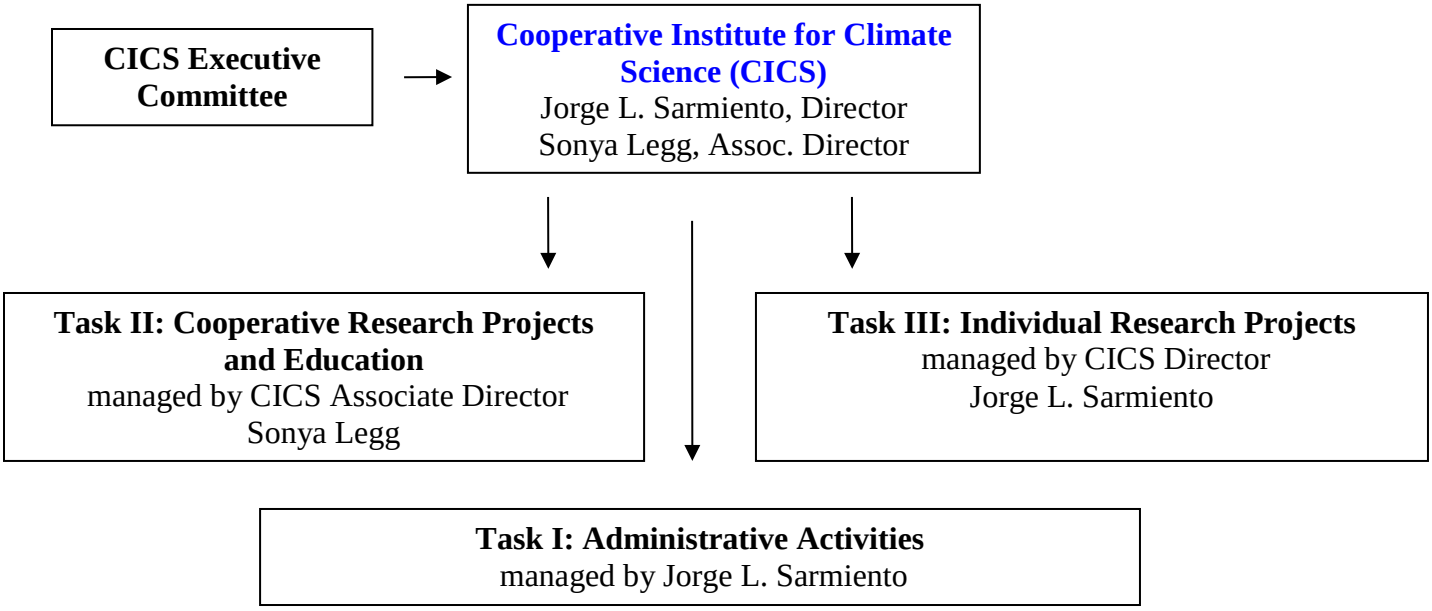
III. Principal Investigator led research projects supported by grants from NOAA that comply with the themes of CICS. These all occur within AOS and the Princeton Environmental Institute (PEI), and may also include subcontracts to research groups at other institutions on an as needed basis.

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

Executive Committee
Jorge L. Sarmiento – Director of CICS and Professor of Geosciences
Sonya Legg – Associate Director of CICS, Senior Research Oceanographer, Atmospheric and Oceanic Sciences, Lecturer in Geosciences
Thomas Delworth – Lecturer in Geosciences and Atmospheric and Oceanic Sciences, GFDL Supervisory Physical Scientist
Stephan Fueglistaler – Associate Professor of Geosciences, Director of the Program in Atmospheric and Oceanic Sciences
Isaac Held – Lecturer with rank of Professor in Geosciences and Atmospheric and Oceanic Sciences, GFDL Senior Research Scientist
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
Gabriel Vecchi – Professor of Geosciences and the Princeton Environmental Institute

Former Executive Committee Members
Denise Mauzerall –Professor of Civil and Environmental Engineering and Public and International Affairs, WWS (through March 2017)
James Smith – Professor of Engineering and Applied Science, Chair and Professor of Civil and Environmental Engineering (through March 2017)

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

Comprehensive Earth system models require accurate representation of physical, biological and chemical processes, and they rely on robust computational infrastructures that allow for efficient model performance and analysis of the model results. Thus, Earth system model development and analysis requires fundamental research into specific component processes of the climate system, analysis of simulations generated by the complex models, as well as development of efficient and scalable algorithms and well-structured modeling architectures and workflow systems. Here we summarize and highlight some of the activities in model development and analysis over the past year.

Ocean Mixing Processes and their Representation in Ocean Models

Ocean mixing has strong effects on the state of the ocean, formation and transformation of water masses, and, as a result, on the large-scale ocean circulation and its effects on climate. Ocean mixing occurs due to a number of physical processes operating throughout the ocean – at its surface, in the interior and at the bottom. A CICS researcher **Sonya Legg**, in collaboration with a GFDL scientist Robert Hallberg and former CICS researchers Angelique Melet and Benjamin Mater, has been investigating tidally-generated internal waves and their dissipation on large-scale ocean circulation. **Robert Nazarian,** a CICS/AOS graduate student, has investigated the scattering of low-mode internal waves at continental slope canyons under Legg's supervision. A Princeton University geosciences undergraduate student Young (Paul) Yi has investigated breaking of tidally-generated internal waves. Another aspect of the large-scale ocean circulation that small-scale mixing has strong controls is dense-water formation and overflows. A CICS/AOS graduate student **Elizabeth Yankovsky**, under the supervision of Sonya Legg, investigates the dense-water overflows on the Arctic shelves, and their controls on Arctic thermohaline circulation, which influences deep-water formation and sea-ice processes. Yankovsky and Legg find that the dynamics of these overflows are governed by the interplay of local atmospheric forcing and air-sea processes that produce the dense waters and that the small-scale mixing defines the properties of the descending water. Ocean mixing at the surface has strong effects not only on the ocean state, but also on the air-sea interactions. CICS/AOS postdoctoral research associate **Brandon Reichl** has been focusing on Langmuir turbulence (a mechanism by which waves enhance upper ocean vertical mixing). He has identified relevant ocean surface boundary layer parameters that are important for controlling the contribution of Langmuir turbulence. Based on this result, Reichl, in collaboration with CICS researcher **Alistair Adcroft** and Robert Hallberg, has developed a skillful parameterization to use in ocean models.

Dynamics of the Tropics

The tropical region exhibits strong influence on the Earth's climate. Processes taking place in this region (e.g. cyclone formation, dynamics of the intertropical convergence zone (ITCZ), etc.) impact climate dynamics throughout the globe. CICS researchers have taken a variety of approaches to improve the understanding of climate processes in this region and develop a better representation of these processes in the Earth system model. CICS/AOS associate research scholar **Max Popp**, in collaboration with a GFDL scientist Isaac Held, CICS/AOS associate research scholar **Levi Silvers** and CICS/AOS graduate student **Nicholas Lutsko**, has considered a fundamental problem of the cloud-radiative effects on the position of

the ITCZ. They find that the cloud-radiative effect controls the strength of the atmospheric overturning circulations, and as a result changes convection and precipitation that determine the ITCZ position. CICS/AOS graduate student **Spencer Clark**, under the supervision of GFDL scientists Isaac Held and Yi Ming, has investigated the role of the water vapor feedbacks in the ITCZ response to hemispherically asymmetric forcings. Using idealized configurations of the atmospheric circulation model, Clark and colleagues find that the water-vapor transport determines sensitivity and location of the ITCZ. Princeton Assistant Professor **Ning Lin**, a CICS researcher, has developed a probabilistic model to predict tropical cyclones. In collaboration with a GFDL scientist Thomas Knutson, Lin has used advanced statistical methods to establish relationships between the storm intensity and atmospheric and ocean characteristics. The developed model has fewer input parameters, but provides better predictions compared to existing real-time forecasting models. CICS/AOS associate research scholar **Sulagna Ray** investigates dynamics and variability of the Tropical Pacific. The major focus of her studies is to improve the Earth system model performance in this region. In collaboration with a GFDL scientist Andrew Wittenberg and NCEP scientists Yan Xue and Arun Kumar, Ray has diagnosed the spatiotemporal structure of tropical Pacific climatological biases in the Earth system model coupled simulations, reanalysis systems, and forecasts. She has identified the sources of these biases and has developed methods to mitigate them in order to improve the Earth system model's forecasting skills.

Model Architecture and Data Infrastructure

Earth system modeling strongly relies on robust and well-structured model architecture and a workflow system. CICS scientist **V. Balaji**, together with a number of CICS and GFDL scientists, has been developing and maintaining the Flexible Model System (FMS) to enable the efficient performance of various components of the Earth system model and their coupling. In collaboration with CICS and GFDL researchers, CICS/AOS postdoctoral research associate **Linjiong Zhou** and **Xi Chen,** a CICS/AOS associate research scholar, have been developing a prototype of the Next Generation Global Prediction System (NGGPS) for the National Weather Service. This is a new, high-resolution (3 km) dynamical core model that includes comprehensive physical representation of atmospheric dynamics. Xi Chen has developed new computationally efficient algorithms allowing this high-resolution dynamic core model to be used in forecast systems. Zhou has been focusing on the improvement of the forecast skill of the system.

Earth system model simulations produce large volumes of output data. To analyze these data, CICS researcher **Serguei Nikonov** has developed a data-publishing infrastructure, known as the Curator. New development in the Curator system allows for automatic modifications of the model development database to fulfill requests for new output fields.

EARTH SYSTEM MODELING: APPLICATIONS

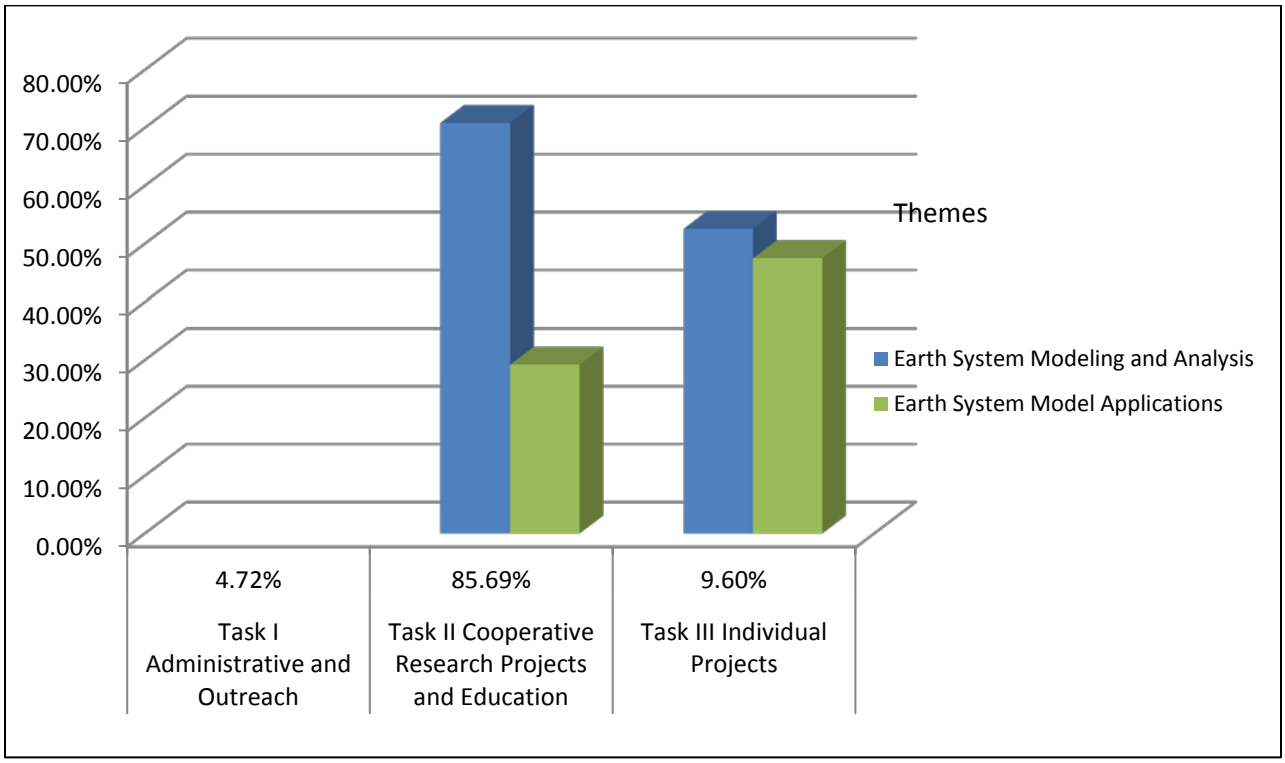
The earth system models developed by CICS and GFDL researchers are applied to examine a variety of societally relevant problems, including the impact of climate change on fisheries. Here we highlight some of the most interesting and exciting applications made over the past year.

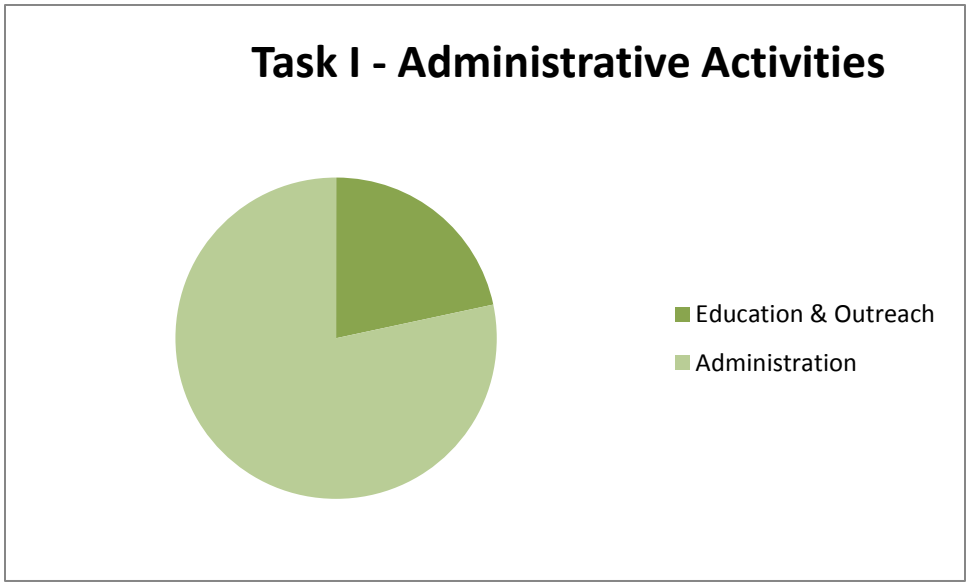
Fisheries

CICS researchers **Nicolas van Oostende and Bess Ward** (Princeton Geosciences) worked with GFDL scientists to better capture coastal diatom blooms in GFDL's ESMs and demonstrated that this can improve the simulation of coastal hypoxia. CICS scientist **Desiree Tommasi** pioneered applications of seasonal to decadal climate predictions to marine resource management, leading a comprehensive community synthesis on this topic and showing how such predictions can increase fisheries yields for

Pacific Sardine while guarding against collapse. CICS researchers **Andrew Barton and Fernando Taboada** developed novel comparisons of observed and simulated biogeochemical variability that have laid the groundwork for seasonal to decadal biogeochemical prediction. **Barbara Muhling**, a CICS researcher, developed a statistical climate downscaling approach for estuarine habitats and applied it to understand the impact of climate change on marine pathogens in the Chesapeake Bay.

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 summer interns and QUEST Summer Institute in Weather and Climate.

Budget Amount and Milestones

During the past CICS-Princeton reporting year, April 1, 2016 – March 31, 2017, Princeton received funds in the amount of $5,795,311 for Task II and Task III research projects (see details in ***CICS FY'17 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

- Bring Your Scientist to Work Day 2016
- CICS Research Internships
- CW2017: The Fourth Workshop on Coupling Technologies for Earth System Models
- Fall Model Hierarchies Workshop
- Modeling a Living Planet: A Symposium in Honor of Jorge Sarmiento
- Ocean Fun Days 2016
- Summer Institute in Weather and Climate

Earth System Modeling and Analysis Projects

- Hybrid Ocean Model Development (Alistair Adcroft)
- The Effect of Divergence Damping on Deep Convection in Cloud-Resolving Simulations (Usama Anber)
- Flexible Modeling System (FMS) (V. Balaji)
- Understanding the Role of Asian Orography in Precipitation and Quantifying the Risk of Compound Heat Wave Events (Jane Baldwin)
- Harnessing Big Data to Rethink Heterogeneity in the GFDL Land Model (Nathaniel Chaney)
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- Resistance of Resolution Errors to Hypohydrostatic Correction in Moist Baroclinic Eddies (Tsung-Lin Hsieh)
- Idealized Cloud-Resolving Modeling with GFDL's FV3 (Nadir Jeevanjee)
- Climate Prediction on Seasonal Time Scales (Liwei Jia)
- Aerosol Instantaneous Radiative Forcing Component of the RFMIP (Alexandra Jones)

Earth System Modeling and Analysis Projects continued

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- Ozone and Secondary Organic Aerosols over Southeast US (Jingqiu Mao)
- Modeling Ice Shelf/Ocean Interactions (Gustavo Marques)
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- Exploring the Relationship of Extremes in Surface Ozone, Particulate Matter, and Heat Waves to Meteorology in a Global Chemistry-Climate Model (Jordan Schnell)
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- Kelvin-Rossby Instability and the Maintenance of the Momentum Balance (Pablo Zurita-Gotor)

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- Geoengineering Outlet Glaciers and Ice Streams (Michael Wolovick)
- Examining Climate Impacts of Antarctic Open-Ocean Polynyas (Hannah Zanowski)
- Decadal Detectability of Anthropogenic Hydroclimate Changes on Regional and Global Scales (Honghai Zhang)
- Decadal Climate Variability and Predictability (Liping Zhang)

Project Titles
(Projects listed by research area)

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

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- Hybrid Ocean Model Development (Alistair Adcroft)
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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), Olga Sergienko (Princeton), Alon Stern (Princeton), Brandon Reichl (Princeton)

Other Participating Researchers: Malte Jansen (U. Chicago), Sina Khani (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 (20%)
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts (70%)
Resilient Coastal Communities and Economies Goal: Coastal and Great Lakes Communities are Environmentally and Economically Sustainable (10%)

Objectives: Development of GFDL's next generation ocean circulation, sea-ice and iceberg models

Methods and Results/Accomplishments:

The majority of my time was spent developing OM4, the ¼° ice-ocean component of CM4, which is near completion. The coupled working group plans to document both the individual components and fully coupled model by summer of 2017. The rms SST bias in the coupled model has been as low as 0.8°C, under contemporary forcing, which compares favorably with ~1.0°C in previous generations of GFDL models. This has been achieved by pushing forward the atmosphere and ocean model development together. On the ocean side, significant improvements arose from continued development of the energetic planetary boundary by Brandon Reichl (Reichl and Hallberg, 2017).

Evaluation of eddy-parameterizations in the context of an idealized planet called "Neverland" began with post-doc Sina Khani and collaborator Malte Jansen. The planet has some recognizable characteristics, such as continents, a Drake Passage, etc., but is smaller enough that we can afford to run eddy-resolving simulations which define a "ground truth" climatology. Our aim is to replicate the resolved climate in lower resolution simulations in which we will parameterize the unresolved mesoscale turbulence.

Development of the tabular-iceberg model continued with post-doc Alon Stern and colleague Olga Sergienko. The point-particle model of icebergs (Martin and Adcroft, 2010; Stern et al., 2016) now has interacting particles of finite extent and can represent large structures by joining these finite extent particles together with bonds. We have demonstrated that we can represent the break-off of a large piece of an ice-shelf (by breaking bonds) and can simulate the subsequent propagation as either the resulting large tabular iceberg or the drift of numerous smaller icebergs resulting from disintegration of the shelf piece. A technical paper describing this work is being prepared.

Outreach Activities: Raised funding for an intern, but have not used the money yet.

References:

Martin, T., and Adcroft. A., 2010: Parameterizing the fresh-water flux from land ice to ocean with interactive icebergs in a coupled climate model. Ocean Modelling, 34, 111-124, doi:10.1016/j.ocemod.2010.05.001.

Publications:

OMIP contribution to CMIP6: experimental and diagnostic protocol for the physical component of the Ocean Model Intercomparison Project. Griffies, S.M., Danabasoglu, G., Durack, P.J., Adcroft, A.J., Balaji, V., Böning, C.W., Chassignet, E.P., Curchitser, E., Deshayes, J., Drange, H., Fox-Kemper, B., Gleckler, P.J., Gregory, J.M., Haak, H., Hallberg, R.W., Heimbach, P., Hewitt, H.T., Holland, D.M., Ilyina, T., Jungclaus, J.H., Komuro, Y., Krasting, J.P., Large, W.G., Marsland, S.J., Masina, S., McDougall, T.J., Nurser, A.J.G., Orr, J.C., Pirani, A., Qiao, F., Stouffer, R.J., Taylor, K.E., Treguier, A.M., Tsujino, H., Uotila, P., Valdivieso, M., Wang, Q., Winton, M., and Yeager, S.G.,2016: Geosci. Model Dev., 9, p. 3231-3296, doi:10.5194/gmd-9-3231-2016.

The effects of Antarctic iceberg calving-size distribution in a global climate model. Stern, A.A., Adcroft. A., and Sergienko, O., 2016: J. Geophys. Res., 121(8), p. 5773–5788, doi:10.1002/2016JC011835.

Presentations:

A positive-definite, down-gradient implementation of neutral diffusion. Adcroft, A., Hallberg, R.W., and Griffies, S.M., 2016: AGU Ocean Sciences.

Flavors of A.L.E. Adcroft, A., and Hallberg, R.W., 2016: Workshop on ALE methods at Environmental Modelling Center.

Addition of Langmuir Turbulence in a Hierarchy of Vertical Mixing Parameterizations for Ocean Climate Modeling. Reichl, B. G., S. Griffies, A. Adcroft, and R. Hallberg, 2016: 20th Amer. Meteor. Soc. Conf. on Air-Sea Interaction, August 2016.

Progress Report Title: **The Effect of Divergence Damping on Deep Convection in Cloud-Resolving Simulations**

Principal Investigator: Usama Anber (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Nadir Jeevanjee (Princeton), Lucas Harris (GFDL), Leo Donner (GFDL), Shian-Jiann Lin (GFDL), 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:
Weather-Ready Nation Goal: Society is Prepared for and Responds to Weather-Related Events

Objectives: Testing convective intensity dependence on numerical parameters in cloud-resolving version of the GFDL-AM4 Model

Methods and Results/Accomplishments:

Divergence damping is a tool used to filter out acoustic modes in compressible non-hydrostatic models; the smaller the damping, the nosier the simulated fields and the faster the energy build-up at shortwaves. The Geophysical Fluid Dynamics Laboratory- Atmospheric Model version 4 (GFDL AM4) at a cloud resolving resolution is adopted in radiative-convective equilibrium regime to investigate the effect of higher order divergence damping on the convective state. The model is run in idealized setting, operating on a doubly periodic domain of varying sizes (124x124 Km, 180X180 Km, and 512X512 Km) and resolutions (2 km, and 1km). The order of the explicit diffusion damping is varied over the range of the 2nd, 4th, and 6th order, and the damping coefficient is also varied over the range 0.15, 0.1, and 0.05 for each order.

It is shown that such parameters introduce significant impacts on the aggregated state of convection; the size of the updraft area, cloud cover, and relative humidity. The results have particular implications for the hydrological cycle and precipitation extremes.

Outreach Activities: Princeton University Computing Day (Oct. 2016)

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

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

CICS/GFDL Collaborator: Alistair Adcroft (Princeton), Stephan Fueglistaler (Princeton), Sergey Nikonov (Princeton), Karen Paffendorf (Princeton), Gabriel Vecchi (GFDL), Rusty Benson (GFDL), Keith Dixon (GFDL), Jeff Durachta (GFDL), Isaac Held (GFDL), S-J Lin (GFDL), Yi Ming (GFDL), Bruce Wyman (GFDL)

Other Participating Researchers: Luca Cinquini (JPL), Cecelia Deluca (NOAA/ESRL), Veronika Eyring (DLR), Carlos Gaitan (Oklahoma), Andrew Gettelman (NCAR), Peter Gleckler (PCMDI), Frederic Hourdin (IPSL), Bryan Lawrence (Reading), Eric Maisonnave (CERFACS), Thorsten Mauritsen (MPI-M, Hamburg), Berrien Moore (Oklahoma), Karl Taylor (PCMDI), Gerhard Theurich (NOAA/ESRL), Dean Williams (PCMDI)

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: Building model components, data standards and workflow system consistent with the common model infrastructure FMS in support of Princeton/GFDL modeling activities

Methods and Results/Accomplishments:

I am the Head of Modeling Systems Group overseeing Princeton and GFDL model development activities and the Flexible Modeling System (FMS). I am also a member of GFDL Science Board. Significant accomplishments in 2016-2017 include the selection of the FV3 model for the Next Generation Global Prediction System (NGGPS) for the National Weather Service; and the selection of MOM6 for the next generation NCEP seasonal prediction and NCAR community climate model.

As co-chair of the WGCM Infrastructure Panel (WIP), we have provided standards and guidelines to the WGCM (WCRP Working Group on Coupled Modeling), to modeling groups around the world, and the Earth System Grid Federation (ESGF) on the infrastructure design for CMIP6 which has just begun.
My work has resulted in eight refereed publications, two lead-author, and one National Academies panel report.

Workshops organized: Model Hierarchies Workshop, Princeton University, 2-4 November 2016; WGCM-20 Meeting, Princeton University, 1-2 November 2016; and Advanced School on Earth System Modelling and Workshop on Climate Change and Regional Impacts over South Asia, Indian Institute of Tropical Meteorology, Pune INDIA, 18-29 July 2016.

Several invited talks during 2016, including Columbia University; Carnegie Institute at Stanford University; iCAS2015; IPSL; CERFACS; and Centre Alexandre Koyr´e. Keynote talk at ENES Meeting on Workflows in Lisbon; and two GFDL lunchtime seminars.

Service on several major review boards, including on the Science Advisory Board for the Max Planck Institut for Meteorology, Hamburg; DOE ACME Project; Barcelona Supercomputing Centre Earth Science Division (BSC-ES).

Publications:

Hourdin, F., T. Mauritsen, A. Gettelman, J.-C. Golaz, V. Balaji, Q. Duan, D. Folini, D. Ji, D. Klocke, Y. Qian, F. Rauser, C. Rio, L. Tomassini, M. Watanabe, and D. Williamson, 2016: The art and science of climate model tuning. Bull. Amer. Met. Soc., 97, early online release, doi:10.1175/BAMS-D-15-00135.1.

Balaji, Maisonnave, Zadeh, Lawrence, Biercamp, Fladrich, Aloisio, Benson, Caubel, Durachta, Foujols, Lister, Mocavero, Underwood, and Wright: CPMIP: measurements of real computational performance of Earth system models in CMIP6. Geoscientific Model Development, 10, 19–34, doi:10.5194/gmd-10-19-2017.

Balaji, V., R. Benson, B. Wyman, and I. Held, 2016: Coarse-grained component concurrency in Earth system modeling: parallelizing atmospheric radiative transfer in the GFDL AM3 model using the Flexible Modeling System coupling framework. Geoscientific Model Development, 9, 3605–3616.

NASEM, 2016: From Maps to Models: Augmenting the Nation's Geospatial Intelligence Capabilities. The National Academies Press, Washington, DC.

Gaitán, C. F., V. Balaji, and B. Moore III, 2016: Can we obtain viable alternatives to Mannings equation using genetic programming? Artificial Intelligence Research, 5, p92.

Eyring, V., P. J. Gleckler, C. Heinze, R. J. Stouffer, K. E. Taylor, V. Balaji, E. Guilyardi, S. Joussaume, S. Kindermann, B. N. Lawrence, G. A. Meehl, M. Righi, and D. N. Williams, 2016: Towards improved and more routine Earth system model evaluation in CMIP. Earth System Dynamics, 7, 813–830, doi:10.5194/esd-7-813-2016.

Theurich, G., et al., 2016: The earth system prediction suite: toward a coordinated us modeling capability. Bulletin of the American Meteorological Society, 97, 1229–1247.

Dixon, K. W., J. R. Lanzante, M. J. Nath, K. Hayhoe, A. Stoner, A. Radhakrishnan, V. Balaji, and C. F. Gaitán, 2016: Evaluating the stationarity assumption in statistically downscaled climate projections: is past performance an indicator of future results? Climatic Change, 1–14.

Progress Report Title: **Understanding the Role of Asian Orography in Precipitation and Quantifying the Risk of Compound Heat Wave Events**

Principal Investigator: Jane 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 Modeling and Analysis

NOAA Goals:
Weather-Ready Nation Goal: Society is Prepared for and Responds to Weather-Related Events (20%)
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts (80%)

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

Methods and Results/Accomplishments:

This year I have primarily focused on two projects, which I have presented at conferences and am currently writing up for publication.

First, advised by Dr. Gabriel Vecchi, I have completed and analyzed a series of GCM simulations with flattened topography across the Asian continent. Unlike prior studies exploring the influence of the Tibetan Plateau on the Asian monsoons which used relatively low resolution, atmosphere-only simulations with forced SSTs, these simulations are performed with GFDL CM2.5-FLOR—a fully coupled atmosphere-ocean model run with a 50 km resolution in the atmosphere and land. These simulations suggest a few important conclusions regarding the role of Asian orography in precipitation: 1) while prior studies have suggested the Tibetan Plateau is primarily important for the monsoon onset over the Western North Pacific, but less so for the monsoon peak, atmosphere-ocean coupling allows the Tibetan Plateau to remotely increase precipitation in this region throughout the entire year, 2) the distribution of tropical cyclones is significantly influenced by Tibet, with large increases in tropical cyclone density over the Western North Pacific, and strong decreases over the northern Arabian Sea.

The second project I have focused on is part of my WWS-STEP fellowship advised by Prof. Michael Oppenheimer, and explores the temporal structure of heat waves. Many heat wave definitions employed by meteorologists require a certain number of threshold-exceeding hot days in a row to constitute a heat wave. In reality, the temporal structure of heat waves having substantial human impact varies significantly, with many featuring hot days interspersed with cooler breaks. We developed more flexible heat wave definitions that count hot days that follow short breaks, quantifying the hazard of these temporally compounded hot days. We then applied these definitions to analyze daily temperature data from observations, GFDL GCM simulations of the past and projected future, and synthetically generated time series. Using results from this analysis, we demonstrated that hot days that closely follow prior hot days or heat waves will constitute a greater proportion of heat wave hazard as the climate

warms, and suggest an explanation for this phenomenon. These results have important implications for climate change adaptation, result suggesting that in order to limit heat-related mortality and morbidity as the climate warms, there is a need to consider added vulnerability caused by prior heat waves.

I have also performed a series of experiments to understand to what degree improved model simulation at higher resolution is simply due to better resolving topography. I am currently in the process of analyzing these experiments.

Additionally, two studies based on prior work were published: a paper examining the influence of the Tianshan Mountains on arid extratropical Asia, and an interdisciplinary report exploring prospects for fusion energy.

Outreach Activities: Last spring I finished my tenure of a high school environmental outreach program I co-founded between Princeton Day School and a graduate student group called Princeton Energy and Climate Scholars; the collaboration has continued this year with a new graduate student in charge. In January I presented a seminar on research in atmospheric and oceanic science for the Undergraduate Women in Physics Conference, a national event taking place at Princeton to motivate young women studying physics. I also presented a guest lecture on the science of climate change for reporter Michael Lemonick and Flora Lichtman's Princeton undergraduate seminar "ENV 316: Climate Science and Communications". Finally, I have continued to work as a resident graduate student at Princeton, performing scientific outreach in numerous capacities from organizing a university-wide monthly Energy and Climate dinner discussion table, to mentoring individual undergraduates applying to graduate school or interested in climate change and related issues.

Publications:

Baldwin, J. and G. Vecchi. Influence of the Tian Shan Mountains on Arid Extratropical Asia. Journal of Climate, July 27, 2016. doi:10.1175/JCLI-D-15-0490.1.

Chou, C., J. Jhaveri, J. Baldwin, P. Hannam, K. Keller, W. Peng, S. Rabin, A. Ravikumar, A. Trierweiler, X. Wang, and R. Socolow. Fusion Energy via Magnetic Confinement: An Energy Technology Distillate. Andlinger Center for Energy and the Environment, Princeton University, May 13, 2016.

Presentations:

Baldwin, J., J. Dessy, M. Oppenheimer, and G. Vecchi, Jan 2017: Quantifying the Risk of Compound Heat Wave Events. American Meteorological Society 97th Annual Meeting, Eighth Conference on Environment and Health, Seattle, WA. ORAL.

Baldwin, J. and G. Vecchi, Dec 2016: The Tibetan Plateau's Impact on Tropical Cyclones and Implications for the Asian Monsoons. American Geophysical Union Fall Meeting, San Francisco, CA. ORAL.

Baldwin, J. and G. Vecchi, Oct 2016: Crushing Mountains in Global Climate Models. Princeton Institute for Computational Science & Engineering Research Computing Day, Princeton, New Jersey. ORAL.

Baldwin, J. and G. Vecchi, Jul 2016: Influence of the Tian Shan Mountains on Arid Extratropical Asia. Asia-Oceania Geosciences Society Meeting, Beijing, China. ORAL.

Baldwin, J., C. Chou, J. Jhaveri, W. Peng, and R. Socolow, May 2016: Panel Discussion on the Fusion Energy Distillate. Andlinger Center for Energy and the Environment Opening Symposium, Princeton, NJ. ORAL.

Baldwin, J., J. Dessy, G. Vecchi, and M. Oppenheimer, May 2016: Quantifying the Risk of Compound Heat Wave Events. Andlinger Center for Energy and the Environment Opening Symposium, Princeton, NJ. POSTER.

Progress Report Title: **Harnessing Big Data to Rethink Heterogeneity in the GFDL Land Model**

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

CICS/GFDL Collaborator: Elena Shevliakova (GFDL), Sergey Malyshev (Princeton), Chris Milly (USGS), Marjolein Van Huijgevoort (Princeton)

Other Participating Researchers: Alexander McBratney (University of Sydney), Mike Ek (NCEP/EMC), Eric F. Wood (Princeton), Patrick Reed (Cornell)

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 environmental datasets over land to improve the representation of spatial heterogeneity in the GFDL land model; This updated model is being used to understand the role of fine-scale spatial heterogeneity in the Earth system, provide field-scale model predictions to stakeholders, and to accelerate model development through improved model evaluation.

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 finished recoding the GFDL land model to enable it to efficiently handle very high-resolution land datasets. This has led to a much simpler code base and a more flexible land tiling scheme within the land model. This will allow to not only explicitly model land processes at field-scales but also to provide very high-resolution simulations for model applications and evaluations. Figure 1 shows the flow chart of this new framework that is used to assemble the tiling structure for each macroscale grid cell. *Model simulations over the Contiguous United States* – The new modeling framework has been used to improve the fine-scale representation of the GFDL land model over the Contiguous United States (CONUS). The updated model has been run at a ¼ degree spatial resolution over this domain between 1979 and 2014. The model simulations include 100 distinct land models tiles for each ¼ degree grid cell—each tile has a corresponding 30-meter grid cell over CONUS. This enables not only an improved representation of spatial heterogeneity in the land model but also to translate the tiling results to provide field-scale model simulations. *Characterizing the role of field-scale heterogeneity at the macroscale* – The 100 tile per grid CONUS simulation (heterogeneous sub-grid cell simulation) has been compared to a 1 tile per grid cell CONUS simulation (homogenous sub-grid cell simulation) over CONUS to evaluate the importance of sub-grid heterogeneity on the macroscale (1/4 degree results). As expected, this evaluation has shown that the role of sub-grid heterogeneity primarily depends on each grid cell's underlying physical environment. For example, over the Midwest where it is fairly flat and the primary land cover is crop, the

differences between the 1 tile and 100 tile simulations are small. However, over areas of pronounced topographic relief (e.g., Cascades) the differences can be substantial.

Outreach Activities: Boy Scouts of America; Tutoring and mentoring of high school students

Publications:

Chaney, N., E. Shevliakova, M. Van Huijgevoort, S. Malyshev, P.C.D. Milly, (2017), Harnessing Big Data to Rethink Heterogeneity in the GFDL Land Model, Geoscientific Model Development, In preparation.

Presentations:

Chaney, N., E. Shevliakova, S. Malyshev (2016), How to Represent 100-meter Spatial Heterogeneity in Earth System Models, Abstract 16898 presented at 2016 Meeting General Assembly, EGU, Vienna, Austria, 14-18 Dec.

Chaney, N., Shevliakova, E., Malyshev, S. (2016), Harnessing Big Data to Represent 30-meter Spatial Heterogeneity in Earth System Models, Abstract B51E-0455 presented at 2016 Fall Meeting, AGU, San Francisco, California 12-16 Dec.

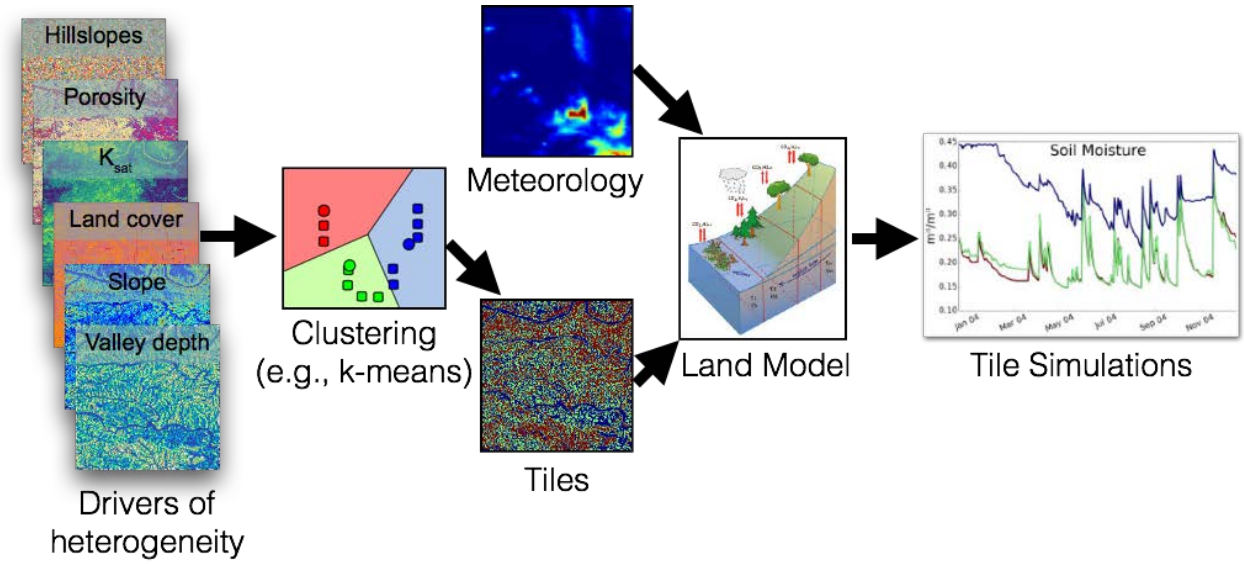

Figure 1. Updated tiling scheme in the GFDL land model. The high-resolution environmental drivers of spatial heterogeneity over land are clustered to define the k representative tiles over the macroscale grid cell. Each tile is then assigned the associated properties given the high-resolution environmental information. The land model is then run offline to produce the simulations for each tile in the grid cell. These tile simulations can then be mapped out in space using the tile map produced using the clustering algorithm.

Progress Report Title: **Exploring the Relations between the Strength of Global Entropy Cycle and Equator-to-Pole Temperature Gradient in an 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 gain a better understanding of the relations between the strength of global entropy cycle and equator-to-pole temperature gradient

Methods and Results/Accomplishments:

Understanding the temperature difference between the tropics and high latitudes requires knowledge of the poleward eddy heat transport. Some studies on turbulent diffusivity theory for the poleward heat flux have derived an expression for diffusivity D in terms of kinetic energy dissipation ε and planetary vorticity gradient β, $D \sim \varepsilon^{3/5}\beta^{-4/5}$ (e.g. Held and Larichev, 1996). Estimating ε from the global entropy budget, Barry et al. (2002) tested the diffusivity scaling with a comprehensive global atmospheric model. Despite the level of model complexity, they showed their theory accurately predicts the simulated eddy heat flux over a range of parameters. We have found it also applies to an idealized dry primitive equation model in the Held-Suarez configuration (Held and Suarez, 1994) when rotation rate is increased or meridional temperature gradient at radiative equilibrium is decreased, that is, for those cases where the eddy scale is comparable to or smaller than in the control simulation. This seems to indicate that the strength of global entropy cycle can play an important role in theories for equator-to-pole temperature gradient, deemphasizing the role played by the available potential energy. Here we discuss these relations in the context of idealized dry GCM. With the Held-Suarez model's diabatic heating formulated as Newtonian relaxation, we can easily calculate the possible range of global entropy destruction subject to different constraints on the equilibrated thermal structure. To the extent that entropy production is mostly caused by kinetic energy dissipation, the global entropy destruction provides a good approximation of ε. It can then be compared to the numerical simulations to study the dependence of ε on external parameters. Based on this analysis, an argument is presented for the joint determination of global entropy cycle strength and equator-to-pole temperature gradient combining thermodynamical and dynamical constraints. We discuss how this approach to eddy closure development highlights the importance of predicting the thermal stratification.

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 V. D. Larichev, 1996: A scaling theory for horizontally homogeneous, baroclinically unstable flow on a beta plane. J. Atmos. *Sci.*, 53, 946–952.

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.

Publications:

Chang, C.-Y., and I. M. Held, 2017: Exploring the relations between the strength of global entropy cycle and equator-to-pole temperature gradient in an idealized general circulation model. In preparation.

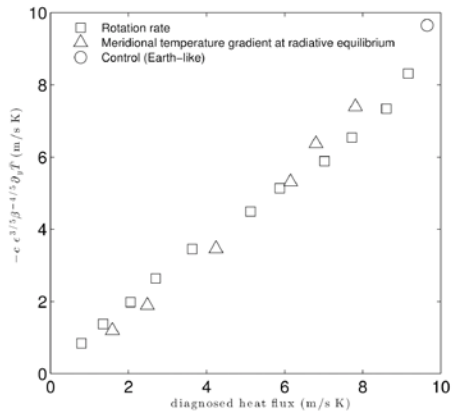

Figure 1. Predicted versus simulated eddy heat fluxes in the GCM simulations. The simulated eddy heat flux is diagnosed from the model as the eddy component of vertically integrated dry static energy flux averaged over midlatitudes. In the scaling relation, ε is estimated by the time mean diabatic entropy destruction in the global entropy budget and $\partial_y T$ is estimated by the near surface meridional temperature gradient from the simulations.

Progress Report Title: **Observational Verification of Mechanisms for MCS Development and Maintenance**

Principal Investigator: Shawn Cheeks (Princeton Graduate Student)

CICS/GFDL Collaborator: Steve Garner (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: Existing Mesoscale Convective System theory is based on idealized models or limited observational studies. This project establishes a new dataset consisting of the historical record of Mesoscale Convective Systems in the Continental United States that is then used to test theory.

Methods and Results/Accomplishments:

Investigation into the literature regarding Mesoscale Convective Systems (MCSs) indicates that our theoretical understanding is based on idealized models, individual case studies, and small climatological surveys.

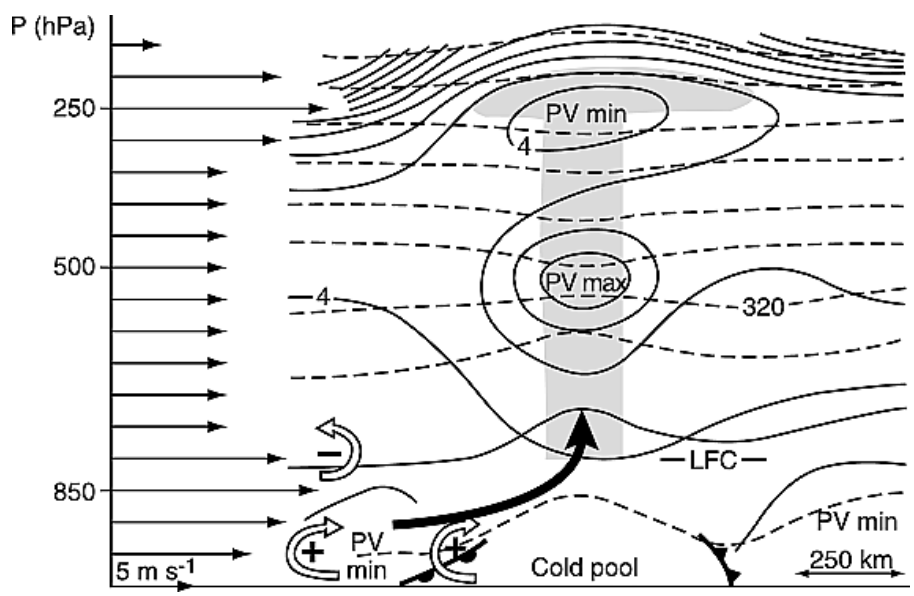

Figure from Fritsch et al 1994

A comprehensive historical record of these events does not exist, and many MCS theories have not been thoroughly confirmed by observations as a result. Given the demonstrable impact that MCSs have on both extreme weather events and climatological precipitation in the United States, our understanding of MCSs directly affects our understanding of United States climate as a whole. This project produces

this comprehensive historical record, identifies MCS theories that can be tested using this record, and conducts many of these tests.

The comprehensive historical record dataset is produced utilizing the fully automated algorithm presented in Whitehall (2014). Current work involves incorporating reanalysis data from the North American Regional Reanalysis (NARR) to this historical record, which will allow for testing of dynamics-based MCS mechanisms.

Outreach Activities: Pi Day activities at Village Charter School, Trenton, NJ – March 14, 2017. Introduced middle school students to the career path of a scientist and the work done at NOAA/GFDL/Princeton.

References:

Fritsch, J. M., J. D. Murphy, and J. S. Kain (1994), Warm core vortex amplification over land, J. Atmos. Sci., 51, 1781–1806.

Whitehall, Kim Dionne. "Investigating an Automated Method to Explore Mesoscale Convective Complexes in West Africa." (2014).

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

Principal Investigator: Xi Chen (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Shian-Jiann Lin (GFDL), Rusty Benson (GFDL), Lucas Harris (GFDL), Jan-Huey Chen (GFDL), Zhi Liang (GFDL), Tim Marchok (GFDL), Morris Bender (GFDL), Shannon Rees (GFDL), Matt Morin (GFDL), Ming Zhao (GFDL), Linjiong Zhou (Princeton), Weiye Yao (Princeton), Junyi Chai (Princeton)

Other Participating Researchers: Mark Taylor (Sandia National Laboratory)

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: Validating FV3 development towards the ultra-high resolution (uniform 3km), and extending FV3 with grid imprinting free, low-diffusivity features

Methods and Results/Accomplishments:

FV3 has been selected as the atmospheric dynamical core of the NOAA's Next Generation Global Prediction System. During the Phase II process, I have helped my team to exhibit that FV3 shows better performance in almost every crucial aspect than our competitor. Particularly, the interface I developed to allow FV3 to work with the GSI Data Assimilation system indicates that the Root Mean Square error of FV3 initial condition is even smaller than the operational GFS from the National Weather Service (Fig. 1).

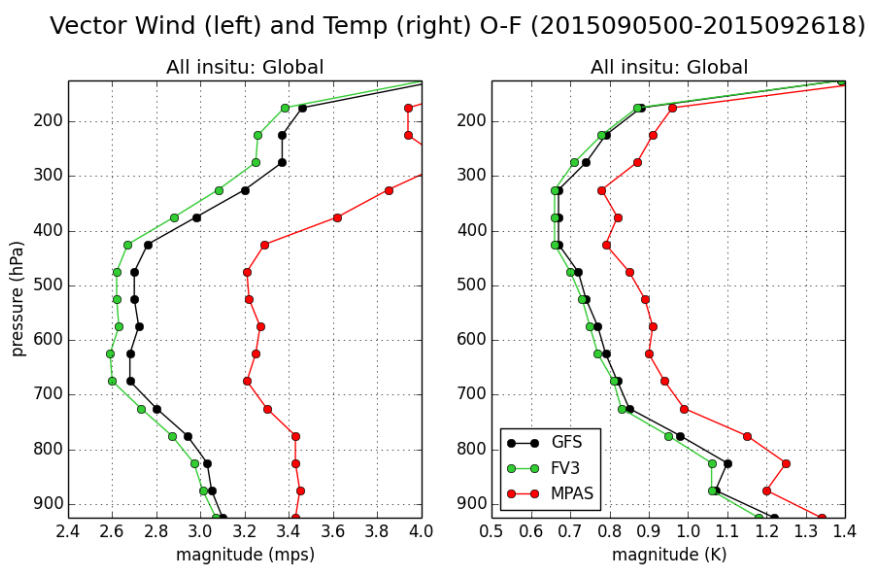

Figure 1. DA Cycling: RMS Fit to First-Guess to All in-situ Observations (in progress, preliminary)

I have also served as the Modeling Mentor of FV3 in Dynamical Core Model Intercomparison Project 2016 (DCMIP2016). I have guided the students to demonstrate numerical properties of FV3 in all three idealized tests and created many cool animations (test1, test2, test3).

My primary focus is dynamical core algorithm development. With my collaborators, we have submitted a new idealized test case that validating the capabilities to resolve rotational flows of the dynamical cores by using a pair of colliding modons. I have also developed a numerical approach to the traditional Von Nuemann Analysis and created a new idealized test to achieve similar validating capabilities to the theoretical approach.

References:

http://www.weather.gov/sti/stimodeling_nggps_implementation_atmdynamics
https://www.earthsystemcog.org/projects/dcmip-2016/fv3

Publications:

Xi Chen, Shian-Jiann Lin, and Lucas M. Harris. Building An unstaggered Finite-Volume dynamical core with a fast Riemann solver: the linearized analysis to the dissipative and dispersive proper- ties and noise handling solutions. Journal of Computational Physics, under internal review.

Shian-Jiann Lin, Lucas M. Harris, Xi Chen, Weiye Yao, and Junyi Chai. Colliding modons: A nonlinear test for the evaluation of global dynamical cores. The Journal of Advances in Modeling Earth Systems, submitted.

Presentations:

Xi Chen, Shian-Jiann Lin, and Lucas M. Harris. Building an unstaggered Finite Volume dynamical core with a fast Riemann solver: the dry hydrostatic application. In 2017 GFDL Winter Expo, Princeton, GFDL, USA, Feb 1 2014.

Linjiong Zhou, Shian-Jiann Lin, Jan-Huey Chen, Lucas M. Harris, and Xi Chen. GFDL Single-Moment Six-Class Cloud Microphysics and Its Application in NGGPS. In 2017 GFDL Winter Expo, Prince- ton, GFDL, USA, Feb 1 2014.

Linjiong Zhou, Shian-Jiann Lin, Jan-Huey Chen, Lucas M. Harris, and Xi Chen. Ten-day Weather Forecasts using a 4-45km Variable-resolution Global Model: fvGFS. In 2017 AMS Annual Meeting, Seattle, WA, USA, Jan 24 2017.

Shian-Jiann Lin, Lucas M. Harris, Rusty Benson, Linjiong Zhou, Jan-Huey Chen, and Xi Chen. Towards a unified prediction system from Weather to Climate time-scale. In 2017 AMS Annual Meeting, Seattle, WA, USA, Jan 24 2017.

Jan-Huey Chen, Shian-Jiann Lin, Lucas M. Harris, Linjiong Zhou, and Xi Chen. Tropical Cyclone Forecasts in a Next Generation Global Model. In 2017 AMS Annual Meeting, Seattle, WA, USA, Jan 24 2017.

Jan-Huey Chen, Shian-Jiann Lin, Andrew Hazelton, Lucas Harris, Linjiong Zhou, Shannon Rees, and Xi Chen. Tropical Cyclone Forecasts in GFDL fvGFS. In AGU Fall Meeting, San Francisco, CA, USA, Dec 12-16 2016.

Shannon L. Rees, Shian-Jiann Lin, Lucas M. Harris, Jan-Huey Chen, Rusty Benson, Xi Chen, Zhi Liang, Matthew Morin, and Linjiong Zhou. Improved Global Weather Prediction with GFDLs FV3 Dynamical Core. In Supercomputing Conference 2016, Salt Lake City, Utah, USA, Nov 13-18 2016.

Shannon L. Rees, Shian-Jiann Lin, Jan-Huey Chen, Rusty Benson, Xi Chen, Lucas M. Harris, Zhi Liang, and Linjiong Zhou. FV3 and the Next Generation Global Prediction System. In 32nd Conference on Hurricanes and Tropical Meteorology, San Juan, PR, Apr 17-21 2016.

Progress Report Title: **Improving the Representation of Ice Nucleation in Earth System Models**

Principal Investigator: Pablo G. Debenedetti (Princeton Professor), Athanassios Z. Panagiotopoulos (Princeton Professor)

CICS/GFDL Collaborator: Yi Ming (GFDL), Amir Haji-Akbari (Princeton)

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 objective of this work is to improve the representation of ice nucleation in Earth System Models (ESM) by applying molecular simulation methods to study heterogeneous ice nucleation.

Methods and Results/Accomplishments:

One of the biggest unresolved questions regarding ice formation is whether a vapor-liquid interface enhances or suppresses nucleation in its vicinity: this is regarded as one of the ten key unresolved questions on the physics of ice and snow. It is, however, extremely challenging to address this question directly in experiments due to the insufficient spatiotemporal resolution of the existing experimental techniques. All efforts in this regard have therefore been indirect and focus around examining how volumetric nucleation rate in a microdroplet scales with its size. But the findings emanating from those studies have so far been inconclusive. Computer simulations of droplets and free-standing thin films of supercooled water have recently emerged as attractive alternatives in this quest.

We used a path sampling molecular-based computer simulation technique known as forward flux sampling to directly compute the nucleation rate in a free-standing 4 nm-thick film of supercooled water. We employed the TIP4P/Ice force field, which is one of the best existing molecular models of water, and computed a seven order- of-magnitude increase in the nucleation rate in the presence of a free interface. By analyzing the nucleation pathway, we found that freezing in the film is homogeneous in nature, and initiates not at the surface, but within an interior region that facilitates the formation of double diamond cages. This facilitates freezing by favoring the formation of predominantly cubic ice nuclei, which, as demonstrated in our recent work (Haji-Akbari and Debenedetti, *PNAS, 112,* 10582, 2015), are more likely to grow and overcome the nucleation barrier.

Our calculations suggest that surface freezing under atmospherically-relevant conditions may be driven by microscopic structural features of the film that decay over length scales that are much larger than those corresponding to thermodynamic quantities, such as density.

Publications:

Haji-Akbari A, Debenedetti PG, Computational investigation of surface freezing in a molecular model of water, PNAS, 114(13), 3316–3321, doi: 10.1073/pnas.1620999114, (2017).

Presentations:

Haji-Akbari A, Debenedetti PG, Computational investigation of surface freezing in a molecular model of water. APS March Meeting, Session B26: Chemical Physics of Hydrogen Bonding II. New

Orleans, LA, March 13, 2017.

Haji-Akbari A, Debenedetti PG, Kinetics and mechanism of homogeneous ice nucleation in freestanding nanofilms of supercooled water. AIChE Annual Meeting, Session on Thermodynamics at the Nanoscale. San Francisco, CA, November 17, 2016.

Haji-Akbari A, Debenedetti PG, Direct calculation of the rate of homogeneous ice nucleation for a molecular model of water. APS March Meeting, Session S31: Ice Nucleation, Amorphous Ices and the Role of Interfaces. Baltimore, MD, March 17, 2016.

Progress Report Title: **Towards Improved Parameterizations of Iceberg Motion and Melt**

Principal Investigator: Anna FitzMaurice (Princeton Graduate Student)

CICS/GFDL Collaborator: Robert Hallberg (GFDL), Alon Stern (GFDL), Alistair Adcroft (GFDL)

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

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: Through a combination of observation, laboratory experiments, and numerical modelling we have investigated controls on iceberg motion and melting, with the eventual goal of improving the representation of icebergs in global climate models.

Methods and Results/Accomplishments:

Icebergs account for approximately half of the mass flux from the Greenland ice sheet, and consequently constitute a leading order component of the ice sheet's freshwater flux to the North Atlantic. Due to a lack of observational data, the distribution, trajectories, and melt of icebergs around Greenland are currently poorly constrained. We analyzed acoustic data from Sermilik Fjord in southeastern Greenland to obtain a one-year record of iceberg speed and draft in the fjord. This was used in conjunction with local ADCP and wind data to study the dominant balances controlling iceberg motion. We found that icebergs subject to strongly sheared flows predominantly move with the vertical average of the ocean currents. If, as typical in iceberg parameterizations, only the surface ocean velocity is taken into account, iceberg speed and basal melt may have errors in excess of 60%. These results emphasized the need for parameterizations to consider ocean properties over the entire iceberg draft.

Following the finding that icebergs calving into Greenlandic Fjords are frequently subject to strongly sheared flows over the range of their draft, we conducted a series of laboratory experiments to determine the dependence of submarine melt rates on relative velocity, and found that two distinct regimes of melting exist depending on the melt plume behavior (side-attached or side-detached), with correspondingly different melt water spreading behavior. Including this velocity dependence in melting parameterizations was found to increase iceberg side melt in a fjord environment by an order of magnitude, and we demonstrated that real icebergs may be in either the attached or detached plume regime, indicating that meltwater may either be distributed in an undiluted surface layer or mixed at depth depending on ocean conditions. Further experiments were conducted to explore the melting of ice in a sheared flow.

Current work is focused on idealized numerical studies of an iceberg melting in a uniform flow to assess and compare current melt parameterizations. It is our intention that the findings of these three studies (observational, experimental, and numerical) will eventually be drawn together to implement an improved parameterization of iceberg motion and melting in a GCM. In the context of the currently increasing discharge of icebergs from both poles, accurate modelling of the melt flux from icebergs is an important component of assessing the potential impacts of future climate change.

Publications:

FitzMaurice, A., F. Straneo, C. Cenedese, M. Andres, Iceberg motion and melt from observational and laboratory studies. Talk presented at: International Symposium on Interactions of Ice Sheets and Glaciers with the Ocean; La Jolla, California, USA, July 2016.

FitzMaurice, A., F. Straneo, C. Cenedese, and M. Andres *(*2016*)*, Effect of a sheared flow on iceberg motion and melting, Geophys. Res. Lett., 43, 12,520–12,527, doi:10.1002/2016GL071602.

FitzMaurice, A., Cenedese, C., and Straneo, F. (In Prep). Iceberg Side Melt Variability in Ocean Currents. Geophysical Research Letters.

Progress Report Title: **Advancing Mechanistic Representation of Photosynthesis and Respiration in the GFDL land model LM3-PPA and the Next Generation of the GFDL Earth System Model**

Principal Investigator: Paul PG Gauthier (Princeton Associate Research Scholar), Stephen W. Pacala (Princeton Professor)

CICS/GFDL Collaborator: Elena Shevliakova (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: Improving plant carbon cycling in the GFDL land model PPA-LM3 by improving the parameterization of leaf respiration and reflect the dynamic control of Photosynthesis on Respiration and vice-versa

Methods and Results/Accomplishments:

Plant carbon is characterized by two main and opposed metabolic rates: photosynthesis and respiration. While the definition of photosynthesis in LM3 is well constrained, the parameterization of respiration is very simplistic as in many ecosystem models and Earth system models. A new module for plant respiration has been implemented in LM3 with new parameterizations accounting for the inhibition of respiration under elevated irradiance, the distinct temperature response of respiration compared to photosynthesis and the reduction of leaf area under non-optimal carbon productivity.

Parameterization accounting for the inhibition of respiration in the light has been implemented in LM3 and successfully integrated on a global scale. Results showed that this parameterization had a higher impact in higher latitude than in the tropics as expected. This led us to consider the different temperature response of respiration versus photosynthesis. In previous versions of LM3, a similar Arrhenius function was used for both processes. The new temperature function implemented by Gauthier used experimental analysis by Bernacchi et al 2001 and Medlyn et al 2002 complemented with Gauthier et al 2014. The new function is an optimal function with different temperature optimum for photosynthesis and respiration. As a consequence, Net ecosystem exchange in temperate and arctic ecosystem was slightly reduced. Gauthier is currently collecting optimum values for different functional type from TRY database (Kattge et al 2011) to input realistic temperature optimal values for the different regions. Additionally, an analysis of the temperature responses of leaf metabolism detailed in Heskel et al 2014, 2016 and O'Sullivan et al 2017, has been used to parameterize the module. Finally, the consequence of light inhibition of respiration led to evaluate carbon balance of lower canopy leaves. The photosynthetic function has been improved to evaluate carbon partitioning to new leaf production considering their long-term vs short-term carbon balance. A direct consequence of this parametrization is that leaf area index (LAI) in the Tropics and the Arctic were reduced to more realistic values and the excess carbon was allocated to other part of the plant or soil. Gauthier, Shevliakova and Malyshev are currently working on merging this code with newly developed soil C and N module and on publishing the results.

Outreach Activities: Gauthier organized the 18th New Phytologist Workshop: The Kok effect: beyond the artefact, emerging leaf mechanisms (6–8 July 2016, University of Angers, France).

References:

Bernacchi CJ, Singsaas EL, Pimentel C, Portis AR, Long SP .2001. Improved temperature response functions for models of Rubisco-limited photosynthesis. Plant Cell and Environment 24: 253-259

Gauthier PPG, Crous K, Ayub G, Duan H, Weerasinghe, LK, Ellsworth DS, Tissue DT, Evans JR and Atkin OK. 2014. Drought increases heat tolerance of leaf respiration in Eucalyptus globulus saplings grown under both ambient and elevated atmospheric [CO_2] and temperature. Journal of Experimental Botany, 65 (22): 6471-6485

Heskel MA, Greaves HE, Turnbull MH, O'sullivan OS, Shaver GR, Griffin KL, Atkin OK. Thermal acclimation of shoot respiration in an Arctic woody plant species subjected to 22 years of warming and altered nutrient supply. 2014. Global change biology20(8):2618-30.

Heskel MA, O'Sullivan OS, Reich PB, Tjoelker MG, Weerasinghe LK, Penillard A, Egerton JJ, Creek D, Bloomfield KJ, Xiang J, Sinca F. Convergence in the temperature response of leaf respiration across biomes and plant functional types. Proceedings of the National Academy of Sciences. 2016 Apr 5;113(14):3832-7.

Kattge, J., Diaz, S., Lavorel, S., Prentice, I.C., Leadley, P., Bönisch, G., Garnier, E., Westoby, M., Reich, P.B., Wright, I.J. and Cornelissen, J.H.C., 2011. TRY–a global database of plant traits. Global change biology, 17(9): 2905-2935.

Medlyn, B.E., Dreyer, E., Ellsworth, D., Forstreuter, M., Harley, P.C., Kirschbaum, M.U.F., Le Roux, X., Montpied, P., Strassemeyer, J., Walcroft, A. and Wang, K., 2002. Temperature response of parameters of a biochemically based model of photosynthesis. II. A review of experimental data. Plant, Cell & Environment, 25(9): 1167-1179.

O'sullivan OS, Heskel MA, Reich PB, Tjoelker MG, Weerasinghe LK, Penillard A, Zhu L, Egerton JJ, Bloomfield KJ, Creek D, Bahar NH. Thermal limits of leaf metabolism across biomes. 2017. Global change biology. 23(1):209-23.

Publications:

Tcherkez GGB, Gauthier PPG, Buckley T, Farquhar G, Barbour M, Atkin OK, Turnbull M, Heskel M, Bush F, Cornic G, Crous K, Adams M, Way D, Bender ML, Bruhn D, Xiaoying Gong. Tracking the origins of the Kok effect, 70 years after its discovery. New Phytologist. doi:10.1111/nph.14527.

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 marine ice sheet dynamics

Methods and Results/Accomplishments:

Marine ice sheets are ice sheets that rest on bed below sea level. At the grounding line, the ice becomes thin enough to float and the ice sheet forms an ice shelf. A long-standing problem in glaciology is determining the position and stability of grounding lines. In particular, the *marine ice sheet hypothesis* states that grounding line positions on beds that are sloping upwards towards the ocean (so-called retrograde beds) are unstable, and that small changes in the grounding line position can lead to a run-away advance or retreat of the grounding line in these cases. This hypothesis has been proven for laterally unconfined marine ice sheets.

However, in laterally confined marine ice sheets ice shelves transmit ocean forcing (e.g. variations in basal melt rates) inland by changing the stress balance at the grounding line through a process called buttressing. To investigate the effect of buttressing on grounding line dynamics, we have constructed approximate analytical solutions for the ice shelf flow. This approach allows us to determine the stress at the grounding line as a function of ice shelf properties such as shelf width and length, and to calculate how the ice flux at the grounding line changes with different ice shelf properties. We find that the steady state position and stability of marine ice sheets depend on the boundary conditions at the ice shelf front, and compare the effects of different calving laws on grounding line dynamics. Our results show that in the presence of buttressing, the position and stability of the grounding line depend on the calving law, and that the marine ice sheet hypothesis does not hold for laterally confined marine ice sheets. By identifying the calving law as an important control on grounding line dynamics and by providing analytical benchmark solutions, our results will help to improve numerical ice sheet models.

Outreach Activities: Princeton Prison Teaching Initiative

Publications:

Haseloff, M. and Sergienko, O. (2017): The effect of buttressing on grounding line dynamics, submitted to Journal of Glaciology.

Presentations:

Haseloff, M., Sergienko, O. (2016), The effect of ice shelves on the ice flux at the grounding line and implications for marine ice sheet stability, AGU Fall Meeting, San Francisco, CA, 12.12.2016-16.12.2016 (talk).

Haseloff, M., Sergienko, O. (2016), The effect of ice shelves on the ice flux at the grounding line and implications for marine ice sheet stability, WAIS workshop, Sterling, VA, USA, 03.10.2016-06.10.2016 (talk).

Haseloff, M., Sergienko, O. (2016), The effect of ice shelves on grounding line stability, IGS symposium, La Jolla, CA, USA, 10.07.2016-15.07.2016 (talk).

Progress Report Title: **The Land Phosphorous Cycle: Interactions with Carbon and Nitrogen across Neotropical Ecosystems**

Principal Investigator: Lars Hedin (Princeton Professor)

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

Other Participating Researchers: Cleo Chou (Princeton Postdoctoral Research Associate)

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 goal of this research is to develop a dynamical plant-soil phosphorus (P) cycle for LM4 that is driven by mechanisms derived from empirical datasets of ecosystem carbon and nutrient use. The inclusion and coupling of this P cycle with the carbon (C) and nitrogen (N) cycles in LM4 will improve modeling of the land carbon sink, especially in carbon-rich tropical forests, helping us better predict and mitigate climate change.

Methods and Results/Accomplishments:

It is increasingly recognized that nutrients such as N and P may significantly constrain the land carbon sink (Wieder et al. 2015). However, incorporation of these nutrient cycles into Earth System Models is uncommon, especially for P, and current examples often lack a dynamic ecological framework (Goll et al. 2012, Yang et al. 2014). Since the start of this project in October 2016, we have developed a novel framework for approaching nutrient limitation of forest ecosystems from a dynamic perspective, focused on the role of secondary forest succession and canopy gap disturbances as bottlenecks of high plant nutrient demand and limitation. This framework will provide insight on the key mechanisms and feedbacks needed to model the P cycle and to accurately capture nutrient limitation of the forest carbon sink. In addition, the framework allows us to address fundamental questions about the connection between the P cycle and N and C cycles in forested ecosystems worldwide.

Currently, we are building a database of forest succession biomass accumulation in forest biomes globally in order to test and further develop this framework with an empirical foundation. We will use this dataset to determine key drivers of nutrient limitation that may vary by biome using a combination of statistical regression methods, a forest competition simulation model from my dissertation research (Chou et al. *in prep*), and new data-driven conceptual simulation models. Preliminary analyses of this dataset show large differences in biomass accumulation and biomass nutrient demand across boreal, temperate, and tropical forest biomes. This work will both advance biogeochemical theory on forest nutrient limitation as well as help us design a plant-soil P cycle for LM4 that is ecologically informed and dynamic. We have also begun monthly terrestrial biogeochemistry discussions with the Shevliakova group at GFDL to ensure that development of the P cycle is well integrated with other biogeochemical research in LM4.

Outreach Activities: Women in Science Partnership (WISP): mentoring of graduate students in Princeton Ecology and Evolutionary Biology

References:

Chou, C.B., Hedin, L.O., and S.W. Pacala. In preparation. Competition for light drives tree and ecosystem nitrogen limitation in tropical rainforests through leaf lifespan: an individual-based forest gap model.

Goll, D.S., Brovkin, V., Parida, B.R., Reick, C.H., Kattge, J., Reich, P.B., Van Bodegom, P.M. & Niinemets, Ü. (2012) Nutrient limitation reduces land carbon uptake in simulations with a model of combined carbon, nitrogen and phosphorus cycling. Biogeosciences, 9, 3547–3569.

Wieder, W.R., Cleveland, C.C., Smith, W.K. & Todd-Brown, K. (2015) Future productivity and carbon storage limited by terrestrial nutrient availability. Nature Geoscience, 8, 441–444.

Yang, X., Thornton, P.E., Ricciuto, D.M. & Post, W.M. (2014) The role of phosphorus dynamics in tropical forests – a modeling study using CLM-CNP. Biogeosciences, 11, 1667–1681.

Publications:

Chou, C.B., Hedin, L.O., and S.W. Pacala. In revision. Functional groups, species, and light interact with nutrient limitation during tropical rainforest sapling bottleneck. Journal of Ecology.

Chou, C.B., Hedin, L.O., and S.W. Pacala. Stem and foliar responses of tropical rainforest saplings to N,P,K fertilization and light vary with functional group and species identity. Phosphorus Cycling in Terrestrial Ecosystems: Advancing our fundamental understanding through a model-data connection, DOE/ NSF/ INTERFACE workshop, Townsend, TN, May 22-25, 2016.

Progress Report Title: **Resistance of Resolution Errors to Hypohydrostatic Correction in Moist Baroclinic Eddies**

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

CICS/GFDL Collaborator: Stephen Garner (GFDL), 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 evaluate the potential of using the hypohydrostatic rescaling to better represent convection in climate models and to understand the processes by which convection influences the climate.

Methods and Results/Accomplishments:

Upscale feedback of underresolved moist convection to baroclinic eddies was investigated using a beta-plane model without convective parameterization. At a typical GCM resolution, the aspect ratio of the grid-scale convection renders it hydrostatic, leading to a resolution-dependent vertical velocity and mean stratification. In the first set of experiments, the grid spacing is decreased from 40 km to 10 km to allow nonhydrostatic effects; in the second set of experiments, the hypohydrostatic rescaling is applied to artificially increase the nonhydrostasy of the model. Similarity theory predicts wider and slower convective motions in the rescaled model and was quantitatively verified by the experiments. The dependence of convective vertical velocity on the effective resolution, defined as the grid spacing divided by the rescaling factor, was mapped out. The mean climate was found to be insensitive to the hypohydrostatic rescaling unless the effective resolution is beyond the gray zone. However, the significant slowing of convection leads to biases in the mean stratification in the warm sector, despite better resolving the convective cells. This work has been presented at the Dynamical Core Model Intercomparison Project Workshop, the Model Hierarchies Workshop, and the American Geophysical Union Fall Meeting.

Progress Report Title: **Idealized Cloud-Resolving Modeling with GFDL's FV3**

Principal Investigator: Nadir Jeevanjee (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Leo J. Donner (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: Understand how convective clouds in GFDL's FV3 model responds to changes in their equations of motion, model grid spacing, and diffusion

Methods and Results/Accomplishments:

Global atmospheric models are becoming able to partially resolve convective clouds, but there is uncertainty regarding how well convective motions are represented at a given resolution, or with a given model dynamical solver (i.e. one that employs the hydrostatic approximation to the atmospheric equations of motion, or not).

Convective motions are encapsulated by their vertical velocity w (m/s). We have developed some basic theory that suggests that w in a non-hydrostatic model will only converge at grid spacings finer than ~ 1 km, and that w in a hydrostatic model will actually diverge to infinity at finer and finer grid spacings (Fig. 1). We then confirmed this using GFDL's FV3 atmospheric model, which has a unique capability to run in either hydrostatic or non-hydrostatic mode with the flip of a switch (Fig. 2)

In pursuing this research, we also found that model diffusion parameters have a surprisingly large impact on the simulated climate, and in particular the relative humidity; see Fig. 3.

Outreach Activities: Gave talk to the Princeton Post-Doctoral Council, scheduled to present at Princeton Research Day. Scheduled to present basic science experiments at the University League Nursery School in April 2017.

Publications:

N. Jeevanjee, Vertical velocity in the gray zone, manuscript in preparation.

N. Jeevanjee, Vertical Velocity in the Gray Zone, invited oral presentation at American Geophysical Union Annual Meeting, Dec. 2017, San Francisco CA.

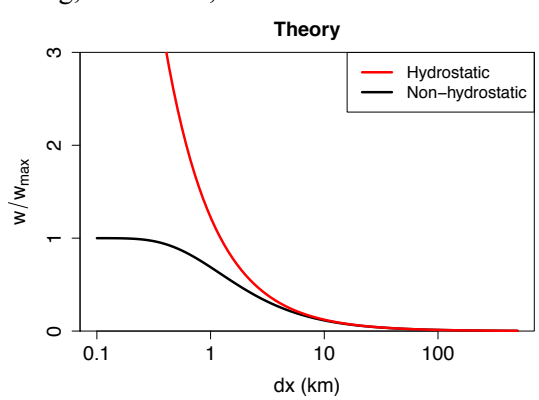

Figure 1

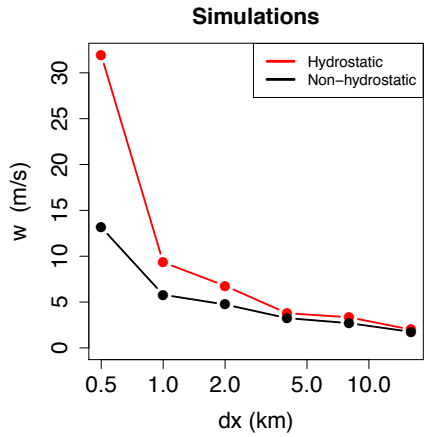

Figure 2

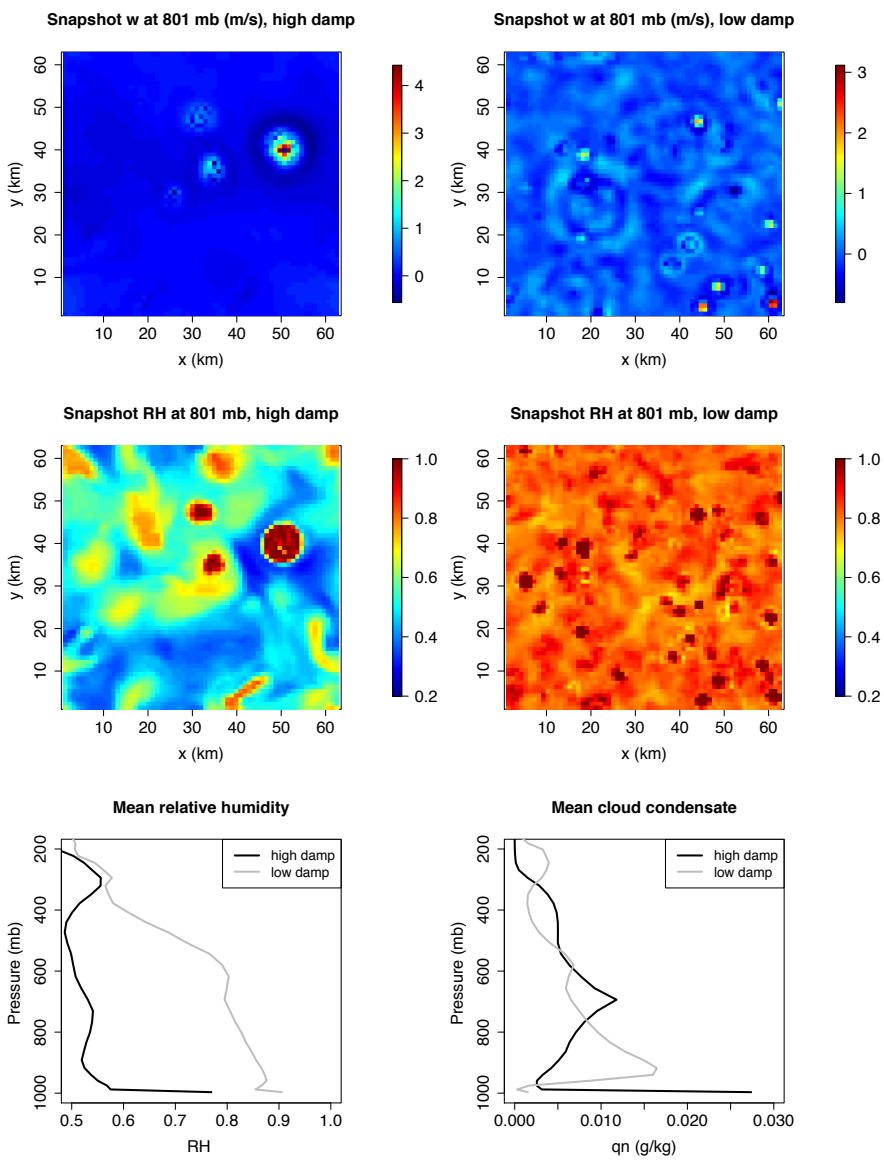

Figure 3

Progress Report Title: **Climate Prediction on Seasonal Time Scales**

Principal Investigator: Liwei Jia (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Gabriel Vecchi (GFDL), Xiaosong Yang (UCAR), Pu Lin (Princeton), Stephan Fueglistaler (Princeton)

Other Participating Researchers: Adam Scaife (Met Office), Rich Gudgel (GFDL), Tom Delworth (GFDL), S.J. Lin (GFDL), Seth Underwood (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: The objective is to identify the driver of skillful seasonal prediction of surface climate.

Methods and Results/Accomplishments:

My study explores the role of the stratosphere as a driver of skillful prediction of near surface land temperature over extra-tropics. A series of experiments including both simulations and retrospective forecasts using FLOR model were set up to isolate the influence of the stratosphere on near surface temperature prediction. We found that most of the 0-lead spring skill of near surface land temperature over the extra-tropics, particularly over northern Eurasia, was from the stratospheric initialization. We revealed the skillful prediction of the temperature arises from skillful prediction of the Arctic Oscillation, which connected to the stratosphere.

Outreach Activities: I hosted a CICS summer intern during Jun.-Aug., 2016.

Publications:

Liwei Jia Xiaosong Yang, Gabriel A Vecchi, Richard Gudgel, Thomas Delworth, Stephan Fueglistaler, Pu Lin, Adam A. Scaife , Seth Underwood and Shian-Jiann Lin, 2017: Seasonal Prediction Skill of Extratropical Surface Temperature Driven by the Stratosphere. J. Climate, accepted.

Xiaosong Yang, Gabriel A. Vecchi, Liwei Jia, Sarah Kapnick, Tom Delworth, Rich Gudgel, Seth Underwood, 2017: From failure to success in predicting western United States winter precipitation from the large 2015/16 El Niño.Monthly Weather Review, submitted.

Liping Zhang, Thomas L. Delworth and Liwei Jia, 2017: Diagnosis of Decadal Predictability of Southern Ocean Sea Surface Temperature in the GFDL model. J. Climate, accepted.

H. Murakami, G. A. Vecchi, T. L. Delworth, A. T. Wittenberg, S. Underwood, R. Gudgel, X. Yang, L. Jia, F. Zeng, K. Paffendorf and W. Zhang, 2016: Dominant Role of Subtropical Pacific Warming in Extreme Eastern Pacific Hurricane Season: 2015 and the Future. J. Climate, 30, 243-264.

W. Zhang, G.A. Vecchi, H. Murakami, G. Villarini, T.L. Delworth, K. Paffendorf, R. Gudgel, L. Jia, F. Zeng, X. Yang, 2017: Influences of Natural Variability and Anthropogenic Forcing on the Extreme 2015 Accumulated Cyclone Energy in the Western North Pacific. BAMS, 97 S131-S135.

Jie He, Michael Winton, Gabriel Vecchi, Maria Rugenstein, Liwei Jia, 2016: Transient Climate Sensitivity Depends on Base Climate Ocean Circulation, J. Climate, 30, 1493-1504.

Honghai Zhang, Thomas L. Delworth, Fanrong Zeng, Gabriel Vecchi, Karen Paffendorf, Liwei Jia, 2016: Detection, Attribution and Projection of Regional Rainfall Changes on Multi-Decadal Time Scales: A Focus on Southeastern South America. J. Climate, 29. 8515-8534.

Karin van der Wiel, Sarah B Kapnick, Gabriel A Vecchi, William Cooke, Thomas L Delworth, Liwei Jia, Hiroyuki Murakami, Seth Underwood and Fanrong Zeng, 2016: The Resolution Dependence of US Precipitation Extremes in Response to CO2 Forcing. J. Climate, 29, 7991-8012.

Salvatore Pascale, Simona Bordoni, Sarah B. Kapnick, Gabriel A. Vecchi and Liwei Jia, 2016: The impact of horizontal resolution on North American monsoon Gulf of California moisture surges in a suite of high-resolution coupled models, J. Climate, 29, 7911-7936.

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, J. Climate, 29, 8231-8248.

Di Tian, Ming Pan, Liwei Jia, Gabriel Vecchi and Eric F. Wood, 2016: Assessing GFDL High-resolution Climate Model Water and Energy Budgets from AMIP Simulations over Africa, J. Geophys. Res. Atmos., 121, doi:10.1002/2016JD025068.

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, DOI 10.1007/s00382-016-3099-2.

Presentations:

Jia, L., Oct. 2016, National Oceanic and Atmospheric Administration's 41st Climate Diagnostics and Prediction Workshop: Seasonal Prediction Skill of Northern Extratropical Surface Temperature Driven by the Stratosphere.

Jia, L., Oct. 2016, National Oceanic and Atmospheric Administration's 41st Climate Diagnostics and Prediction Workshop: The Roles of Radiative Forcing, Sea Surface Temperature, Atmospheric and Land Initial Conditions to U.S. Summer Warming Episodes.

Progress Report Title: **Aerosol Instantaneous Radiative Forcing Component of the RFMIP**

Principal Investigator: Alexandra L. Jones (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: David Paynter, Stuart Freidenreich and V. Ramaswamy (GFDL)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Other Participating Researchers: Daniel Feldman and William Collins (Lawrence Berkeley National Laboratory)

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: GFDL's contribution to RFMIP is in reducing spread due to radiative transfer parameterization error in the instantaneous radiative forcing by aerosols. Other objectives include performing research into the transfer of solar and longwave radiation in the Earth's atmosphere with the aim of quantifying the roles of greenhouse gases, aerosols, and clouds.

Methods and Results/Accomplishments:

To reduce spread due to radiative transfer parameterization error in the instantaneous radiative forcing by aerosols each participating model's fluxes of solar radiation will be reproduced with a line-by-line radiation code, which will ingest the meteorological state and the aerosol optical properties directly from each model. Thus, a framework to extract this information, provide it as input, and run a line-by-line model globally in a computationally feasible way is needed. This is what I have spent my first year primarily working on. More specifically I have: converted the software framework to MPI for more flexible and efficient parallelization; added functionality to allow for dynamic allocation of dimensions based on model's native grid, different run configurations to compute LW or SW fluxes from RFM or RRTMg, or produce files in netcdf or direct access format to be read by an external code; produced results showing global distribution of error in GFDL AM4 aerosol forcing relative to LBL solutions, and presented those results at AGU; and adjusted model to read in CESM data, and currently sorting out whether aerosol forcing errors are due to true model error or improper inputs or interpretation of the inputs.

Outreach Activities: Co-supervision of AOS Graduate Student Shiv Priyam Raghuraman; Presentation to P.E.O. NJ Chapter Y on Climate change and its impacts in NJ

Publications:

Jones, Alexandra, D. Paynter, S. Freidenreich, D. Feldman, V. Ramaswamy, W. D. Collins, (Poster Presentation) "Reducing the Spread in Modeled Aerosol Radiative Forcing with a Global, Scattering, Line-by-Line Model as Part of RFMIP", AGU Fall Meeting, Monday, December 12, 2016, San Francisco, CA.

Progress Report Title: **Climate Model Assessment of Changes in Winter-Spring Streamflow Timing over North America**

Principal Investigator: Jonghun Kam (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Thomas R. Knutson (GFDL)

Other Participating Researchers: P. C. D. 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: This project is aimed at improved understanding of the causes of changes in winter-spring streamflow center time (WSCT) over North America. We used climate models and observations to assess the possible role of anthropogenic forcing in changes in WSCT and to test whether historical model simulations are consistent with observations.

Methods and Results/Accomplishments:

For this project, we have analyzed changes in WSCT over North America during 1933-2012; we developed a method for detection and attribution for the changes in WSCT. This work was submitted to Scientific Reports and is now under revision. While much of the methodology follows previous contributions by Knutson et al. (2013), this article which I led focused on observed streamflow records and simulated runoff data tested the robustness of the changes in WSCT across models. A model/observational comparison, using nine CMIP5 models to simulate internal climate variability and the response to historical anthropogenic and natural forcings, was applied to the middle latitudes of North America exhibiting earlier WSCT climatology and variability in the climate models at high latitudes and altitudes of North America compared with those from observed streamflow records.

In this study, we found an emerging detectable anthropogenic influence is in north-central U.S. (according to four or five of nine models), the mountainous western U.S./southwestern Canada and in extreme northeastern U.S./Canadian Maritimes (three of nine models). In other (including warm, snow-free) regions, observed trends were typically not detectable, although in the U.S. central plains we found detectable delays in streamflow, which were inconsistent with forced model experiments. We included an important enhancement relative to our previous studies for temperature anomalies: detection, attribution, and consistency test with adjusted simulated decadal variances.

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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, and P. C. D. Milly, Climate model assessment of changes in winter-spring streamflow timing over North America, Scientific Reports, in revision.

Presentations:

Kam, J., Invited Talk, Climate model assessment of changes in winter-spring streamflow timing over North America, Seoul National University, Nov. 16, 2016, Seoul, South Korea.

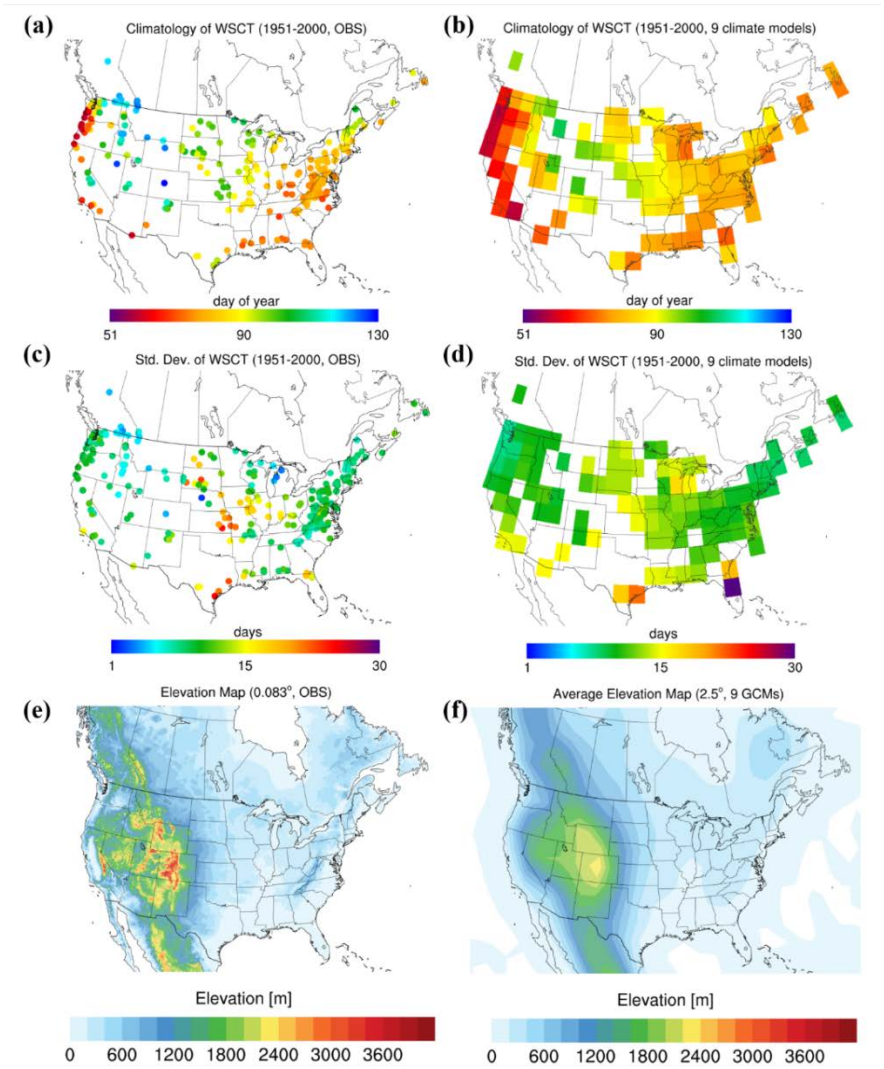

Fig. 1: Comparison of WSCT climatology and standard deviations and elevations between observations and CMIP5. Comparison of WSCT climatology and interannual variability between observations and CMIP5 models. Spatial distributions of the climatology (a and b) and interannual standard deviation (c and d) for WSCT are compared between observations and models. The model grand ensemble mean climatology (b) is based on the average of ensemble means of the nine CMIP5 model HIST-ALL forcing runs. For the models' interannual variability (d) the standard deviations of individual ensemble members for each of the nine models are computed and averaged to create an ensemble standard deviation estimate for each model. These are then averaged across the nine models to create a grand ensemble standard deviation. The colors depict the calendar day of a year (a, b) or number of days (c, d). (e) Digital elevation map at 8 km (0.083˚) spatial resolution from observations, and (f) the averaged elevation at 250 km (2.5˚) spatial resolution from the nine CMIP5 models. Panels (a) - (f) were created in NCAR Command Language (NCL) version 6.3.0, a free software provided by the National Center for Atmospheric Research (http://dx.doi.org/10.5065/D6WD3XH5)

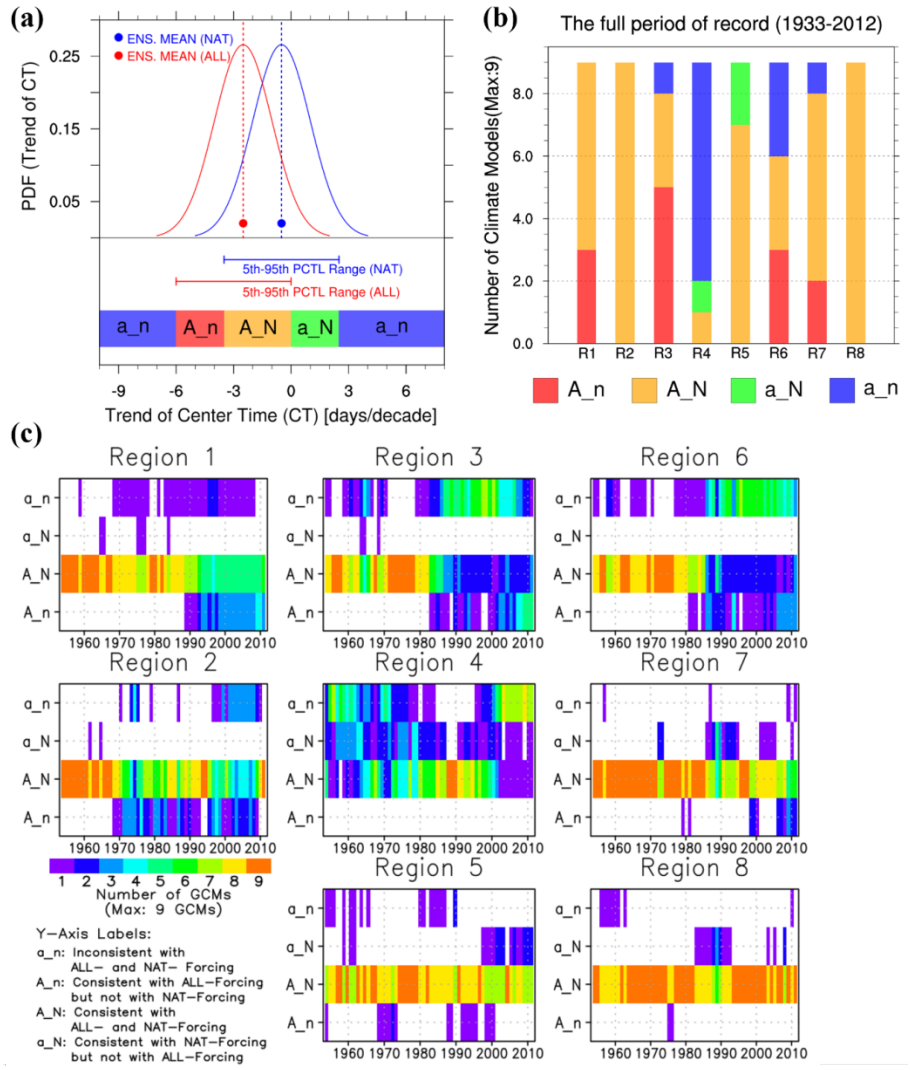

Fig. 2: Detection, attribution, and consistency of WSCT trends. (a) Schematic diagram of the categories for the detection, attribution, and consistency assessments. Four categories, depicted at the bottom, include: A_N: observed trend consistent with both HIST-ALL and HIST-NAT model simulation; A_n: observed trend consistent with HIST-ALL, but not with HIST-NAT; a_N: observed trend consistent with HIST-NAT but not with HIST-ALL; and a_n: observed trend not consistent with either HIST-ALL or HIST-NAT (see text). (b) Summary of the number of climate models assigned to each of the four categories based on the trend analysis for the full period of record (1933-2012) (c) Time series of the number of climate models in each of the four categories, with all the trends starting in 1933. X-axis depicts the end years of the trends.

Progress Report Title: **The Role of Temperature and Oxygen for the Remineralization of Sinking Organic Matter; Effects of Variability in Iron Forcing**

Principal Investigator: Charlotte Laufkotter (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborators: John P. (GFDL), Charles Stock (GFDL), 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: Laufkötter has mainly focused on (1) analyzing the biogeochemical consequences of a temperature-dependent remineralization of sinking particles and (2) improving the representation of the iron cycle by using inter-annually varying dust and iron inputs from icebergs. These topics have emerged as two of the most important causes of uncertainty in projections of marine primary (NPP) and export production. Additionally, she has contributed to a publication that constrains future tropical NPP projections by using the observed inter-annual variability in NPP as emergent constraint. Her contribution was to analyze and compare the drivers of inter-annual NPP variability with the drivers of long-term NPP changes.

Methods and Results/Accomplishments:

Charlotte Laufkötter has tested two temperature-dependent parameterizations of remineralization in the ecosystem model "Carbon, Ocean Biogeochemistry and Lower Trophics" (COBALT) coupled to GFDL's ESM2M Coupled Climate–Carbon Earth System Model. For each parameterization, the model has been spun-up for 500 years and thoroughly evaluated. The new remineralization parameterizations redistribute the POC flux with stronger flux in the cold high latitudes and weaker flux in the low latitudes. It also decreases the volume of the oxygen minimum zones, partly addressing a long-standing bias in global climate models. In terms of future changes, the new parameterizations cause an additional 10% decrease in global POC flux at 500m depth, but no significant change in global POC flux at 2000m under the RCP8.5 future projection. A manuscript is currently under review at Global Biogeochemical Cycles.

Using observations of dust deposition and soluble iron fractions, Charlotte Laufkötter developed a parameterization of the soluble iron content in dust depending on the total dust concentration. In comparison with the previous parameterization that assumes a constant soluble iron fraction, iron inputs are increased by an order of magnitude in low deposition areas such as the Southern Ocean and decreased in high dust deposition areas. To obtain a projection with inter-annually varying iron inputs, Charlotte Laufkötter replaced the offline iron forcing with dust emissions calculated in the LM3 land model which features changes in dust emission depending on changes in land surface. Currently she is tuning the parameterization of the iron cycle in COBALT to adapt to the new dust forcing.

In terms of iron inputs from icebergs, Charlotte Laufkötter calculated a range of estimates for iron input from several glacial sources (icebergs, glacial melt water, ice shelf melt) in collaboration with Dr.

Alon Stern, based on estimates of iron concentration in icebergs by Raiswell et al. 2008 and Death et al. 2014. She is currently running test simulations to determine which of the estimates results in most realistic surface iron concentrations. Once a reasonable configuration is established she will analyze the importance and seasonal effects of iceberg iron on the carbon cycle in the Southern Ocean.

Publications:

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L. Kwiatkowski, L. Bopp, O. Aumont, P. Ciais, P. M. Cox, C. Laufkötter, Y. Li, R. Seferian, "Emergent constraints on projections of declining primary production in the tropical oceans", Nature Climate Change (accepted).

C. Laufkötter, M. Vogt, N. Gruber, O. Aumont, L. Bopp, S.C. Doney, J. Dunne, J. Hauck, J. John, I.D. Lima, R. Seferian, and C. Völker, "Projected decreases in future marine export production: the role of the carbon flux through the upper ocean ecosystem ", Biogeosciences, 13 (2016), 4023–4047.

Presentations:

C. Laufkötter, J.G. John, C. A. Stock, J.P. Dunne, "Temperature and Oxygen effects on Remineralization of Particulate Organic Matter", OCB Meeting 2016, Woods Hole, Massachusetts (poster).

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Progress Report Title: **Nitrogen Dynamics in the Land Biospheres: Insights from the GFDL Earth System Modeling Framework**

Principal Investigator: Minjin Lee (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Charles Stock (GFDL), Elena Shevliakova (GFDL), Sergey Malyshev (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 the dynamic land model LM3-TAN to investigate 1) the evolving impacts of historical (1780-2010) nitrogen storage in the land biospheres on atmospheric and oceanic pollution and 2) implications of climate variability and extremes for global distribution of coastal hypoxic "dead" zones.

Methods and Results/Accomplishments:

To develop a more complete representation of the nitrogen (N) cycle on the land biospheres, we extended LM3-TAN (Lee et al., 2014) by incorporating a dynamic lake N cycle (Lee et al., 2017a, in prep). The resultant model couples water, C, and N cycles within a vegetation-soil-river-lake (terrestrial-freshwater or land) system, and simulates the exchanges between and transformations within each sub-system for three N species (i.e., organic, ammonium, and nitrate plus nitrite N). Following a 9572-year spin-up under pre-industrial conditions and a subsequent 80-year (1700-1779) spin-up of land-use and land-cover change (LULCC), we ran the model globally from 1780 to 2010 at 30-minute temporal and 1-degree spatial scales, with historically reconstructed LULCC (Hurtt et al., 2006). Terrestrial and freshwater N inputs include biological N fixation (BNF), atmospheric depositions (Green et al., 2004), fertilizers and manure (Bouwman et al., 2013), and urban wastewater (Drecht et al., 2009). The simulation agrees with measurement-based empirical estimates of regional dissolved organic and inorganic N exports from world's 39 large rivers (Harrison et al., 2005; Dumont et al., 2005) and global terrestrial and freshwater N storage and fluxes (Galloway et al., 2004; Post et al., 1985) for preindustrial and contemporary times.

Land biospheres provide a potentially valuable ecosystem service by retaining reactive nitrogen (Nr) inputs, which buffers coasts against eutrophication and reduces greenhouse gas emissions. We used the land model, and estimated the magnitude of land ecosystem service, its regional variations, and their evolving impacts on atmospheric and oceanic pollution from 1780 to 2010 (Lee et al., 2017a, in prep). We classified 159 river basins as nitrogen sinks or sources, based on whether the land biospheres reduce (accumulating nitrogen storage) or augment (releasing stored nitrogen) net nitrogen losses to the atmosphere and oceans. A global net transition of the land biospheres from source to sink since 1950 reflects enhanced productivity and nitrogen demands of terrestrial ecosystems, due to growing reforestation and carbon dioxide fertilization. Currently, 87% of the global lands are sinks, yet with large regional variations in added reactive nitrogen sequestration (~76%). Meanwhile, recent agricultural intensification in the other lands has offset the benefits of carbon dioxide fertilization.

In general, high rainfalls or river flows lead to high river DN exports (i.e., flow-export relationship). Yet, observational studies showed high river DN export anomalies from the flow-export relationship (Foster and Walling, 1978; Morecroft et al., 2000; Kaushal et al., 2008) and subsequent severe algal blooms (Acker et al., 2005), caused by high rainfalls following dry periods (i.e., climate variability/extremes). Unlike flow data, observations of aqueous N are seldom available for long-term periods to analyze impacts of changing climate on water quality. We used the land model and found that previous longer and more severe droughts in the Susquehanna River Bain likely lead to higher Susquehanna River DN export anomalies (i.e., basin memory effect) (Lee et al., 2016). We extended this regional analysis to a global scale (Lee et al., 2017b, in prep). Preliminary results show that 76% of 159 river basins present significant basin memory effects, and which appear to be stronger in basins largely influenced by anthropogenic N inputs. Our study provides a fundamental implication that possible future increases in climate variability and extremes – specifically, high rainfalls occurring after dry spells – could likely enhance basin memory effects, and thus lead to significantly high DN export anomalies and expand costal hypoxic "dead" zones worldwide. This work was presented at the 2017 AGU Chapman Conference in San Juan, Puerto Rico.

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Lee, M., Stock, C., Shevliakova, E., Malyshev, S., Milly, P.C.D. (2017b, in prep), Future increases in climate variability and extremes will expand coastal hypoxic “dead” zones worldwide.

Presentations:

Lee, M., Shevliakova, E., Malyshev, S., Milly, P.C.D., Jaffe, P. Stock, C. (2017), Increased climate variability and extremes amplify risks of coastal hypoxia worldwide: Implications of enhanced basin memory effects on river dissolved nitrogen in the GFDL Earth system modeling framework, AGU Chapman Conference, San Juan, Puerto Rico, USA.

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

Principal Investigator: Sonya Legg (Princeton Senior Research Oceanographer)

CICS/GFDL Collaborator: Robert Hallberg, Stephen Griffies (GFDL), Alistair Adcroft, Robert Nazarian, Gustavo Marques, Elizabeth Yankovsky (Princeton), Leonardo Rodriguez Gutierrez (CICS Intern/University of Illinois)

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), Rachel Flecker (UBristol), Michael Rogerson (U Hull), Paul Yi (Princeton), Robert Turnewitsch (SAMS)

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 continued to collaborate with past CPT postdocs Angelique Melet and Benjamin Mater, funded by NOAA through CICS. In the past year one study of impacts internal wave dissipation on large-scale ocean climate was published (Melet et al, 2016a), and another describing a ray-tracing based model of the distribution of low-mode dissipation is in preparation. These projects were described in posters at the CLIVAR 2016 Open Science conference (Legg et al, 2016a, Melet et al 2016b, Mater et al 2016) and the WCRP model hierarchies workshop (Legg et al, 2016b). A significant achievement of the past year was the submission of a synthesis article describing all the progress in understanding and parameterizing internal wave-driven mixing made by the CPT (MacKinnon et al, 2017).

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 American Physical Society Fluid Dynamics meeting, and submitted to Ocean Modelling (Nazarian et al, 2017). 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 senior thesis project, funded by PEI. This work was presented at the International Symposium on Stratified Flows (Yi et al 2016).

Another application of internal tide-driven mixing is to explain the distribution of ocean sediments. Collaboration with ocean sedimentologist Robert Turnewitsch led to the publication of Turnewitsch et al (2016).

Legg's overflow-related work has largely focused on the Orkney passage overflow, through collaboration 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 the field program which takes place in March-May this year, and compare results with climate model parameterizations of mixing in overflows. This project is largely funded by NSF, but makes use of GFDL computing and contributes to improvement of overflow representation in GFDL models. As part of this project, Legg also supervised student intern Leonardo Rodriguez who examined this overflow region in MOM6 ocean-ice simulations.

A further overflow-related project involved collaboration with Michael Rogerson (U Hull) and Rachel Flecker (U Bristol) to simulate the Mediterranean Outflow for different paleoclimate periods, in preparation for a workshop last November on Investigating the Miocene Mediterranean-Atlantic Exchange funded by the International Continental Drilling Program.

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 was a co-author of a whitepaper summarizing a USCLIVAR workshop on translating process understanding to climate model improvements, held at GFDL in 2015 (Subramanian et al, 2016).

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 Women in Science lunch discussion at Hunterdon Regional High School, and a discussion with a girls' robotics 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. Legg was also the senior invited lecturer at the Physical Oceanography Dissertation Symposium organized by NSF/NAS/NOAA. A major new initiative which Legg has spearheaded is the CICS research internships, targeted at increasing diversity in earth and climate sciences. 8 undergraduates participated in the first year of this internship scheme in 2016, and selection of the 2nd year candidates is in progress.

Publications:

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Klymak; Eric Kunze; William G. Large; Sonya Legg; Benjamin Mater; Angelique V. Melet; Lynne M. Merchant; Ruth Musgrave; Jonathan D. Nash; Nancy J Norton; Andrew Pickering; Robert Pinkel; Kurt Polzin; Harper L. Simmons; Louis C. St. Laurent; Oliver M. Sun; David S. Trossman; Amy F. Waterhouse; Caitlin B. Whalen; Zhongxiang Zhao, 2017: Climate Process Team on Internal-Wave Driven Ocean Mixing, Bull. Am. Met. Soc, submitted.

Nazarian R., and S. Legg, 2017: Internal wave scattering in continental slope canyons: a dual ray tracing and numerical modeling approach. Ocean Modelling, submitted.

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Subramanian, A, C Ummenhofer, A Giannini, M M Holland, Sonya Legg, A Mahadevan, D Perovich, J Small, J Teixeira, and L Thompson, August 2016: Translating process understanding to improve climate models, A US CLIVAR white paper, Report 2016-3, DOI:10.5065/D63X851Q 48pp.

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

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: To understand the rapid decline of Arctic sea ice over the satellite era; We study the low-frequency variabilities of Arctic sea ice extent in coupled climate models, and assess the relative roles of external forcing versus internal climate variability in causing the decline.

Methods and Results/Accomplishments:

We analyzed the mechanisms for low-frequency variability of summer Arctic sea ice using long control simulations from three coupled climate models (GFDL CM2.1, GFDL CM3, and NCAR CESM). Despite different Arctic sea ice mean states, there are many robust features in the response of low-frequency summer Arctic sea ice variability to the three key predictors (Atlantic/Pacific oceanic heat transport into the Arctic and the Arctic Dipole) across all three models. In all three models, an enhanced Atlantic (Pacific) heat transport into the Arctic induces summer Arctic sea ice decline and surface warming, especially over the Atlantic (Pacific) sector of the Arctic. A positive phase of the Arctic Dipole induces summer Arctic sea ice decline and surface warming on the Pacific side, and opposite changes on the Atlantic side. There is robust Bjerknes Compensation at low frequency, so that the northward atmospheric heat transport provides a negative feedback to summer Arctic sea ice variations. The influence of the Arctic Dipole on summer Arctic sea ice extent is more (less) effective in simulations with less (excessive) climatological summer sea ice in the Atlantic sector. The response of Arctic sea ice thickness (SIT) to the three key predictors is stronger in models that have thicker climatological Arctic sea ice. We developed a simple theory to show that, at low frequency, changes in SIT induced by ocean-to-ice heat flux anomalies are approximately proportional to the square of the climatological SIT, and thus much larger in regions with thicker climatological sea ice.

We identified major discrepancies in the spatial patterns of winter Northern Hemisphere sea ice concentration trends over the satellite period between observations and CMIP5 multi-model mean externally forced response. The CMIP5 externally forced decline in Barents Sea winter SIE is much weaker than that observed. Across CMIP5 ensemble members, March Barents Sea SIE trends have little correlation with global mean surface air temperature trends, but are strongly anti-correlated with trends in Atlantic heat transport across the Barents Sea Opening (BSO). Further comparison with control simulations from coupled climate models suggests that enhanced Atlantic heat transport across the BSO associated with regional internal variability may have played a leading role in the observed decline in winter Barents Sea SIE since 1979.

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Li, D., R. Zhang, and T.R. Knutson, Comparison of Low-Frequency Variability of Summer Arctic Sea Ice in Three Coupled Climate Models, AMS Annual Meeting. Seattle, WA, January 2017.

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 (TC) model

Methods and Results/Accomplishments:

We further developed our statistical TC intensity models to predict 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 obtained 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 also found that the considered environmental variables have limited predictability for the occurrence of extreme/rapid intensification. Thus, we are currently adding oceanic and inner-core process predictors to further improve the predictability of these models. Moreover, these statistical analyses were applied to observed storm and environmental datasets. We are currently applying these statistical modeling analyses to storm and environmental datasets generated by climate and regional models, such as those developed at GFDL.

We continue to study TC size (spatial dimension). We previously investigated TC size in QuikSCAT satellite observations. However, the satellite observation is limited. Thus, we examined the fidelity of outer region TC size and wind field structure in four atmospheric reanalysis datasets, in comparison with the QuikSCAT observations. We found that both outer region TC size and structure in reanalyses closely match QuikSCAT data as revealed by strong correlations, similar standard deviations, and generally small biases. Of the TC size metrics examined, the radii of 6–8 m/s winds in the North Atlantic and radii of 6–10 m/s winds in the western North Pacific are generally most comparable to QuikSCAT. Compared to western North Pacific TCs, North Atlantic TC size and structure is represented with greater fidelity. Among the four reanalyses examined, the National Centers for Environmental Prediction Climate Forecast System Reanalysis and the Japanese Meteorological Agency Japanese 55-yr Re-Analysis TC size and structure are generally represented with the greatest fidelity within both basins.

Publications:

Lin N., R. Jing, Y. Wang, E. Yonekura, J. Fan, and L. Xue (2017). A statistical investigation of the dependence of tropical cyclone intensity change on the surrounding environment. Monthly Weather Review (accepted).

Schenkel, B., N. Lin, D. Chavas, M. Oppenheimer, A. Brammer (2017). Evaluating Tropical Cyclone Size in Reanalysis Datasets using QuikSCAT Data. Submitted to Journal of Climate .

Progress Report Title: **Simulating Stratospheric Circulations in a Changing Climate**

Principal Investigator: Pu Lin (Princeton Associate Research Scholar)

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

Other Participating Researchers: Lorenzo Polvani (Columbia University), Gustavo Correa (Lamont-Doherty Earth Observatory)

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 and reconcile the inter-model difference in the simulated circulation responses to ozone depletion. We also tried to improve the representation of the stratosphere in the current climate model.

Methods and Results/Accomplishments:

Stratospheric ozone has undergone severe reduction over the past few decades, which would further induce cooling in the stratosphere and poleward shift of jet in the troposphere. These altered circulation patterns composed a large fraction of the changes in the climate system over the recent past (Polvani et al. 2011). Climate models have been employed to simulate the response to ozone depletion. However, a large spread is found among models (Gerber and Son 2014). In this project, we compared the simulated ozone responses in two climate models: GFDL AM3 and NCAR CAM3. With the identical changes in the ozone concentration, CAM3 simulated stronger stratospheric cooling than AM3. Our analysis showed that the difference arises from the dynamical response to ozone depletion. CAM3 has a bias in its zonal wind climatology and the polar vortex breakdown is delayed compared to observations. Associated with this delay is a delayed and weaker dynamical warming in response to ozone depletion. AM3, on the other hand, is immune from this bias. Given that the delayed polar vortex breakdown is common bias in many climate models, our results suggest that previous model assessments of climate response to ozone depletion may be overestimated. These results are summarized into a paper to be submitted to *Geophysical. Research Letters.*

Quasi-Biennial oscillation (QBO) is a prominent feature observed in the equatorial stratosphere (Baldwin et al. 2001). It modulates the transport from the tropics to polar region, and may have a direct influence in the tropical troposphere. Given its strong periodicity, it also plays a role in the seasonal forecast. Most current general climate models are in capable to simulate the QBO. Here, we are able to simulate a QBO-like oscillation in the GFDL AM4 with increased vertical resolution and modified parameterization for the convective gravity waves. We find that the behavior of this QBO-like oscillation is affected whether an interactive ozone scheme is implemented. Detailed spectrum analysis is carried out to identify the waves that are responsible for the QBO. By studying the behavior of these waves propagating in the atmosphere, we hope to gain insights of how waves of different scales interact with the mean flow and to achieve a more realistic representation of the QBO in our model.

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Publications:

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Lin, P., and J. Wilson, 2016: Simulate QBO with interactive ozone. Talk. SPARC QBO workshop: the QBO and its global influence-past, present and future, SPARC, Oxford, United Kingdom.

Progress Report Title: **Lower Tropospheric Eddy Momentum Fluxes in Idealized Models and Reanalysis Data**

Principal Investigator: Nicholas Lutsko (Princeton Graduate Student)

CICS/GFDL Collaborator: Isaac Held (GFDL), Pablo Zurita-Gotor (Universidad Complutense de Madrid)

Other Participating Researchers: Amanda O'Rourke (University of Michigan)

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 investigate the structure of the eddy momentum fluxes (EMFs) in the lower tropospheres of two different idealized models of the atmosphere, as well as in a reanalysis dataset that incorporates observations. The idealized models can then be used to develop theoretical interpretations for the structure of the EMFs in the reanalysis data.

Methods and Results/Accomplishments:

The EMFs in the lower tropospheres of two different idealized models of the atmosphere and the southern hemisphere of a reanalysis dataset are investigated. The lower layer EMFs are very similar in the two models, with EMF convergence at phase speeds close to the lower layer jet speed and EMF divergence at slower phase speeds. These regions are bordered by regions of EMF divergence and EMF convergence, respectively. Calculating the EMFs as a function of wavenumber shows that long, slow waves are responsible for the EMF divergence, while short, fast waves are responsible for the EMF convergence. Many of the same features are seen in the co-spectra of the reanalysis data, particularly in austral summer. This suggests that the same fundamental dynamics are at play in the models as well as in the reanalysis data.

The idealized models are then used to interpret the behavior of the eddies. The EMF divergence is attributed to the weak, negative potential vorticity gradient in the lower troposphere and also to the width of the disturbance which excites the baroclinic eddies. Lower tropospheric eddies that are excited near their critical latitudes break and accelerate the flow, the mean potential vorticity gradient being negative, with little meridional propagation. There is compensating deceleration in the center of the domain where there is eddy generation but no breaking. The EMF convergence at faster phase speeds is due to coupled, equivalent barotropic modes which mostly propagate on the upper tropospheric potential vorticity gradient.

Publications:

Lutsko, N. J., I. M. Held, P. Zurita-Gotor, A. K. O'Rourke, 2017: Lower Tropospheric Eddy Momentum Fluxes in Idealized Models and Reanalysis Data. Journal of the Atmospheric Sciences, (Submitted).

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), Jingyi Li (Princeton), Fabien Paulot (Princeton), Songmiao Fan (GFDL)

Other Participating Researchers: Arlene Fiore (Columbia U.)

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:

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

Accomplishments: (1) We have implemented a new set of chemistry and radiation code for GFDL AM4 model. This includes radiation code for chemistry (Fast-JX v7.1), a new isoprene oxidation mechanism, and a new set of heterogeneous chemistry. (2) 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, and also largely improves model SOA over high latitude. (3) We have developed a new module to couple land model (LM3) with biogenic emission (MGEAN). This module is currently being evaluated by satellite HCHO columns.(4) We publish a paper on glyoxal production from isoprene oxidation using field observations and GFDL AM3 model.(5) We submit a paper on the outcome form Southeast Atmosphere Study workshop held at GFDL in 2015. The paper is under review on ACPD. (6) We are preparing a paper on the decadal change of reactive nitrogen and ozone over Southeast. The paper is to be submitted within next few weeks. We are preparing another manuscript on SOA formation over Southeast US. (7) We published a paper on aerosol chemistry and soluble iron on Environmental Science Technology Letters.

Publications:

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Progress Report Title: **Modeling Ice Shelf/Ocean Interactions**

Principal Investigator: Gustavo Marques (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Robert Hallberg (GFDL), Matthew Harrison (GFDL), Olga Sergienko (Princeton), Alon Stern (Princeton), Alistair Adcroft (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: Investigate processes controlling the circulation around Antarctica and their role in regulating the melting of ice shelves and the formation and export of bottom water; Lead GFDL's participation in the Ice Shelf Ocean Model Intercomparison Project; and develop/improve the ice shelf module in MOM6

Methods and Results/Accomplishments:

Ice Shelf Ocean Model Intercomparison Project (ISOMIP+). I have been leading GFDL's effort in the ISOMIP+ participation. This project consists of a set of experiments aimed to improve the understanding of the models capabilities and limitations, as well as the physical processes involved in ice-ocean interactions (Asay-Davis et al. 2016). We already completed the first set of four experiments and the results are currently being analyzed and compared against other models. The next phase of the project requires simulations that represent the movement of boundaries between different model components, including the migration of the grounding line. I have recently added this option in MOM6 and the results are very promising (Fig. 1). This project has been extremely useful to test MOM6 and to identify parts of the model that need to be improved. For example, we found the presence of large pressure gradient errors under the ice shelf base when using vertical coordinates based on the Arbitrary Lagrangian-Eulerian (ALE) algorithm. We have identified the source of the problem and are currently working on possible ways of minimizing it.

Model development. Over the last year, I became very active in developing and testing GFDL's ocean model (MOM6) and its ice sheet component. My contributions to MOM6 included the implementation of a sponge layer module that works with ALE vertical coordinates, improvements in the model diagnostics and many upgrades in the ice shelf module (including the option to simulate the movement of boundaries between different model components, see Fig. 1). A full list of all my contributions can be found in the following link: https://github.com/NOAA-GFDL/MOM6/commits?author=gustavo-marques.

Idealized simulations of Antarctic margins. I am currently conducting idealized simulations designed to represent the interaction between the ocean, sea ice and thermodynamic active ice shelves around Antarctica (Fig. 2a). An important aspect of these simulations is the high horizontal resolution employed (up to 500 m), which is sufficient to resolve the first baroclinic radius of deformation under ice shelf cavities. The goal of this study is to pinpoint how the melting and circulation underneath ice shelves, as well as the formation and export of dense shelf water, behave to changes in forcing (wind stress and sensible heat flux), ice shelf geometry, horizontal grid resolution, choice of vertical coordinate and in the presence/absence of troughs along the continental shelf. An example of a model experiment showing the

intrusion of Circumpolar Deep Water through a topographic trough is shown in Fig. 2b. Such intrusion leads to high sub-ice-shelf melting rates and the subsequent outflow of meltwater forms anticyclonic eddies over the continental shelf (Fig.2 c). Our preliminary results show that increasing the magnitude of the westerlies leads to a significant increase in the mean melt rate.

Analysis of forced global simulations with thermodynamically active ice shelves. I have been analyzing the results from global 1/8 degree ice-ocean simulations designed to investigate interactions between the ocean circulation and Antarctic ice shelves. These simulations have been useful in assessing the impact of model improvements in representing important physical processes. My analysis shows that these simulations represent the formation of dense shelf water and its consequent offshore export through troughs along continental shelves around Antarctica relatively well. Inspection of the ocean heat and freshwater budgets allowed me to identify biases and shortcomings in the experimental design and in the model itself. Efforts to address these issues are currently underway and they will lead to substantial improvements in MOM6's ability to represent polar processes.

Modeling ice-shelf cavities and calving tabular icebergs. I have been participating in a project aimed at developing a model of an ice-shelf cavity using a Lagrangian ice shelf. This project, which is led by AOS postdoc Alon Stern, uses the idealized ice-shelf cavity developed in the ISOMIP+ study to demonstrate how a tabular iceberg can break away from an ice shelf.

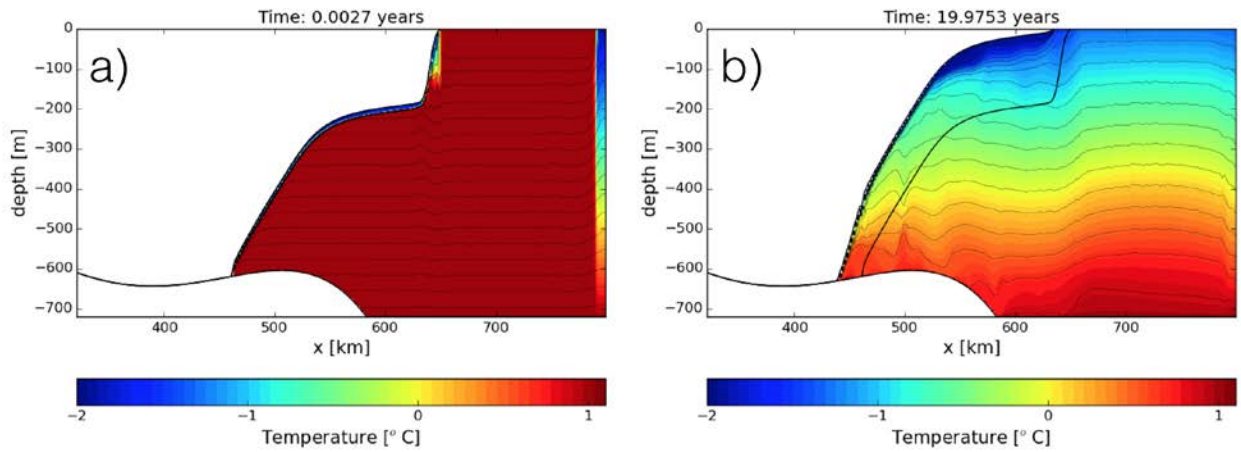

Figure 1: Snapshots of potential temperature and density contours (every 0.04 kg/m^3) taken at the (a) start and (b) end of the simulation. The black thick contour in (b) highlights the initial position of the ice shelf. These figures illustrate the model's capability to represent the movement of boundaries between the different components (ocean/ice shelf), including the migration of the grounding line.

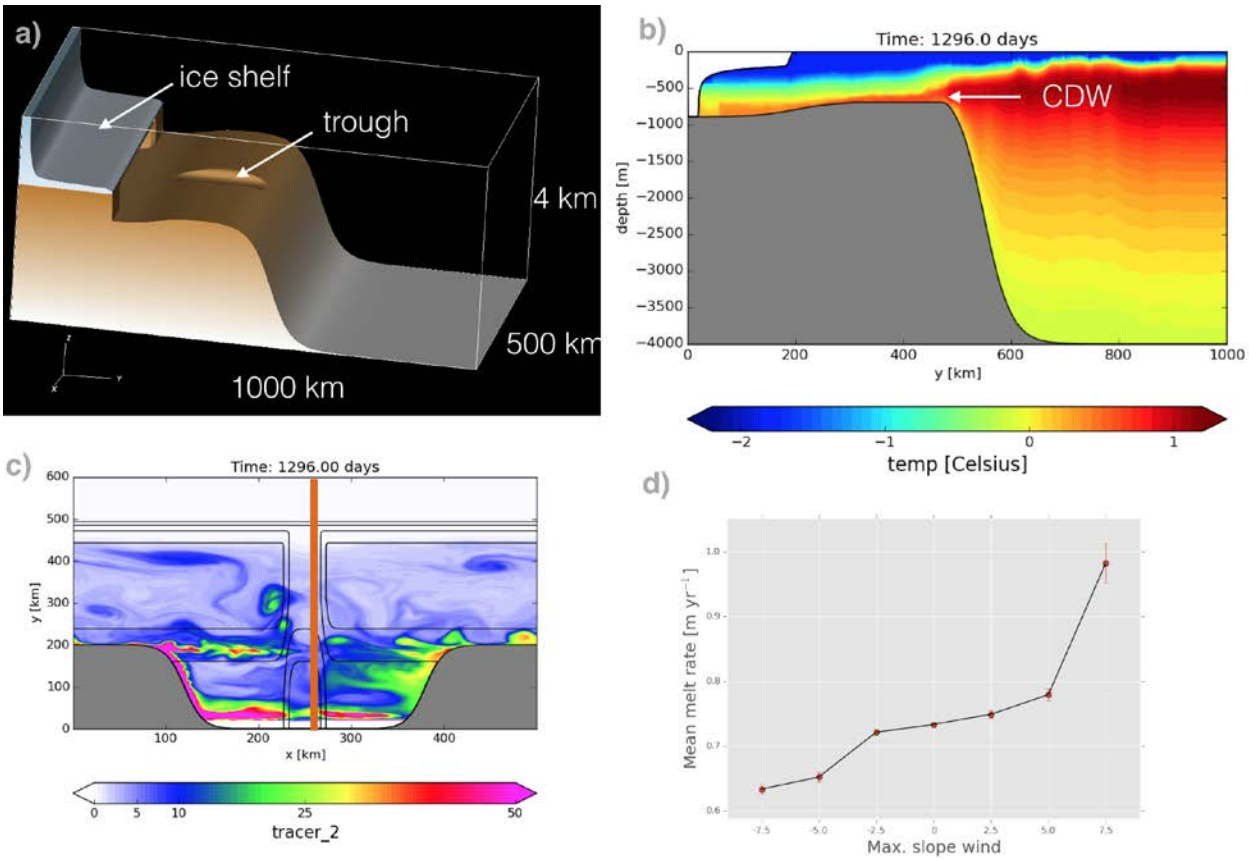

Figure 2: (a) Geometry of the idealized setup. (b) Snapshot of potential temperature showing the intrusion of Circumpolar Deep Water (CDW) through the trough (section taken along the orange line highlighted in panel (c)). (c) Snapshot of depth-averaged melt water tracer concentration showing the presence of eddies that occur due to sub-ice-shelf melting (1 tracer unit = 10^{-4} kg of melt water per kg of seawater). (d) Mean sub-ice-shelf melt rate as a function of the magnitude and direction of the maximum wind over the shelf slope (error bars, in red, show ± one standard deviation). Increasing the magnitude of the westerlies leads to a significant increase in the mean melt rate.

Outreach Activities: In conjunction with Prof. Sonya Legg, I have co-advised an undergraduate summer intern (Leonardo Rodriguez).

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Publications:

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

Principal Investigator: Denise L. Mauzerall (Princeton Professor)

CICS/GFDL Collaborator: Peter Phillipps (GFDL), Elena Shevliakova (GFDL), Sergey Malyshev (Princeton)

Other Participating Researchers: Paul Gauthier (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: Improving the representation of croplands in LM3 by implementing crop-specific parameterizations of physiology, phenology and management characteristics and prognostic planting and harvesting of major crops as proxy for land-use and C productivity

Methods and Results/Accomplishments:

For each tile modeled in LM3, one particular type of vegetation is determined according to its geographical location, temperature, growing periods, light availability etc. LM3 has 5 predefined plant functional types and each of them present specific physiological properties. Because most of crops are identified as C3, the current physiological properties used to model croplands productivity won't vary between species. To correct for this oversimplification a crop module to input information on global crop distributions, and improved the parameterization of major crop types has been introduced.

In 2015-2016, Dr. Xin Zhang began implementing the MIRCA 2000 cropland distribution dataset into LM3. Xin also identified a harvesting parameterization which could be integrated into LM3. During 2016-2017 we continued to refine Xin's code for ingesting MIRCA dataset and begin modifying grassland parameters to represent the crops in the MIRCA dataset. For each of the 26 major crops, physiological characteristics are currently being implemented by Gauthier and Phillipps by merging crop specific physiological traits from BETY (Le Bauer et al 2017) and TRY databases (Kattge et al 2011). Two sets of parameters are being implemented: (1) phenology traits including leaf mass per area, shoot-to-root allocation, developmental stages or harvest index and (2) physiological traits including photosynthesis efficiency (Vcmax, Jmax, G*), respiration of different plant's parts (root, stem, leaves), nitrogen use efficiency or hydraulics. In addition, in MIRCA dataset, multi-cropping was identified as source of uncertainties for cropland productivity. Implementation of crop specific parameterizations will allow LM3 to account for crop rotations or monoculture to better simulate cropland carbon, nitrogen and water biogeochemical cycles. On completion of the implementation, outputs of native and implemented LM3 will be compared globally in a stand -alone mode.

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Progress Report Title: **Cross-timescale Interactions and Diagnostics for Coupled Circulation Models**

Principal Investigator: Ángel G. Muñoz (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Gabriel A. Vecchi (GFDL), Xiaosong Yang (GFDL), William F. Cooke (GFDL)

Other Participating Researchers: Lisa Goddard (IRI-Columbia University), Andrew Robertson (IRI-Columbia University), Simon Mason (IRI-Columbia University), James Doss-Gollin (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: Using a weather-within-climate approach, to explore how the interaction of climate modes acting at different timescales can improve prediction skill and be used to diagnose coupled climate models

Methods and Results/Accomplishments:

The research uses weather types defined via a standard k-means classification method to better understand physical mechanisms associated with extreme events and their sources of predictability across timescales. The same approach is used to diagnose numerical circulation models. The evaluation of the goodness of a model is not always linked to the understanding of physical processes that may be correctly represented, distorted or even absent in the model universe. As physical mechanisms are frequently related to interactions at multiple time and spatial scales, cross-scale model diagnostic tools are not only desirable, but required.

This study proposes an integrated diagnostic framework based on weather type's spatial patterns and frequencies of occurrence to facilitate the identification of model systematic errors across multiple timescales. To illustrate the approach, three sets of 32-year-long simulations are analyzed for Northeastern North America and for the March-May season, using the Geophysical Fluid Dynamics Laboratory's LOAR and FLOR coupled models. Regime-dependent biases are explored in the light of different atmospheric horizontal resolutions and under different nudging approaches.

It is found that both models exhibit a fair representation of the observed circulation regime's spatial patterns and frequencies of occurrence, although some biases are present independently of the horizontal resolution or the nudging approach, and are associated with a misrepresentation of troughs centered north of the Great Lakes and deep coastal troughs. Overall, inter-experiment differences in the mean frequencies of occurrence of the simulated weather types, and their variability across multiple timescales, tend to be negligible. This result suggests that low-resolution models could be of potential use to diagnose and predict physical variables (e.g., rainfall climatology) via their simulated weather type characteristics.

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Publications:

Muñoz ÁG, Goddard L, Mason SJ, Robertson AW. Cross–Time Scale Interactions and Rainfall Extreme Events in Southeastern South America for the Austral Summer. Part II: Predictive Skill. J Clim 29(16):5915–34. 2016. Available from: http://journals.ametsoc.org/doi/10.1175/JCLI-D-15-0699.1

Muñoz, ÁG, Yang, X, Vecchi, GA, Cooke, WF. A Cross-timescale Diagnostic Framework for Coupled Circulation Models. J Clim (sub judice).

Presentations:

Muñoz, ÁG, Vecchi, GA, Yang, X, Goddard, L, Robertson, AW. Atmospheric cryptography: Using weather regimes to 'crack the code' of subseasonal-to-seasonal extreme rainfall events. Conference paper. 16th EMS/11th ECAC, European Meteorological Society. Trieste (Italy), 2016. Volume: 13: EMS2016-684.

Muñoz, ÁG, Yang, X, Vecchi, GA, Cooke, WF. Cross-timescale Diagnostics for Coupled Circulation Models. Conference Paper. Sub-seasonal to Seasonal Workshop, Columbia University. New York. 2016. doi: 10.13140/RG.2.2.19490.84164.

Doss-Gollin, J, Muñoz, ÁG, Pastén, M. Physical Mechanisms and S2S Predictability of 2015/16 Paraguay River Flooding. Conference Paper. Sub-seasonal to Seasonal Workshop, Columbia University. New York. 2016.

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, Amy Waterhouse and Matthew Alford (SIO)

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:

To tackle this problem, I have conducted 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, this allows us to identify a parameter space in which instability, and thus wave breaking and mixing, is possible. Additionally, through the use of the Froude number, we identity how large this envelope of instability is for each canyon in the parameter space and gain insight into the physical processes leading to instability. Using ray density as a proxy for instability (in the linear theory, instability is proportional to the square root of ray density), we analytically predict the instability, and thus mixing, for our parameter space of canyons.

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 to interact with and scatter off the topography. To first-order, we find that the processes studied are not resolution dependent. Two diagnostics of energy loss in the canyon are in good agreement with the analytical calculation derived from the ray tracing algorithm. Additionally, the envelopes of instability for individual canyons in the parameter space, diagnosed by the Richardson number, are in good agreement with those identified through the ray tracing. The numerical model results also suggest 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 width 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. These results have been submitted to *Ocean Modelling* for consideration for publication.

While initial model simulations have a relatively simple V-shaped geometry, we have also run simulations that more closely mirror observed submarine canyons, such as Veitch, La Jolla and Eel Canyons (collaboration with M. Hamann, A. Waterhouse and M. Alford, SIO). These simulations are currently being analyzed. First, we are analyzing how well these simulations fit into our idealized parameter space. Second, we are analyzing the effects of rotation, which was not considered in the case of the idealized parameter space. Simulations both with and without rotation have been conducted to get at this question. Additionally, the ray tracing algorithm has been updated to reflect this realistic topography, as well as the rotation and non-uniform stratification so that we may continue to compare the results of the numerical simulations and linear theory. At the conclusion of this project, we will be pursuing publication in the *Journal of Physical Oceanography*.

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. This parameterization will take place this summer and the implementation in a GCM will occur after my PhD, utilizing the theory and tools that I have developed as a CICS collaborator.

Outreach Activities: Mentored undergraduate with Sonya Legg (Princeton University Senior, Paul Yi); 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

Publications:

Nazarian, R., and S. Legg: "Internal Wave Scattering in Continental Slope Canyons: A Dual Ray Tracing and Numerical Modeling Approach". Ocean Modelling. Submitted.

Presentations:

Nazarian, R., and S. Legg, November 20, 2016: "Internal Wave Scattering in Idealized and Realistic Continental Slope Canyons". American Physics Society, Division of Fluid Dynamics Meeting.

Legg, S., R. Nazarian, P. Yi, J. Klymak, M. Nikurashin, and M. Buijsman, September 23, 2016: "Internal Wave Driven Mixing: Numerical Process Studies of Breaking Internal Tides". CLIVAR, Open Science Conference: Charting the Course for Climate and Ocean Research.

Yi, P., S. Legg, and R. Nazarian, August 30, 2016: "A Process Study of Tidal Mixing Over Rough Topography". International Association for Hydro-Environment Engineering and Research, Eighth International Symposium on Stratified Flows.

Progress Report Title: **Predictability of Marine Biogeochemistry**

Principal Investigator: Jong-yeon Park (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Charles A. Stock, John P. Dunne, Jasmin G. John, and Xiaosong Yang (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 assess predictability of marine biogeochemical variables; to provide an experimental basis for a global biogeochemistry prediction system

Methods and Results/Accomplishments:

The current biogeochemistry predictability research consists of three steps. In the first step, the potential biogeochemistry predictability is examined by conducting a perfect model simulation using the GFDL's earth system model. Results suggest a potential predictability for biogeochemical variables of up to 8 years in the subtropical southern Pacific. This potential predictive skill is not simply caused by persistence of nutrient anomalies but is expected to be associated with natural climate variability of climate system such as the El Niño-Southern Oscillation (ENSO). The detailed mechanism will be further investigated. We will start to write a paper examining this upper limit of biogeochemistry predictability after identifying the mechanistic understanding of the predictability.

In the second step, a strategy to estimate historical biogeochemistry is developed. The historical biogeochemical variables will be used for initializing retrospective prediction runs which will be our third step of this research. Here we robustly integrate an ocean biogeochemical model with an ensemble coupled-climate data assimilation system used for seasonal to decadal global climate prediction. Strong wind constraints proved essential for reducing spurious vertical velocities and subsequent biogeochemistry bias that is caused by high sensitivity to transient momentum imbalances during physical data assimilation. Eliminating these spurious velocities further required enforcing stricter fidelity to the internal model dynamics over data constraints in subsurface equatorial waters (5°S – 5°N). The optimal choice of model-data weights, however, removed spurious biogeochemical signals without significant reductions in physical model skill. The resulting simulation further reduced biogeochemical biases along the equator compared to the version without assimilation - including marked reduction in hypoxic water volume. We are finalizing the figure list for writing a paper entitled "A physical data-constrained strategy to estimate global ocean biogeochemistry".

The third step in which we will perform retrospective prediction runs and access hindcast prediction skill will be started after finishing the draft of the second paper. A set of several year-long, multi-member ensemble runs will be performed every year from 1990 to 2015. These runs will be started from the initial conditions obtained from the second step. We will assess predictions of marine biogeochemistry over the last decades by comparing with both the biogeochemistry retrospective and available observations.

Outreach Activities: Attended DA-MEAP Task Team Workshop at University of California Santa Cruz; attended 2016 AGU fall meeting, session on "Biogeochemistry and Ecosystems of Tropical Pacific and upwelling systems"

Progress Report Title: **Interactions between the Atmospheric Energy Budget and the Tropical Large-Scale Circulation**

Principal Investigator: Max Popp (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Isaac Held (GFDL), Levi G. Silvers (Princeton) and Nicholas J. Lutsko (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: The goal of our research is to further our understanding on the impacts that the atmospheric energy budget has on the tropical large-scale circulation and, in particular, how cloud-radiative effects (CREs) change the position of the intertropical convergence zone (ITCZ).

Methods and Results/Accomplishments:

During the last year we have continued working on our study of how CREs change the ITCZ position in idealized aqua-planet simulations. For this purpose we continued analyzing the results obtained in our simulations with a developmental version of AM4, in order to identify the mechanisms by which CREs affect the position of the ITCZ. Our results suggest that CREs alter the meridional heating gradients. This leads to changes in the strength of the atmospheric overturning circulations which, in turn, affects the zonal-mean meridional advection of low-level moist static energy. The change in zonal-mean meridional advection then alters the distribution of low-level moist static energy and thereby the distribution of convection and precipitation. The effects of this interaction can be adequately illustrated by using a gross moist stability framework (Neelin and Held, 1987) (Fig.1). The results of this work have been submitted to the Journal of Climate.

As a next step we decided to evaluate whether the techniques applied in the aqua-planet simulations can also be applied to the models that took part in the climate model intercomparison project phase 5. This requires an adequate characterization of the mean-meridional structure of the tropical precipitation, which is presently missing in the literature. Therefore, we started developing different indicators for the mean-meridional structure of the tropical precipitation, which we are currently applying to results of the AMIP and CMIP simulations. We test a set of six a priori independent indicators in the two sets of simulations for independence and for their predictive skills of the precipitation structure. We anticipate completing this analysis this week, and will start writing a short manuscript about the material thereafter.

References:

Neelin, J. D., and I. M. Held, 1987: Modeling Tropical Convergence Based on the Moist Static Energy Budget. Monthly Weather Review, 115 (1), 3–12.

Publications:

Max Popp and Levi G. Silvers (2017) Single and double ITCZ's with and without clouds. Submitted to the Journal of Climate.

Presentations:

Max Popp and Levi G. Silvers, Double and single ITCZs with and without clouds, EGU General Assembly 2016, Vienna, and Austria.

Max Popp and Levi G. Silvers, Shifting the ITCZ with longwave and shortwave cloud-radiative effects, EGU General Assembly 2017, Vienna, Austria.

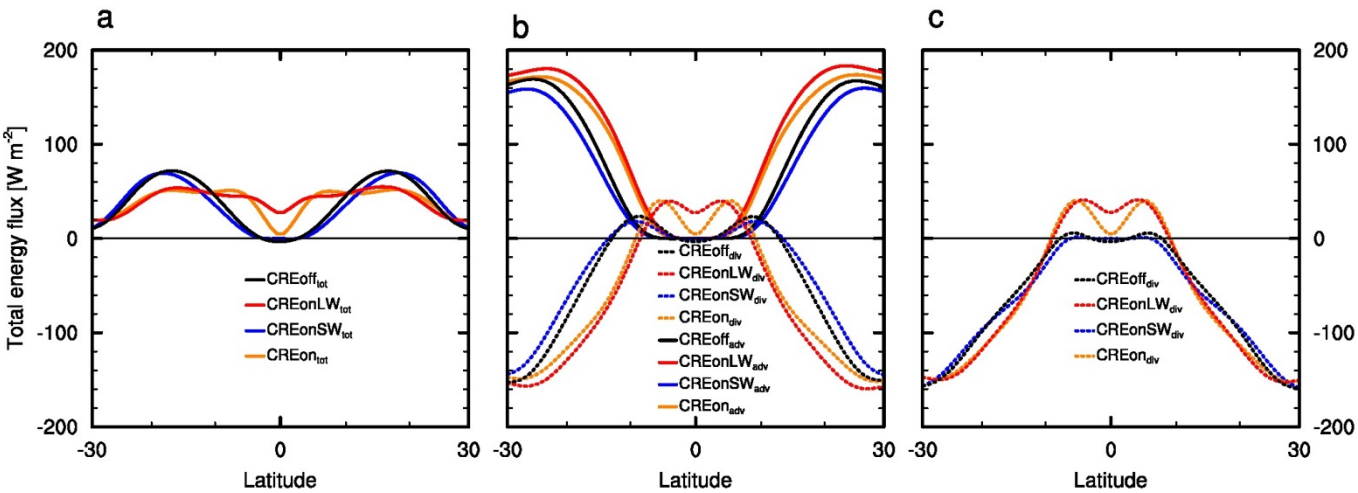

Fig. 1: Panel a) shows the implied energy uptake by the atmosphere obtained by dividing the vertically integrated zonal-mean wind by an analytical fit for the gross-moist stability. Panel b) shows the divergence (dotted) and the advective (solid) terms of the energy transport necessary to balance the atmospheric energy uptake. Panel c) shows the implied divergence term obtained when we subtract the advective term of the experiment with the CRE turned on (CREon) from the implied energy uptake shown in panel a) for all four experiments. The other three experiments are: Only the longwave CRE is turned on (CREonLW), only the shortwave CRE is turned on (CREonSW) and both CREs turned off (CREoff). The implied energy divergence then moves to the same location, implying that it is the change in energy advection which leads to the different positions of the ITCZ in the different experiments.

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)

Other Participating Researchers: Fabien Paulot (Princeton), 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 the mechanisms associated with dust activities in the United States and the connection between the Pacific decadal oscillation (PDO) and Syrian dust activities in spring

Methods and Results/Accomplishments:

The 2015 severe dust storm in Syria raised concerns as whether dust activities will increase in the region. First step toward answering this question is to understand the dust activities driven by the natural climate variability. We used dust optical depth (DOD) data derived from MODIS Deep Blue aerosol products, reanalysis datasets, and GFDL AM3 model output to examine the connection between springtime dust event frequency in Syria and a remote forcing, the PDO. The significant negative connection between the two is largely due to the influences of the PDO on i) the circulation pattern favorable to dust emission and transport and ii) on precipitation over the dust source regions in the Arabian Peninsula.

Climate models projected rising drought risks over the southwestern and central U.S. in the 21st century due to increasing greenhouse gases. However, whether dust activity in U.S. will increase in these drying regions in the future is not clear due to large uncertainties of dust modeling. Using satellite observation and multi-model output we project that under the Representative Concentration Pathways 8.5 scenario dust activity will increase in the southern Great Plains from spring to fall in the late half of the 21st century but will decrease in the northern Great Plains in spring.

Outreach Activities: Volunteer for the 11th annual science fair at Monmouth Junction Elementary School (grades K through 5) on 03/18/17.

Publications:

Pu, B., and P. Ginoux, 2017: Dustier United States in the late 21st century? Submitted to Sci. Rep., under review.

Pu, B., and P. Ginoux, 2016: The impact of the Pacific Decadal Oscillation on springtime dust activity in Syria. Atmos. Chem. Phys., 16, 13431-13448, doi:10.5194/acp-16-13431-2016.

Presentations:

Pu, B., and P. Ginoux, 2017: Will drought intensify dust activities in the United States? The 97th American Meteorological Society (AMS) Annual Meeting, Seattle, WA.

Pu, B., and P. Ginoux, 2016: The impact of the Pacific Decadal Oscillation on springtime dust activity in Syria, the American Geophysical Union (AGU) Fall Meeting, San Francisco, CA.

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)

Other Participating Researchers: Yan Xue (NCEP), Arun Kumar (NCEP)

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 2 we expanded our diagnostics that were developed in year 1 to analyze the sources of the equatorial Pacific cold tongue bias in GFDL-FLOR. We analyzed the monthly and daily mixed layer heat budget, and compared our results to available atmospheric and oceanic observations and reanalyses. We examined the budgets of two adjacent vertical layers: (1) a surface mixed layer, whose temperature is highly correlated with SST, and for which the air-sea heat flux is largely balanced by submonthly-scale advection and vertical diffusion of heat across the mixed layer base, and (2) an underlying advective-diffusive layer, in which advection by monthly-scale currents nearly balances the submonthly advective and diffusive fluxes received from the surface mixed layer. Together these two layers comprise a thicker advective layer, for which the net surface heat flux is mainly balanced by monthly-scale advective fluxes, with internal redistribution of heat by submonthly advection and diffusion. We find that for all three layers, the annual-mean heat budget is well approximated by the corresponding budget for a stationary (but spatially-varying) layer with the same time-mean depth. This greatly simplifies the analysis, and also expands its applicability to other models and observations, by eliminating the need to consider entrainment terms arising from changing layer thicknesses.

We find that below the surface mixed layer at the equator, GFDL-FLOR shows an excessive monthly-scale advective cooling, which is balanced by excessive downward diffusion of heat from the surface mixed layer. In the surface layer, the excessive cooling from downward diffusion is aided by insufficient equatorward heat transport from submonthly Tropical Instability Waves (TIWs) between 2°N-5°N. The TIWs are severely underestimated in GFDL-FLOR, and are not improved even when flux-adjusting the surface climatology toward observations. Analysis of a coupled model (CM2.6) with much higher horizontal ocean resolution shows that it simulates much stronger and more realistic TIWs, and has

a reduced equatorial Pacific cold bias. These results are described in a manuscript that will be submitted to *J. Climate* in April.

Our present foci are (1) further understanding the TIW heat budget and interannual variability, including the role of TIWs in vertical mixing, meridional heat transport, and biases in ocean reanalyses; (2) applying the heat budget analysis to understanding the warm SST bias near the coast of Ecuador and Peru, a common bias in many coupled GCMs; and (3) comparing the equatorial Pacific heat budgets among different GFDL coupled models with different ocean model formulations, including FLOR, LOAR2, and CM2.6. We aim to address these topics and finalize the publication of the above J. Climate article, before Dr. Ray's dedicated NOAA/CPO funding is exhausted on 31 August 2017.

References:

Kim, Seung-Bum, Tong Lee, and Ichiro Fukumori (2007): Mechanisms controlling the interannual variation of mixed layer temperature averaged over the Niño-3 region. J.Clim., 20 (15), 3822-3843.

Publications:

Ray, S., A.T. Wittenberg, S. Griffies, F, Zeng (in prep): Understanding the equatorial Pacific cold tongue through and oceanic mixed layer heat budget in a coupled GCM. to be submitted to J.Clim.

Presentations:

Ray, S., and A.T. Wittenberg, 2017: Heat budget of the equatorial cold tongue in GFDL FLOR global coupled model, AMS Annual Meeting, January, 2017, Seattle, 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.

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 Diagnostics Workshop. October, 2015, Denver, USA.

Progress Report Title: **Langmuir Turbulence and its Impact on the Coupled Climate System**

Principal Investigator: Brandon Reichl (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Stephen Griffies (GFDL), Alistair Adcroft (Princeton), Robert Hallberg (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 (30%)
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts (70%)

Objectives: Improve the parameterization of upper-ocean mixing including the impact of surface gravity waves for use in GFDL's MOM6 ocean model; Understand the importance and variability of the wave-driven component of vertical mixing (Langmuir turbulence) in climate simulations

Methods and Results/Accomplishments:

My research focuses on understanding and parameterizing processes related to surface ocean waves and air-sea interaction. One specific surface wave related phenomenon with important implications for climate simulations is Langmuir turbulence (a mechanism by which waves enhance upper ocean vertical mixing). Previous studies have suggested that a sea-state (wave conditions) dependent Langmuir turbulence parameterization can reduce well-documented biases in global ocean simulations (see Fan and Griffies, 2014; Li et al., 2016). With that in mind, I have focused on developing and implementing a Langmuir turbulence parameterization for use in GFDL's MOM6 ocean model. This parameterization will be useful to investigate the contribution of Langmuir turbulence and the role of surface gravity waves in the Earth's climate system.

Within GFDL's MOM6 ocean model, the standard upper ocean mixing parameterization is the energetic Planetary Boundary Layer model (ePBL, based on an early description by Hallberg, 2003). Prior to implementing a Langmuir turbulence parameterization in ePBL, we needed to analyze and refine the parameterization of several of the non-wave processes within ePBL. This was done using more complex (but computationally demanding) methods including two-equation turbulence closure and high resolution Large Eddy Simulations. The developments to ePBL from this work have been incorporated into the operational version of MOM6, resulting in improved sea-surface temperature biases in coupled climate simulations.

To investigate my primary objective (the role of Langmuir turbulence), a parameterization of such processes must be developed within the ePBL framework. Therefore, I have devoted considerable effort toward understanding how to include these processes in the model in a physically accurate and computationally efficient manner. Recently we have determined which relevant ocean surface boundary layer parameters are important for controlling the contribution of Langmuir turbulence. Based on this result, we have developed a skillful parameterization to use in the model. The implementation and evaluation of this parameterization is now underway in the GFDL modeling systems. An additional component of this work includes collaboration with NOAA/NCEP (National Center for Environmental Prediction) to make modifications to their WAVEWATCH-III surface wave model to provide the

necessary wave parameters needed by MOM6. In collaboration with NCEP scientists we will be developing the modeling tools needed to advance our capabilities for these coupled atmosphere-wave-ocean experiments.

References:

Fan, Y., and S. M. Griffies, June 2014: Impacts of parameterized Langmuir turbulence and non-breaking wave mixing in global climate simulations. Journal of Climate, 27(12), doi:10.1175/JCLI-D-13-00583.1

Hallberg, R.W., 2003: The suitability of large-scale ocean models for adapting parameterizations of boundary mixing and a description of a refined bulk mixed layer model. In: Miller, P., Garrett, C. (Eds.), Near-Boundary Processes and Their Parameterization. Proceedings of the 13th Aha Huliko'a Hawaiian Winter Workshop. University of Hawaii at Manoa, 187–203.

Li, Q., A. Webb, B. Fox-Kemper, A. Craig, G. Danabasoglu, W. G. Large, and M. Vertenstein, 2016: Langmuir mixing effects on global climate: WAVEWATCH III in CESM. Ocean Modell., 103, 145–160, doi:10.1016/j.ocemod.2015.07.020.

Publications:

Reichl, B.G. and R. Hallberg, in prep: The Energetic Planetary Boundary Layer: An Energetically Constrained Parameterization of Shear and Buoyancy Driven Turbulent Mixing for the Ocean Surface Boundary Layer.

Presentations:

Reichl, B. G., S. Griffies, A. Adcroft, R. Hallberg: Addition of Langmuir Turbulence in a Hierarchy of Vertical Mixing Parameterizations for Ocean Climate Modeling (poster). 20th Amer. Meteor. Soc. Conf. on Air-Sea Interaction, Aug 2016.

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), Frederic Castruccio (NCAR), Stephen Yeager (NCAR), Gokhan Danabasoglu (NCAR)

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 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/Accomplishments:

During my postdoctoral research at GFDL, I used a suite of climate models to investigate: 1) The climate impacts of the Atlantic Multidecadal Variability (AMV) and their associated predictability, and 2) The physical mechanisms driving the AMV. To answer the first question, I set-up an experimental protocol which allows to explore the teleconnections of the observed AMV using coupled models. Within this protocol, the model North Atlantic sea surface temperatures are restored to anomalies corresponding to the observed AMV. This protocol has been adopted by the Decadal Climate Predictability Panel (DCPP) of CMIP6 and it will be used for internationally coordinated experiments. The outputs of the experiments I performed at GFDL have led to the writing of three articles.

The first article focuses on the global impacts of the AMV (Ruprich-Robert et al. 2016). In this study we show that the AMV alters the Walker Circulation and generates precipitation anomalies over the whole tropical belt and modulates by a factor of about 2 the frequency of occurrence of El Niño/La Niña events. This response is associated with anomalies over the Pacific that project onto the Interdecadal Pacific Oscillation pattern. Over continents, we show that a warm phase of the AMV yields reduced precipitation over western US, drier conditions over the Mediterranean basin, and wetter conditions over Northern Europe. The second study focuses on the Arctic sea-ice extent (Castruccio et al. 2017), which has declined sharply over the satellite era. While almost all climate model historical simulations reproduce a decline, few simulations show trends matching the observations, suggesting a strong role for natural variability. Our experiments indicate that AMV can drive low-frequency Arctic sea ice fluctuations through atmospheric teleconnections. The third study concentrates on the impacts of the AMV on the occurrence of North American heat waves (Ruprich-Robert et al. 2017a). It shows that the AMV modulates by about 30% the occurrence of heat waves over North Mexico and the South-West of USA, with more heat waves during a warm phase of the AMV.

I am currently working on the importance of the mean model biases in the representation of the AMV climate impacts. Using the FLOR model (Vecchi et al. 2014), we show that the decrease of the mean sea surface temperature biases leads to a strong increase of the AMV climate impacts, both in terms

of mean response and in terms of extreme weathers (such as heat waves and tropical cyclones). This study will be submitted to Geophysical Research Letters in the next few months (Ruprich-Robert et al. 2017b). I am also working on the Atlantic Meridional Overturning Circulation response to different atmospheric forcings and on the predictability of associated with this response.

References:

Vecchi, G. A., and Coauthors, 2014: On the Seasonal Forecasting of Regional Tropical Cyclone Activity. J. Clim., 27, 7994–8016, doi:10.1175/JCLI-D-14-00158.1.

Publications:

Ruprich-Robert, Y., R. Msadek, F. Castruccio, S. Yeager, T. Delworth, and G. Danabasoglu, 2016: Assessing the Climate impacts of the observed Atlantic Mulitdecadal Variability using the GFDL CM2.1 and NCAR CESM1 Global Coupled Models. J. Clim., JCLI – D – 16–0127.1, doi:10.1175/JCLI-D-16-0127.1. http://journals.ametsoc.org/doi/10.1175/JCLI-D-16-0127.1.

Castruccio, F., Y. Ruprich-Robert, S. Yeager, G. Danabasoglu, R. Msadek, and T. Delworth, 2017: Modulation of Arctic Sea Ice Loss by Atmospheric Teleconnections from Atlantic Multi-decadal Variability. Submitted to Geophysical Research Letters.

Ruprich-Robert, Y., T. Delworth, R. Msadek, F. Castruccio, S. Yeager, and G. Danabasoglu, 2017a: Impacts of the Atlantic Multidecadal Variability on North American Heat Waves. Submitted to Journal of Climate.

Ruprich-Robert Y., T. Delworth, and R. Msadek, 2017b: Assessing the Atlantic Multidecadal Variability impacts on weather extremes using coupled Global Climate Models: sensitivity to the mean state biases. To be submitted to Geophysical Research Letters.

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) Impacts of the Atlantic Multidecadal Variability on North American Heat Waves, CLIVAR open conference 2016, September 2016, Qingdao (China).

Ruprich-Robert Y., Msadek R., Castruccio F., Delworth T., Yeager S., Danabasoglu G. (poster) Impacts of the Atlantic Multidecadal Variability on the North Pacific, WCRP Hierarchy Workshop 2016, November 2016, Princeton (NJ).

Ruprich-Robert Y., Msadek R., Castruccio F., Delworth T., Yeager S., Danabasoglu G. (talk) Impacts of the Atlantic Multidecadal Variability on the North Pacific, NOAA Climate Variability and Predictability Webinar, November 2016, USA.

Ruprich-Robert Y., Msadek R., Castruccio F., Delworth T., Yeager S., Danabasoglu G. (poster) Impacts of the Atlantic Multidecadal Variability on the North Pacific, EGU 2017, April 2017, Vienna (Austria).

Ruprich-Robert Y., Msadek R., Delworth T., Castruccio F., Yeager S., Danabasoglu G. (talk) Impacts of the Atlantic Multidecadal Variability on North American Heat Waves, EGU 2017, April 2017, Vienna (Austria).

Progress Report Title: **Exploring the Relationship of Extremes in Surface Ozone, Particulate Matter, and Heat Waves to Meteorology in a Global Chemistry-Climate Model**

Principal Investigator: Jordan Schnell (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Vaishali Naik (GFDL) Larry Horowitz (GFDL)

Other Participating Researchers: Michael Prather (UC Irvine)

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

Objectives: Develop observational datasets of surface ozone and particulate matter over vulnerable areas (e.g., United States, Europe, India, China) to evaluate the performance of the new-generation GFDL Atmospheric Model version 4 (AM4); use the AM4 to explore the mechanisms responsible for the development and persistence of the worst pollution episodes on a global scale

Methods and Results/Accomplishments:

The beginning of my time at Princeton was spent revising a manuscript to be published in the Proceedings of the National Academy of Sciences (Schnell and Prather, 2017). This work investigated the co-occurrence of summertime extremes in surface ozone, particulate matter, and heat waves over eastern North America. I then developed an observational dataset of fine particulate matter ($PM_{2.5}$) over Northern India. I have run two 35-year simulations with the AM4 that are nudged to observed meteorology and use different emission datasets in order to evaluate the performance of the AM4 in simulating wintertime $PM_{2.5}$ over India and to document the results for two different emission inventories. I am currently writing a manuscript that shows that the AM4 has skill in simulating observed wintertime $PM_{2.5}$ over India and its relationship to meteorology, and that the newest emission inventory substantially improves the performance of the AM4.

I am also developing similar datasets of observations of surface ozone and $PM_{2.5}$ over Europe, western North America, and China. These datasets will be used to (1) evaluate the skill of the AM4 to simulate surface ozone and $PM_{2.5}$ over these regions (2) expand upon the methods employed in Schnell and Prather, (2017) by documenting the co-occurrence of summertime air pollution episodes and heat waves in regions beyond eastern North America; (3) explore the meteorological drivers of (2) as well as the drivers of wintertime $PM_{2.5}$ episodes; and (4) use the AM4 simulations discussed above to see if these drivers have changed in the recent past in order to provide insight into how they may change under future climate warming.

Outreach Activities: Participated as a judge for 11th annual Monmouth Junction Elementary School Science Fair in South Brunswick, NJ on March 18, 2017.

Publications:

Schnell, J. L., and M. J. Prather (2017), Co-occurrence of extremes in surface ozone, particulate matter, and temperature over Eastern North America, Proc. Natl. Acad. Sci., 114 (11), doi:10.1073/pnas.1614453114.

Ordóñez, C., D. Barriopedro, R. García-Herrera, P. M. Sousa, and J. L. Schnell (2017), Regional responses of surface ozone in Europe to the location of high-latitude blocks and subtropical ridges, Atmos. Chem. Phys., 17, 3111-3131, doi:10.5194/acp-17-3111-2017.

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), Gustavo Marques (Princeton), Alon Stern (Princeton), Michael Wolowick (Princeton)

Other Participating Researchers: Jason Amundson (University of Alaska), Jeremy Bassis (University of Michigan), Peter Bromirski (Scripps Oceanographic Institution), David Pollard (Penn State), Leigh Stearns (Kansas 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:

Ice sheets interact with surrounding oceans in a number of different ways. One of them is via energy and mass exchange at the ice-shelf base and ice-shelf front. Melting of ice shelves change ocean circulation and water masses in their vicinity by releasing fresh water. Investigations of the ice-shelf/ocean interactions have been done in collaboration with A. Adcroft, R. Hallberg, M. Harrison and G. Marques using a GFDL sea-ice/ocean model MOM6–SIS2. The results of these investigations demonstrate that atmospheric conditions (winds) and ocean bathymetry have strong controls on coupled ice-shelf/ocean interactions. The results also show that sea ice is an integral component of the ocean-cryospheric system, and plays an important role in determining the state of the ocean (hydrography, circulation patterns, polynyas, etc.).

Another aspect of ice/ocean interactions is iceberg calving and consequent evolution of icebergs and their effects on oceans. In collaboration with J. Amundson, J. Bassis, D. Pollard and L. Stearns, new various formulations of calving processes have been considered. Testing of these formulations in large-scale ice-sheet models demonstrate strong effects of the calving formulations on the model behavior. Once calved, icebergs drift away releasing freshwater as they melt. The effects of icebergs size on the Southern Ocean state have been investigated in collaboration with A. Adcroft and A. Stern. Representation of icebergs as Lagrangian particles has been developed to include into a GFDL climate model CM2.1. Simulations of this model show that iceberg size distribution has strong effects on water masses and sea ice formation in the Southern Ocean. Representation of large tabular icebergs in the global ocean model is being developed.

In collaboration with P. Bromirski, the effects of ocean waves on the Ross Ice Shelf have been investigated using numerical models and observations. Analysis of observations collected by an array of

passive seismometers deployed on the Ross Ice Shelf shows that long ocean waves can excite flexural gravity waves propagating through the ice-shelf/sub-ice-shelf cavity system. Numerical simulations of a three-dimensional ice-shelf/sub-ice-shelf cavity model applied to the Ross Ice Shelf geometry show that higher frequency long-period waves result in larger flexural deformational stresses compared to longer waves. The simulation results also show that the geometry of the cavity exhibits dominant control on propagation of the flexural gravity waves through the system.

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

Publications:

Stern, A. A., A. Adcroft, and O. Sergienko (2016), The effects of Antarctic iceberg calving-size distribution in a global climate model, J. Geophys. Res. Oceans, 121, 5773– 5788, doi:10.1002/2016JC011835.

Hiester, J., O. V. Sergienko, and C. L. Hulbe (2016), Topographically mediated ice stream subglacial drainage networks, J. Geophys. Res. Earth Surf., 121, doi:10.1002/2015JF003660

Presentations:

Sergienko O., A. Adcroft, J. Amundson, J. Bassis, R. Hallberg, D. Pollard , L. Stearns and A. Stern (2016) Climate Process Team "Representing calving and iceberg dynamics in global climate models". AGU Fall Meeting, San Francisco, CA 12-16 December, 2016.

Haseloff M. and O. Sergienko (2016) The ice flux at the grounding line in flowline models with parameterized buttressing: asymptotic solutions and implications for marine ice sheet stability. AGU Fall Meeting, San Francisco, CA 12-16 December, 2016.

Wolowick M. and O. Sergienko (2016). Geoengineering Glacial Fjords. AGU Fall Meeting, San Francisco, CA 12-16 December, 2016.

Haseloff M. and O. Sergienko The effect of ice shelves on the ice flux at the grounding line and implications for marine ice sheet stability. WAIS Workshop, Algonkian Regional Park, Sterling, VA, 3-6 October, 2016.

Sergienko O. The effects of basal topography on subglacial water flow. WAIS Workshop, Algonkian Regional Park, Sterling, VA, 3-6 October, 2016.

Wolowick M. and O. Sergienko. Geoengineering Ice Streams with Artificial Sills. WAIS Workshop, Algonkian Regional Park, Sterling, VA, 3-6 October, 2016.

Haseloff M. and O. Sergienko. The effects of ice shelves on grounding line stability. IGS Symposium on Interactions of Glaciers and Ice Sheets with the Ocean. La Jolla, CA, 10-15 July, 2016.

Stern A., A. Adcroft and O. Sergienko. The effect of calving size distribution on melt patterns and sea-ice formation around Antarctica. IGS Symposium on Interactions of Glaciers and Ice Sheets with the Ocean. La Jolla, CA, 10-15 July, 2016.

Sergienko O. V. The effects of the flexural gravity waves on stress regime of the Ross Ice Shelf IGS Symposium on Interactions of Glaciers and Ice Sheets with the Ocean. La Jolla, CA, 10-15 July, 2016.

Sergienko O., M. Harrison, R. Hallberg and A. Adcroft (2016). Strong coupling among Antarctic ice shelves, ocean circulation and sea ice in a global sea-ice - ocean circulation model. EGU General Assembly 2016, Vienna, Austria, 17-22, April, 2016.

Progress Report Title: **Improvements to Passive Tracer Capabilities in MOM6**

Principal Investigator: Andrew Shao (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Robert Hallberg (GFDL), Alistair Adcroft (Princeton), Stephen Griffies (GFDL), John Dunne (GFDL), Michael Winton (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: Develop framework to simulate passive tracers offline to leverage computational resources; Enhance passive tracer capabilities in the GFDL ocean model (MOM6) and the sea-ice model (SIS2)

Methods and Results/Accomplishments:

My work has been split equally between the two objectives listed above. The development of the offline tracer framework for the GFDL Modular Ocean Model version 6 (MOM6) is ongoing. This effort differs from previous efforts in that it is intended to work in a general coordinate framework arbitrary Lagrangian-Eulerian regridding and remapping scheme. Proof of concept test cases in both small and global test cases using hybrid and geopotential vertical coordinates have shown that the current approach is viable and can be up to 20 times more efficient than online tracer modeling. Initial testing with the GFDL ocean biogeochemistry model, done with Dr. Dunne, shows significant biases between online and offline cases for technical reasons, which are currently being worked on. Additionally, I am also exploring the possibility of remapping the fields necessary to drive tracer transport so that tracers can be run offline in a different vertical coordinate than the original model. The completion of these activities will help investigators understand how biogeochemistry changes of 21st projections of climate change as well as allow for targeted tracer-based studies in specific regions.

The treatment of passive tracers in MOM6 and SIS2 has been the other focus of my time thus far. I am currently in the process of improving the numerical implementation of neutral diffusion and will be performing idealized test cases to demonstrate the efficacy of the method which will lead to a publication with Drs. Adcroft, Hallberg, and Griffies. With regard to SIS2, I implemented a capability for passive tracers to be carried along with the sea-ice. As part of this, the included sea-ice age package is intended to be a template for the development of additional tracer packages like ice biogeochemistry. An initial comparison of modeled ice-age in a hindcast configuration of the ice-ocean simulation yields favorable comparisons to observationally inferred ice-age.

Publications:

Shao, A. E., S. Mecking, L.A. Thompson, and R. E. Sonnerup (2016), Evaluating the use of 1-D transit time distributions to infer the mean state and variability of oceanic ventilation, J. Geophys. Res. Oceans, 121, doi:10.1002/2016JC011900.

Presentations:

Shao, A. E., Oral presentation: Canadian Meteorological and Oceanographic Society (2016), Attenuation of surface variability by oceanic ventilation.

Progress Report Title: **The Influence of Aerosol Absorption on the Extratropical Circulation**

Principal Investigator: Zhaoyi Shen (Princeton Graduate Student)

CICS/GFDL Collaborator: Yi Ming (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: Study the effect of absorbing aerosols on the general circulation and its mechanisms

Methods and Results/Accomplishments:

This study examines how aerosol absorption affects the extratropical circulation by analyzing the response to a globally uniform increase in black carbon (BC) in an atmospheric general circulation model. BC-induced heating in the free troposphere stabilizes the mid-latitude atmospheric column and weakens the meridional temperature gradient on the equatorward flank of the tropospheric jet. This results in a decrease in the Eady growth rate, and thus less energetic baroclinic eddies which reduce meridional energy transport at mid-latitudes. Upper troposphere BC also weakens the tropospheric jet and yields a poleward jet displacement. The effectiveness of BC in altering the general circulation increases with height. Boundary layer BC has no significant influence on the large-scale circulation since most of the heating is diffused by turbulence in the boundary layer.

Dry baroclinic eddy theories can explain most of the extratropical response to free troposphere BC. Specifically, the decrease in vertical eddy heat flux related to a more stable atmosphere is the main mechanism for reestablishing atmospheric energy balance in the presence of BC-induced heating. Similar temperature response to global uniform heating is found in a dry idealized model, which further proves the dominant role of baroclinic eddies in driving changes in atmospheric circulation at mid-latitudes. The strong atmospheric-only response to BC suggests that absorbing aerosols are capable of altering weather patterns. The height dependence of BC-climate interactions highlights the importance of better constraining model-simulated aerosol vertical distributions with satellite and field measurements.

Publications:

Shen, Z., Y. Ming, L.W. Horowitz, V. Ramaswamy, and M. Lin (in press): On the seasonality of Arctic black carbon. J. Climate, doi: 10.1175/JCLI-D-16-0580.1.

Presentations:

Shen, Z., “The influence of aerosol absorption on the extratropical circulation”. Poster. AGU 2016 Fall Meeting, San Francisco, CA. (12/2016).

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

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

CICS/GFDL Collaborator: Ming Zhao (GFDL), David Paynter (GFDL), Huan Guo (UCAR), Rick Hemler (GFDL), Max Popp (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: The research I am working on seeks a better understanding of the role played by clouds in the Earth system. Despite our broad recognition of the connection between lower atmospheric stability and cloud cover, it is unclear what drives the inter-model spread of changes in the lower atmospheric stability. This is a pressing issue because of the tight coupling between the lower atmospheric stability and cloud responses to perturbations. My goal is to identify and improve the physical processes in the GFDL atmospheric model that drives variability in the cloud feedback.

Methods and Results/Projects:

Overview: One of the prominent ways in which clouds impact the Earth system is through their interaction with radiation. My research looks at the connection between the Earth's surface, the physical processes which impacting cloud evolution, and the radiative fluxes at the top of the atmosphere.

AMIP-piForcing: AMIP-piForcing (or 'long-AMIP') experiment is an atmospheric simulation with fixed pre-industrial forcing with observed SST and sea-ice patterns from 1870-present (Gregory and Andrews, 2016, Zhou et al. 2016). Using this framework I am analyzing simulations with AM2.1, AM3, and am4g10r8 to compare and contrast the relationship between the lower atmospheric stability, cloud feedback, and the global mean feedback-parameter (Silvers et al. 2017). My recent work has utilized several diagnostic tools and methods of analysis encompassed within the context of CFMIP that will provide a foundation that the third-year research will build on (Silvers et al. 2016, Popp and Silvers, 2017).

Cess-Sensitivity and SST patterns: Currently I am analyzing and writing up results of SST pattern based experiments with a prototype version of the GFDL atmospheric model. We show that SST patterns with approximately the same global mean lead to varying -of-the-atmosphere responses in radiative fluxes. Our patterns are derived from simulations with SSTs obtained from coupled runs of an abrupt 4xCO2 increase, and a 1% increase of CO2 per year until doubling. This has important implications for how climate model development and tuning at GFDL are conducted.

Estimated Inversion Strength in millennia-length simulations: Through the internal review process and subsequent discussion for Paynter et al. 2017, additional analysis of the original experiments has been performed. This has resulted in a revised manuscript that includes analysis of the connection between the estimated inversion strength and the global feedback.

Over the next year I will be working extensively with the experiments that have been chosen as part of the CMIP6/CFMIP project. These experiments are ideally suited to assist us in further development and improvement of the GFDL models as well as move the institute closer to realizing its research goals.

The following are some preliminary steps that have been completed: Modification of the latest prototype GFDL atmospheric model (am4XX) to allow for APE experiments; continued work to use and improve the necessary diagnostics for the upcoming CFMIP6 series of experiments as part of CMIP6, in particular making the COSP diagnostic package available for use at GFDL (Bodas-Salcedo et al. 2011); and participation in a collaboration with Dr. Timothy Andrews to include GFDL models in a CFMIP pilot study that will explore a multi-model analysis of the amip-piForcing experiment. This is anticipated to be completed in 2017.

Invited talks included 2017, COSP Workshop, Paris, France; 2017, Seminar, Stony Brook University School of Marine and Atmospheric Science, Stony Brook, NY; 2016, Colloquium, Courant Institute of Mathematical Sciences, Center for Atmosphere Ocean Science, New York University, New York, NY; and 2016, Science Workshop Seminar, Bennington College, Bennington, VT.

References:

Gregory J.M., and T. Andrews, 2016: Variation in climate sensitivity and feedback parameters during the historical period. Geophys. Res. Lett., 43, 3911-3920.

Paynter D., T. Frolicher, L. Horowitz, and L. G. Silvers, 2017: Why does IPCC-AR5 underestimate the Equilibrium Temperature of two GFDL GCMs?, internal review, to be submitted to Geophys. Res. Lett.

Popp M. T., and L. G. Silvers, 2017, Double and single ITCZs with and without clouds. Submitted to J. Climate.

Silvers L. G., D. Paynter, M. Zhao, 2017: Decadal variations of cloud feedback in long-AMIP experiments with three GFDL climate models. In Preparation.

Zhou C., M. D. Zelinka, and S. A. Klein, 2016: Impact of decadal cloud variations on the Earth's energy budget. Nat. Geosci., 9, 871-8.

Outreach Activities: Internal Review: Paynter et al. 2017: Why does IPCC-AR5 underestimate the Equilibrium Temperature of two GFDL GCMs?; Internal Review: Schmidt et al. 2017: Practice and philosophy of climate model tuning across six U.S. modeling centers; Organizer of the GFDL Climate Sensitivity Journal Club (with Max Popp); Member of the GFDL Poster Expo team

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. J. Adv. Model. Earth Syst., 8, doi:10.1002/2016MS000629.

Popp M. and L.G. Silvers, 2016: Double and single ITCZs with and without clouds. submitted to Journal of Climate.

Paynter, D., T. Frolicher, L. Horowitz, and L.G. Silvers, 2017: Why does IPCC-AR5 underestimate the Equilibrium Temperature of two GFDL GCMs? In revision, to be submitted to Geoph. Res. Lett.

Silvers, L.G., D. Paynter, and M. Zhao, 2017: Decadal variations of cloud feedback in long-AMIP experiments with three GFDL climate models. To be submitted to Geoph. Res. Lett.

Presentations:

Silvers, L.G., D. Paynter, and M. Zhao: Variability of the climate feedback parameter in AM2.1, AM3, and AM4g10r8. GFDL Lunchtime Seminar, February 8th, 2017.

Silvers, L.G. and M. Zhao: Sea Surface Temperature Patterns and Cloud Feedbacks in an Atmospheric General Circulation Model. CFMIP/WCRP Conference on Cloud Processes, Circulation and Climate Sensitivity, International Centre for Theoretical Physics, Trieste, Italy, July, 2016.

Silvers, L.G. and M. Popp: Cloud Radiative Effects on Single and Double ITCZs. CFMIP/WCRP Conference on Cloud Processes, Circulation and Climate Sensitivity, International Centre for Theoretical Physics, Trieste, Italy, July, 2016.

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 Collaborators: Elena Shevliakova (GFDL), Sergey Malyshev (Princeton), Minjin Lee (Princeton)

Other Participating Researchers: Edward Brzostek (West Virginia University), Richard Phillips (Indiana University), Kim Novick (Indiana University), Duncan Menge (Columbia University), Asmeret Asefaw Berhe (UC Merced), Will Wieder (University of Colorado), Alejandro Salazar (Purdue University), Jessica Moore (University of New Hampshire)

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 impacts and feedbacks by implementing and testing new biological mechanisms in the GFDL land model.

Methods and Results/Accomplishments:

The role of nitrogen (N) limitation in determining carbon (C) uptake by vegetation under rising atmospheric CO_2 concentrations is a critical uncertainty in ESM simulations (Wieder et al, 2015). My primary research focus over the past year has been implementing a new, process-based model of vegetation and soil N cycling within the GFDL land model. This new representation couples plant N demand to C allocation and N uptake through different strategies that include fixation of atmospheric N, uptake of inorganic N from soil, and acceleration of soil organic matter decomposition in order to extract organic N. Recent studies have shown that these feedbacks have important implications for plant growth under elevated CO_2 (Terrer et al, 2016). The model also includes atmospheric N deposition, gaseous N losses through denitrification, and leaching of dissolved N into rivers. We parameterized and tested the new N cycling model by comparing it to ecosystem-scale elevated CO_2 experiments, and the model successfully explained contrasting responses observed at sites with different N acquisition strategies. In preliminary global simulations, the model is successfully reproducing the observed magnitudes and spatial patterns of soil and vegetation N cycling across the globe.

In addition to N cycle model development, I contributed to two papers analyzing the relative roles of atmospheric water vapor demand and soil moisture in limiting photosynthesis and transpiration at the ecosystem scale (Sulman et al, 2016; Novick et al, 2016). The results of these papers are contributing to development and parameterization of new plant hydraulics processes in the model being conducted by GFDL collaborator Elena Shevliakova and other collaborators. I also participated in two model comparison projects focusing on process-based soil C cycle models that explicitly simulate the role of micro-organisms in decomposition. One project, with collaborator Will Wieder, included three models (including the CORPSE model (Sulman et al, 2014) that is implemented in the GFDL land model) in a global testbed that will be used for improving parameterization of these models. The other project, which I am coordinating along with collaborator Jessica Moore, included soil C models from five modeling

centers along with an observational meta-analysis and will help to identify key observations for constraining these models. I am also collaborating with outside researchers on developing and constraining new soil C cycle processes in the CORPSE soil model, including fire effects on soil C cycling (Asmeret Asefaw Berhe) and the role of microbial dormancy (Alejandro Salazar).

References:

Sulman, B. N., R. P. Phillips, A. C. Oishi, E. Shevliakova, and S. W. Pacala (2014), Microbe-driven turnover offsets mineral-mediated storage of soil carbon under elevated CO2, Nature Climate change, 4, 1099–1102, doi:10.1038/nclimate2436.

Terrer, C., S. Vicca, B. A. Hungate, R. P. Phillips, and I. C. Prentice (2016), Mycorrhizal association as a primary control of the CO2 fertilization effect, Science, 353(6294), 72–74, doi:10.1126/science.aaf4610.

Wieder, W. R., C. C. Cleveland, W. K. Smith, and K. Todd-Brown (2015), Future productivity and carbon storage limited by terrestrial nutrient availability, Nature Geoscience, 8(6), 441–444, doi:10.1038/ngeo2413.

Publications:

Novick, K. A. et al. (2016), The increasing importance of atmospheric demand for ecosystem water and carbon fluxes, Nature Climate change, 6, 1023–1027, doi:10.1038/nclimate3114.

Sulman, B. N., D. T. Roman, K. Yi, L. Wang, R. P. Phillips, and K. A. Novick (2016), High atmospheric demand for water can limit forest carbon uptake and transpiration as severely as dry soil, Geophys Res Lett, 43(18), 9686–9695, doi:10.1002/2016GL069416.

Presentations:

B. N. Sulman, E. Shevliakova, S. Malyshev, S. W. Pacala, R. P. Phillips, and E. Brzostek (2016). Plant nitrogen acquisition and soil microbial activity in the GFDL land model. Nutrient limitation on land: how accurate are our global land models? Yangling, Shaanxi, China.

B. N. Sulman, E. Shevliakova, S. Malyshev, S. Pacala, and R. P. Phillips (2016). Microbes, minerals, and roots: Next-generation soil carbon in the GFDL land model. Geophysical Fluid Dynamics Laboratory, USA.

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

B. N. Sulman, J. Moore, C. Averill, R. Abramoff, M. Bradford, A. Classen, M. Hartman, S. Kivlin, Y. Luo, M. Mayes, E. Morrison, B. Riley, A. Salazar, J. Schimel, B. Sridhar, J. Tang, G. Wang, and W. Wieder: Key process uncertainties in soil carbon dynamics: Comparing multiple model structures and observational meta-analysis. American Geophysical Union 2016 Fall Meeting, San Francisco, CA, Dec 2016.

Progress Report Title: **Understanding Interaction between Managed Surface Water Dynamics and Climate Change**

Principal Investigator: Marjolein van Huijgevoort (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Elena Shevliakova (GFDL), Sergey Malyshev (Princeton), Nathaniel Chaney (Princeton)

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: The main objective is to assess the anthropogenic influence on the future hydrologic cycle by 1) adding a water management parameterization to the GFDL land model, for example, irrigation, reservoirs and groundwater abstractions, 2) investigating the impact of these measures on the hydroclimate, and 3) studying the effect of climate change on water availability.

Methods and Results/Accomplishments:

Anthropogenic influence will have a noticeable impact on the future hydrologic cycle through human water management practices; these include diverting water for irrigation, abstraction of groundwater, and reservoir operations that alter the hydrological regime. Hydrologic extremes, in particular, are heavily affected by water management practices, due to the existing stress on the system during droughts and floods. Therefore, it is essential to account for water management and other human influences in Earth System Models like the GFDL land model. We have implemented irrigation and reservoir management in the current version of the land model. Irrigation demand is calculated in the model as the difference between evaporation demand and soil water supply (Figure 1). This process ensures that irrigation depends on the seasonal variability in evaporative demand of the vegetation and the soil water balance. The water needed for irrigation is abstracted from surface water first, thereafter from the groundwater. We have also added algorithms for reservoir outflow to the model and replaced lakes where applicable. This is done to enable a more accurate simulation of the river outflow in the model. The new algorithm takes into account the expected inflow and downstream water demand, as is more conform to real-life reservoir operations. Compared to the model simulations from the control run (only lakes, black line, Figure 2), the hydrological regime in regions with reservoirs changed significantly (red line, Figure 2), resulting in higher discharges in spring and summer, and lower discharges in winter.

Presentations:

Van Huijgevoort, M.H.J., Chaney, N., Malyshev, S.L., Milly, P.C.D., Shevliakova, E., 2016, Implementation of irrigation practices in a global scale land model, Presentation at Workshop Including Water Management in Large Scale Models (GEWEX and GHP), 28-30 September 2016, Gif-sur-Yvette, France.

Van Huijgevoort, M.H.J., Chaney, N., Malyshev, S.L., Milly, P.C.D., Shevliakova, E., 2016, Implementation of Water Management Practices in a Global Scale Land Modeling, AGU Fall Meeting, 12-16 December 2016, San Francisco, USA.

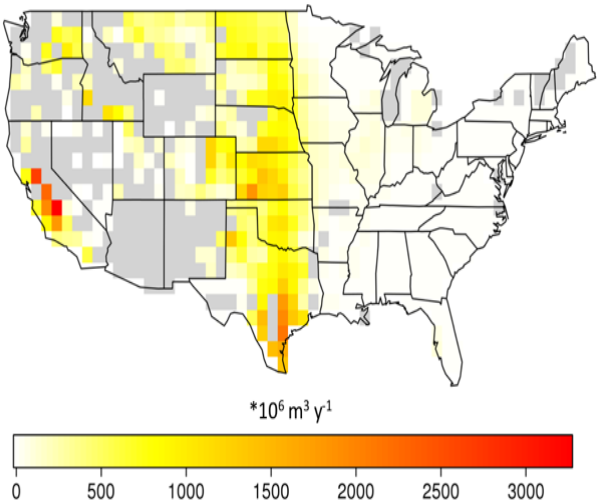

Figure 1. Simulated average yearly irrigation demand for 1960-1999.

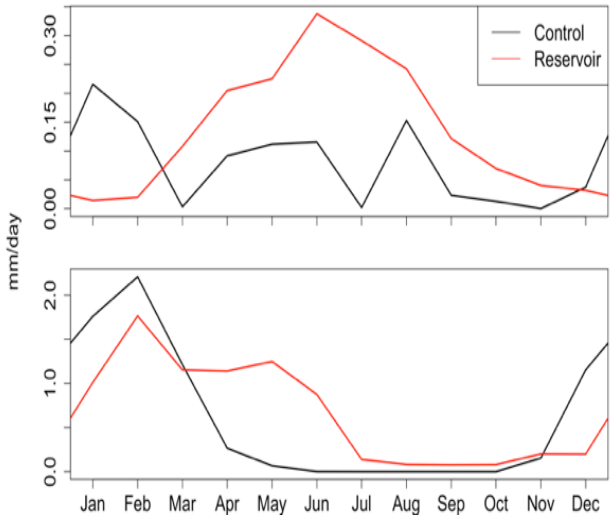

Figure 2. Change in river outflow between simulations with (red line) and without (black line) reservoirs for two example grid cells.

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 (GFDL), Sergey Malyshev (Princeton), John Dunne (GFDL)

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

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 and develop the simulation of fires and their emissions within the land-atmosphere coupled modeling system; Furthermore, to study the impacts of fire emissions 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 the Fire Including Natural and Agricultural Lands (FINAL) model and merging this model code with the latest ESM code release (verona, at the time). Using FINAL in place of the existing annual fire model represents a necessary step in producing credible predictions of fire emissions within the Earth System model. The original version of FINAL (Rabin et al., *In Prep*) was biased low with regard to fire activity in boreal regions (Rabin et al., 2016). I addressed this bias by performing optimization of tunable parameters within the fire model separately for boreal and non-boreal locations. Here, boreal is defined as exhibiting characteristics of a "cold" or "polar" Koppen climate zone (Kottek et al., 2006) and could be calculated online within LM3 to adjust to climate trends. Currently the climate zones are defined using 1950-2000 climate. The new optimization substantially reduces the boreal fire low bias while maintaining realistic global averages.

FINAL also exhibits bias with regard to interannual variability in boreal fires. Variability in fire emissions on annual timescales has been shown to be an important factor for assessing climate impacts of fires, especially in boreal regions (Grandey et al., 2016), and is under predicted by many fire models (Ward et al., 2016). I introduced multi-day burning into FINAL, replacing the original fixed 24-hour fire duration. I also added enhanced fire rate of spread for intense forest fires which can spread to the crown and burn more area at a faster rate. Combined, the multi-day and crown-fire burning allow less frequent but much larger fire events to dominate the total boreal area burned (closer to real-world behavior), and increase the interannual variability in emissions. The results of these model developments are currently in preparation for submission, together with an experiment testing the sensitivity of fire interannual variability to historical land use and climate changes using the new code.

As part of the crown fire model development, FINAL now simulates fire intensity, a measure of the energy released in a fire. The fire intensity predicted in LM3-FINAL is converted to fire radiative power

(FRP), which is both verifiable against satellite data and used to predict the height of fire injection into the atmosphere (Veira et al., 2015). I have coupled the FRP from LM3 into AM3 and use this to compute the injection height using the Sofiev et al. (2012) scheme. I compiled a climatology of FRP and injection height from the Global Fire Assimilation System satellite products for model validation. Testing of the injection height scheme and predictions of fire radiative power are ongoing.

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B. S. Grandey, Lee, H.-H., Wang, C.: Radiative effects of inter-annually varying versus inter-annually invariant aerosol emissions from fires. Atmospheric Chemistry and Physics Discussions, 1–28. http://doi.org/10.5194/acp-2016-599, 2016.

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S. S. Rabin, Melton, J. R., Lasslop, G., Bachelet, D., Forrest, M., Hantson, S., Li, F., Mangeon, S., Yue, C., Arora, V. K., Hickler, T., Kloster, S., Knorr, W., Nieradzik, L., Spessa, A., Folberth, G. A., Sheehan, T., Voulgarakis, A., Prentice, I. C., Sitch, S., Kaplan, J. O., Harrison, S., and Arneth, A.: The Fire Modeling Intercomparison Project (FireMIP), phase 1: Experimental and analytical protocols, Geoscientific Model Development Discussions, pp. 1–31, doi:10.5194/gmd-2016-237, http://www.geosci-model-dev-discuss.net/gmd-2016-237/, 2016.

M. Sofiev, Ermakova, T., Vankevich, R.: Evaluation of the smoke-injection height from wild-land fires using remote-sensing data. Atmospheric Chemistry and Physics, 12(4), 1995–2006. http://doi.org/10.5194/acp-12-1995-2012, 2012.

A. Veira, Kloster, S., Wilkenskjeld, S., Remy, S.: Fire emission heights in the climate system – Part 1: Global plume height patterns simulated by ECHAM6-HAM2. Atmospheric Chemistry and Physics Discussions, 15(5), 6645–6693. http://doi.org/10.5194/acpd-15-6645-2015, 2015.

D. S Ward, Shevliakova, E., Malyshev, S., Lamarque, J.-F., Wittenberg, A.: Variability of fire emissions on interannual to multi-decadal timescales in two Earth System models. Environ. Res. Lett., **11**, doi:10.1088/1748-9326/11/12/125008, 2016.

Publications:

N. M. Mahowald, Ward, D. S., Doney, S. C., Hess, P. G., Randerson, J. T.: The impacts of land use on warming may be underestimated in climate policy. In revision before reviews, Environ. Res. Lett.

S. K. Clark, Ward, D. S., Mahowald, N. M.: Parameterization-based uncertainty in future lightning flash density. In Press, Geophys. Res. Lett.

J. F. Kok, Ridley, D. A., Zhou, Q., Zhao, C., Miller, R. L., Heald, C. L., Ward, D. S., Albani, S., Haustein, K.: Integrative analysis of desert dust size and abundance suggests less dust climate cooling. In Press, Nature Geoscience.

N. M. Mahowald, Lindsey, K., Munoz, E., Doney, S., Lawrence, P., Schlunegger, S., Ward, D., Lawrence, D., and Hoffman, F.: Interactions between land use change and carbon cycle feedbacks. Global Biogeochem. Cy., 31, 96–113, doi:10.1002/2016GB005374, 2017.

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G. H. Kerr, DeGaetano, A. T., Stoof, C., Ward, D. S.: Climate change effects on wildland fire risk in the Northeastern and Great Lakes states predicted by a downscaled multi-model ensemble. J. Theoret. Appl. Climatol., doi:10.1007/s00704-016-1994-4, 2016.

S. N. Riddick, Ward, D. S., Hess, P., Mahowald, N., Massad, R. S., Holland, E. A.: Estimate of changes in agricultural terrestrial nitrogen pathways and ammonia emissions from 1850 to present in the Community Earth System Model, Biogeosciences, 13, 3397-3426, doi:10.5194/bg-13-3397-2016, 2016.

Progress Report Title: **Understanding Multi-Decadal Natural Climate Variability and its Potential Role in Explaining Observed Climate Changes**

Principal Investigator: Xiaoqin Yan (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Rong Zhang (GFDL), Tom 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: Understanding the physical mechanisms causing the observed multi-decadal changes including quantification of contributions from both internal climate variability and responses of the climate system to various natural and anthropogenic forcing agents (e.g., greenhouse gases, aerosols, and volcanic eruptions)

Methods and Results/Accomplishments:

During my first year at CICS/NOAA GFDL, in collaboration with Rong Zhang and Tom Knutson at GFDL, I carried on extensive numerical analyses on both observations and a large amount of model output from CMIP5 archive to understand mechanisms causing the pronounced multi-decadal variability in the observed Atlantic major hurricane frequency.

Atlantic major hurricane activity has caused substantial damage to coastal settlements and infrastructure. Two contrasting hypotheses have been proposed previously as key causes of multi-decadal variability of Atlantic hurricane frequency: i) ocean variability associated with the Atlantic Meridional Overturning Circulation (AMOC) and ii) changes in anthropogenic sulfate aerosol forcing. Using subsurface ocean observations and simulations from climate models containing aerosol indirect effects, my analysis shows that the recent decline in Atlantic major hurricane frequency is consistent with a weakening of the AMOC inferred from ocean observations, but is inconsistent with the simulated response to a recent reduction in anthropogenic aerosols. Coherent multi-decadal variations involving the inferred AMOC and Atlantic major hurricane frequency/Atlantic Multi-decadal Oscillation/wind shear since the late 1950's provide new evidence for the hypothesis of multi-decadal AMOC variability as the prime driver of Atlantic hurricane variability, rather than changes in anthropogenic aerosols. The prescribed reduction of anthropogenic sulfate aerosol emissions in CMIP5 RCP scenarios contributes to the simulated slight AMO warming trends and decreasing trends in the Hurricane Shear Index in the multi-model ensemble means, which contrast with recent observed trends. We expect that whether the Atlantic major hurricane frequency returns to above-normal condition in the next decade will be closely linked to future AMOC changes. Consequently, we propose that monitoring and predicting AMOC changes (especially at northern high latitudes) will be crucial for a predictive understanding of future Atlantic hurricane risk. My work provides a deeper understanding of the underlying mechanisms.

Publications:

Yan, X., R. Zhang, and T.R. Knutson, 2017, What Caused the Rapid Decline of Atlantic Major Hurricane Frequency over the Last Decade? Submitted to Nature Communications and currently under

revision.

Presentations:

Yan, X., Oral presentation, What Are the Best Fingerprints for Detecting Anthropogenic Aerosol Cooling? AGU Fall Meeting 2016 (within the Anthropogenic aerosol forcing: Mechanisms of regional climate variability and change session).

Progress Report Title: **Dynamics of Dense Water Formation and Transport on the Arctic Shelves**

Principal Investigator: Elizabeth Yankovsky (Princeton Graduate Student)

CICS/GFDL Collaborator: Sonya Legg (Princeton)

Other Participating Researchers: Robert Hallberg and Rong Zhang (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 first objective of my project is to study the dynamics of dense water overflows in the continental shelf regions of the Arctic Ocean through high-resolution numerical simulations. The second objective is to apply the insights gained from these studies to developing/improving parameterizations of these small-scale processes in large-scale global climate models.

Methods and Results/Accomplishments:

My current project involves studying the dynamics of dense water formation and transport in the shelf regions of the Arctic Ocean. Dense overflows on the Arctic shelves are key drivers of Arctic thermohaline circulation, which influences deep water formation and sea-ice processes. The dynamics of these overflows is a complex problem governed by the interplay of local atmospheric forcing and air-sea processes that produce the dense waters; the basin-scale processes determining stratification and guiding the descent of the overflows; and the small-scale mixing that ultimately defines the properties of the descending water. We apply the MIT General Circulation Model (MITgcm) to performing high-resolution, non-hydrostatic simulations examining evolution of dense water formed over a continental shelf region through atmospheric heat loss and brine rejection (from sea-ice formation).

Over the past year I have completed a series of idealized numerical simulations with progressively more complex/realistic model assumptions. In the two-dimensional simulations, we identified bottom friction and symmetric instabilities as the primary mechanisms responsible for transporting the dense shelf water to great depths and generating mixing. In the three-dimensional simulations, baroclinic eddies produce dense water cascades capable of ventilating both intermediate and abyssal depths of the Arctic Ocean. The buoyancy forcing parameters as well as topographic features set the properties of these baroclinic eddies, which in turn govern turbulent mixing and entrainment processes. Through high-resolution process studies we thus quantify relationships between forcing and topographic parameters, instability dynamics, and the resulting mixing processes that ultimately determine the overflow path and final water mass characteristics. The future direction of this project is to apply the insights gained from the high-resolution, nonhydrostatic MITgcm studies to testing and subsequently improving the shear mixing and mesoscale eddy kinetic energy parameterizations within the larger-scale, hydrostatic GFDL Modular Ocean Model (MOM6).

Outreach Activities: This year I developed a program titled “Motion of the Ocean” to teach children about the ocean and climate at the local Plainsboro Public Library. I became an active member of the

nonprofit New Jersey-based organization Future City aimed at educating local communities about environmental issues, working with policy-makers and government agencies, and developing environmental initiatives. This organization collaborates with the NY/NJ Harbor Estuary Program to protect the habitat of one of the most populated estuaries and metropolitan areas in the world. I attended the Trash Free Waters Meeting of the Environmental Protection Agency in New York City to discuss pollution issues facing the NY/NJ Harbor Estuary. I also participated in the annual City of Elizabeth Estuary Day where I performed lab experiments and discussed estuarine/oceanic dynamics, ocean acidification, and climate change with ten groups of students from various local schools, including those from predominantly Hispanic communities.

Progress Report Title: **Development of fvGFS, the Prototype Next Generation Global Prediction System (NGGPS)**

Principal Investigator: Linjiong Zhou (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Shian-Jiann Lin (GFDL), Lucas Harris (GFDL), Rusty Benson (GFDL), Zhi Liang (GFDL), Timothy Marchok (GFDL), Xi Chen (Princeton)

Other Participating Researchers: Jan-Huey Chen (UCAR), Shannon Rees (Engility), Matthew Morin (Engility)

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 and develop the second to none global prediction system and comprehensive verification system

Methods and Results/Accomplishments:

In July 2016, FV3 (Finite-Volume Cubed-Sphere Dynamical Core) was elected to be the dynamical core of the Next Generation Global Prediction System (NGGPS) for the next decades. The model developed at GFDL, used in the competition, is called fvGFS (a new model uses FV3 with GFS physical parameterizations). The pre-processing, model itself, post-processing, verification and demonstration assemble a complete forecast system at GFDL. In the past year, we have been engaged in the development of this forecast system, to make the forecast skill gradually improve, and to make the verification more comprehensive.

After the first version of fvGFS was delivered to DTG (Dynamical core Test Group), we occasionally found and fixed several bugs/issues. Those are related to low precision conservation issue, a bug in snow albedo, a bug in OpenMP, et al. Among of which, the bug fix in snow albedo largely reduced the surface temperature cold bias. Every bug/issue fix improved the 10-day forecast skill to some extent. To further improve the forecast skill, we tuned the cloud fraction to improve the energy budget for the full year hindcasts. We tuned the detrainment of deep convection to regulate cloud water and cloud ice to match observation. We also tuned the mountain block parameterization to reduce gravity wave drag to reduce the stratosphere wind bias. All of these tunings improve the 10-day weather forecast skill, especially the tuning of mountain block.

To substantially improve the model, we have to abandon the out-of-date Zhao-Carr cloud microphysics scheme and replace with the advanced single-moment 6-class cloud microphysics developed at GFDL (GFDL MP for short). GFDL MP is developed and continually maintained by SJ Lin for nearly 10 years. Different from traditional bulk cloud microphysics used in weather and climate model, GFDL MP includes many unique features coming from the finite-volume dynamical core. We spent about two weeks to implement GFDL MP into fvGFS and debug. After couples of months' tuning and improvement, fvGFS with GFDL MP finally produces significantly (pass 95% confidence level) better forecast skill than the operational GFS, which GFS would take years to achieve. The tunings of GFDL MP includes improve water species partitioning, improve total energy conservation, improve water

species terminal fall, and so on. We also experimentally incorporate an advanced radius diagnostic formula, but the validation is still under testing. We then documented this GFDL MP the first time ever for further development and reference.

In the analysis by our group members and external experts, we discovered a large cold bias at the 2-meter temperature in the long-term integration, either forecast or AMIP runs. Besides, we found most of the surface variables have unreasonable blocks. This is mainly due to we are using an out-of-date land model and low-resolution/old land data, which have been upgraded in NCEP. So, we spent couples of weeks in generating high-resolution land data, updating terrain using the GMTED2010 new dataset, updating the model's initial condition, and upgrading the land model. Now, 2-meter temperature and surface blocks have gone. Although forecast skill at upper-level atmosphere doesn't change too much, the surface meteorological fields improve a lot.

We built and gradually updated a comprehensive verification package to include a broader view of the model performance. This verification package can automatically handle the model output and create different plots included: anomaly correlation coefficient, bias, root mean square error for different model levels and surface. In a time series plot, seasonal divided plot, and probability density function plot. We also created the script to calculation Equitable Threat Score and Bias score for CONUS precipitation forecast. In the future, more functional plots will be included. On the other hand, different observation, reanalysis datasets have been downloading and reconstructed to be used in the verification package. So far, this package has been frequently used in our model verification and Real-time forecast at GFDL.

Publications:

Liu, P., et al., L. Zhou, et al., 2016: Tracking Persistent Maxima of 500-hPa Geopotential Height. Mon. Wea. Rev., In revision.

Wang, Y., et al., L. Zhou, Yongyun Hu, 2016: Effects of obliquity on the habitability of exoplanets around M dwarfs. Journal Letter Astrophysical, 823, L20.

Documents:

"GFDL Cloud Microphysics", 58 pp, by the GFDL FV3 Team.

"FV3: The GFDL Finite-Volume Cubed-Sphere Dynamical Core", 100 pp, by the GFDL FV3 Team.

Presentations:

Zhou, L., S.-J. Lin, J.-H. Chen, et al., "GFDL Single-Moment Six-Class Cloud Microphysics and Its Application in NGGPS", 2017 GFDL Winter Expo, Princeton, USA. Poster. (February 1st, 2017).

Zhou, L., S.-J. Lin, J.-H. Chen, et al., "Ten-day Weather Forecasts using a 4-45 km Variable-resolution Global Model: fvGFS", 2017 AMS Annual Meeting, Seattle, USA. Talk. (January 24th, 2017).

Progress Report Title: **Kelvin-Rossby Instability and the Maintenance of the Momentum Balance**

Principal Investigator: Pablo Zurita-Gotor (Princeton Visiting Research Scholar)

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: (i) To understand the interaction between extratropical Rossby waves and tropical Kelvin waves and its impact for equatorial superrotation (ii) To assess the role played by horizontal and vertical eddy fluxes of momentum for zonal wind acceleration in the tropics

Methods and Results/Accomplishments:

We have studied the maintenance of the tropical momentum balance in two different settings. First, we have analyzed the equilibration of Kelvin-Rossby instability at non-small Rossby number. This instability has been proposed to drive equatorial superrotation in small/slowly rotating planets (Wang and Mitchell 2014) and may also be responsible for the terrestrial superrotation produced by some climate models at very large CO_2 concentrations (Caballero and Huber 2010). For this part of the project, we studied the nonlinear equilibration of the instability in two idealized models: a shallow water model and a dry primitive equation model. Additionally, we have analyzed the maintenance of the tropical momentum balance on Earth (Dima et al. 2005), focusing on the relative role of horizontal and vertical eddy fluxes and on the dynamics of the vorticity forcing. We have used ERA-interim reanalysis data for this observational part of the study.

The main conclusion of our analysis of the equilibration of Kelvin-Rossby instability is that vertical momentum advection plays a key role for tropical acceleration, as was also found by Showman and Polvani (2011) in a very different context. We found that the equatorward momentum fluxes produced by the instability only change the mass-weighted momentum (but not the Eulerian-mean momentum) in the tropics of the shallow water model, due to the omission of this key process. In contrast, equilibration of the instability leads to equatorial superrotation (for *internal* Kelvin-Rossby modes) in the primitive-equation model, with eddy vertical advection playing the dominant role. We argued that the inefficiency of meridional advection to accelerate the mean flow in this problem was due to the weakness of the eddy vorticity fluxes implied by the smallness of absolute vorticity in the tropics in the parameter regimes relevant for Kelvin-Rossby instability.

In the terrestrial atmosphere, absolute vorticity is also small in the *deep* tropics but vorticity anomalies and fluxes are not negligible, even close to the Equator, because the mean vorticity gradient (beta) is not small. However, if we assume that sufficiently close to the Equator vorticity anomalies are primarily created by meridional advection of this mean gradient (rather than, for example, by vortex stretching or divergent advection), then the maintenance of the enstrophy balance requires vorticity fluxes to be downgradient over this region. The implication is that meridional advection can only decelerate the flow, so that westerly equatorial acceleration must again be driven by vertical momentum advection. This idea appears to be consistent with the observed seasonal cycle of tropical eddy momentum forcing (Fig.

1). If we use a flux form of the momentum equations, the dominant eddy acceleration is due to the convergence of the meridional eddy momentum flux, consistent with previous results by Dima et al. (2005). However, if we use an advective formulation instead, vertical advection is dominant and meridional acceleration primarily decelerates the flow (with the exception of the Northern monsoon season). The resolution to this apparent paradox is that the meridional eddy momentum convergence that accelerates the flow is dominated by the divergent eddy meridional velocity, and is thus associated with vertical momentum advection rather than with horizontal vorticity fluxes.

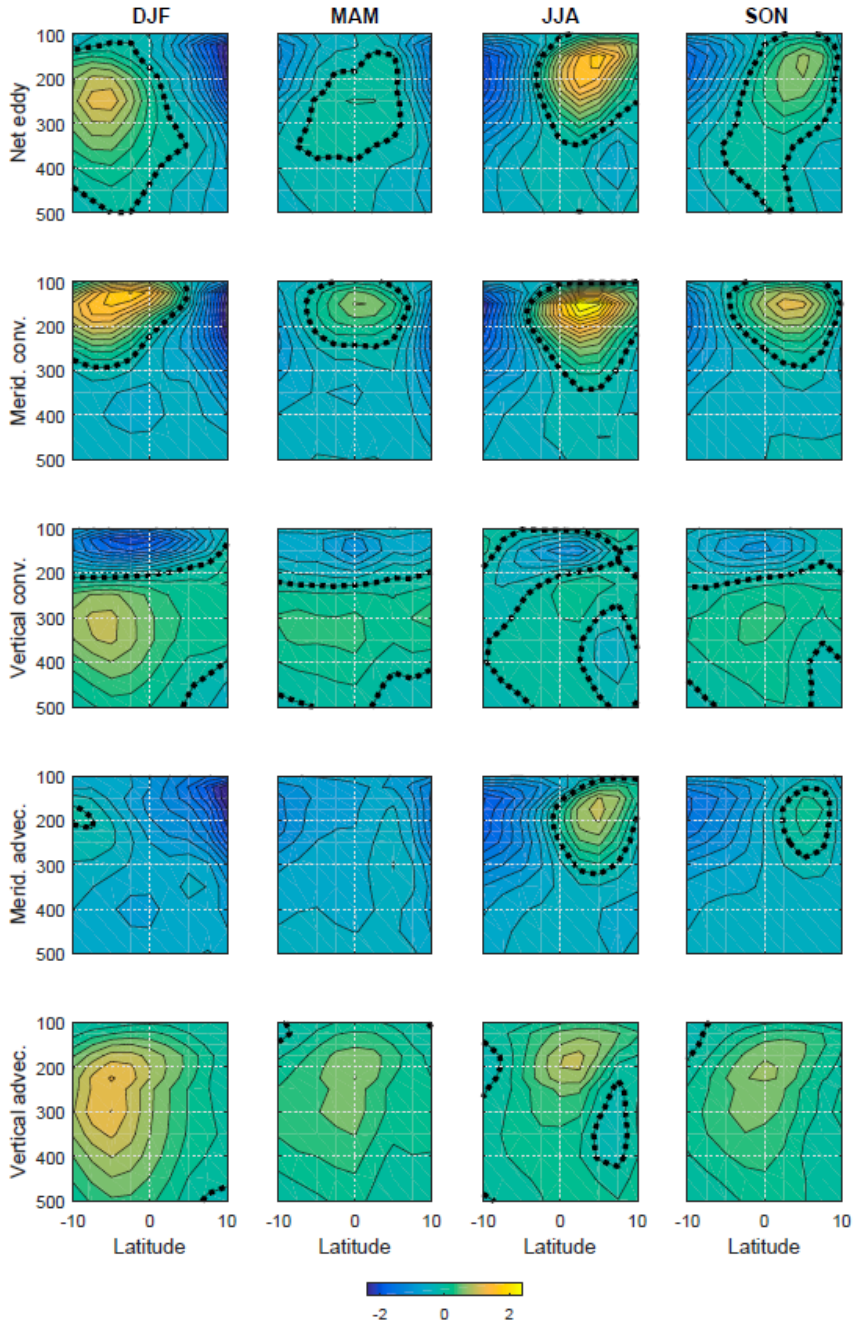


Fig. 1: Net eddy forcing (top row) and meridional-vertical decomposition using a flux formulation (second and third rows) and an advective formulation (fourth and fifth rows) for the seasons indicated.

Outreach Activities: Lecturer on Large Scale Atmospheric Circulation and Climate Change at *Universidad de Mayores* ("University for the elderly"), an initiative to promote science awareness among the retired population in Spain.

References:

Caballero, R. and M. Huber, 2010: Spontaneous transition to superrotation in warm climates simulated by CAM3. Geophys. Resea. Lett., 37 (11).

Dima, I.M., J.M. Wallace and I. Kraucunas, 2005: Tropical zonal momentum balance in the NCEP reanalysis. J. Atmos. Sci., 62, 2499-2513.

Showman, A.P. and L.M. Polvani, 2010: The Matsuno-Gill model and equatorial superrotation. Geophys. Resea. Lett., 37 (18).

Wang, P. and J.L. Mitchell, 2014: Planetary ageostrophic instability leads to superrotation. Geophys. Resea. Lett., 41 (12).

Publications:

Vertical momentum advection and the equilibration of Kelvin-Rossby instability (preliminary draft to be submitted to JAS).

Equatorial acceleration and the vorticity balance of the deep tropics (in preparation).

Progress Reports:

Earth System Model Applications

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: Nicolas Van Oostende (Princeton), Angus Atkinson (Plymouth Marine Laboratory, UK), Claire Widdicombe (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: The objectives of my work have been: a) Diagnose the prevalence of regime shifts in plankton communities in observations and models, and understand their primary drivers, and b) Assess in observations and models how environmental variability imprints on, and is filtered by, marine food webs.

Methods and Results/Accomplishments:

a) Regime shifts, or long-lived and often abrupt transitions from one ecological state to another, are a particularly important and poorly understood aspect of low frequency variability in marine plankton populations and communities. Here, we use a global trait-based plankton community model, as forced by preindustrial greenhouse gas conditions and embedded in realistic physical-chemical environments, to diagnose the distribution and drivers of regime shift-like events in the marine plankton community. Over 100 years of simulation, the model indicates that decadal-scale regime shift events are most common in portions of the global subtropical gyres where there is proportionally more low than high frequency variability in sea surface temperature and surface macronutrients. In contrast, temperate and tropical latitudes tend to exhibit less frequent regime shift behavior in the model, possibly because seasonal to interannual variability in relevant surface ocean properties, driven for example by ENSO, is relatively large here. Among the different model phytoplankton and zooplankton types, the frequency of regime shift events increases with body size and trophic level, a pattern that appears to be tied to the inherently longer generation lengths and tendency toward greater lower frequency variability in larger organisms.

b) Low frequency variability is a common feature of marine plankton populations. Recent results have suggested that low frequency variability results from the cumulative integration of white noise atmospheric forcing (i.e., equal power at all frequencies), with each successive integration resulting in lower frequency variability (i.e., red noise, more power at lower frequencies). Here, we examine the evidence for multiple integrations of atmospheric noise by comparing power spectra of atmospheric and oceanographic conditions to the population dynamics of 150 plankton taxa at station L4, a well-sampled location in the English Channel. The power spectra of oceanographic conditions (sea surface temperature, surface nitrate) are redder than atmospheric forcing (surface wind stress, net heat fluxes) at L4, and plankton taxa across trophic levels and body sizes have power spectral slopes that are generally redder than atmospheric forcing but whiter than oceanographic conditions. While zooplankton have redder

spectral slopes than phytoplankton, there is no significant relationship between power spectral slope and body size or generation length. Results from an idealized predator-prey model suggest that the whitening of plankton time series at L4 relative to oceanographic conditions may arise from noisy plankton bloom dynamics in this strongly seasonal system. The model also suggests that the slight reddening of zooplankton power spectra relative to phytoplankton reflects a weak second integration of phytoplankton variability by their longer-lived zooplankton consumers. Differences in the integration of environmental variability by plankton communities at L4 relative to previous work in other systems highlights the need for comprehensive cross-ecosystem comparisons.

Outreach Activities: I serve on 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. I also serve on the Scientific Steering Committee for the "Trait-based approaches to Marine Ecology" workshop series, the next to be held in Bergen, Norway in August of 2017.

Publications:

Barton, A.D., González-Taboada, F., and C.A. Stock, (2016). Drivers of plankton community tipping points in Earth system models. In preparation.

Barton, A.D., González-Taboada, F., Atkinson, A., and C.A. Stock, (2016). Integration of environmental variation by the marine plankton community. Submitted to Limnology and Oceanography.

González-Taboada, F., Barton, A.D., and C.A. Stock, (2016). Predicting global oceanic net primary productivity with reduced-dimension, linear dynamical spatiotemporal models. Submitted to Progress in Oceanography.

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 over the past year has focused on analyzing Arctic sea ice prediction skill and predictability in the GFDL seasonal forecast system. Using the CM2.1 and FLOR models, we have analyzed seasonal prediction hindcast experiments, control integrations, and performed perturbation experiments in order to study the skill and sources of skill for Arctic sea ice predictions.

One main focus area has been assessing regional prediction skill of Arctic sea ice on seasonal timescales. Analyzing the FLOR hindcasts, we found that this model produces skillful regional forecasts at lead times of 1-11 months. The forecast skill is notably high for predictions of winter sea ice in the Barents, Labrador, and GIN seas, and for summer predictions in the East Siberian and Laptev Seas. We identified subsurface ocean temperature initialization and sea-ice thickness initialization as the crucial sources of skill for these predictions, respectively. This work has recently been submitted to Geophysical Research Letters.

Another area of focus has been examining the sources of predictability for summer sea ice. We identified sea-ice volume persistence as a crucial source of summer prediction skill and additionally identified an enhancement of sea-ice volume anomalies that occurs in the central Arctic. This work has now been published in the Journal of Climate.

Outreach Activities: I was interviewed by Harrison Blackman, an undergraduate student at Princeton, as part of a science journalism course. An article that resulted from these interviews is available here: https://expedictionary.com/2017/02/21/predictions-from-the-edge-of-the-world-meet-mitch-bushuk-climate-forecaster/.

Publications:

Bushuk, M., R. Msadek, M. Winton, G. Vecchi, R. Gudgel, A. Rosati, X. Yang (2017), Summer enhancement of Arctic sea-ice volume anomalies in the September sea-ice zone, Journal of Climate, 30, 2341–2362, doi: 10.1175/JCLI-D-16-0470.1.

Bushuk, M., R. Msadek, M. Winton, G. Vecchi, R. Gudgel, A. Rosati, X. Yang (2017), Skillful regional prediction of Arctic sea ice on seasonal timescales, Geophysical Research Letters, submitted.

Progress Report Title: **The Role of the Water Vapor Feedback in the ITCZ Response to Hemispherically Asymmetry Forcings**

Principal Investigator: Spencer Clark (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: To systematically test and quantify the water vapor feedback's role in changing the sensitivity of the latitude of the intertropical convergence zone (ITCZ) to hemispherically asymmetric forcings using an idealized moist general circulation model.

Methods and Results/Accomplishments:

Many modeling studies have shown that the intertropical convergence zone shifts in response toward the hemisphere with more heating — e.g. if one imposes a cooling in the northern hemisphere as a result of a preponderance of shortwave-radiation-scattering aerosols, the latitude of maximum time and zonal mean precipitation rate shifts southward (e.g. Ming and Ramaswamy, 2011; Hwang et al., 2013). More recent studies, using comprehensive atmospheric models, suggest that the shift of the radiative effect of the column water vapor maximum along with the ITCZ may act to amplify the ITCZ's shift in response to a given hemispherically asymmetric forcing (e.g. Frierson and Hwang, 2011; Voigt et al., 2013). We investigate this sensitivity systemically with a set of experiments using an idealized moist aquaplanet model (Frierson et al., 2006a, 2007; Frierson, 2007), coupled to a full radiative transfer code (Paynter and Ramaswamy 2014).

We conduct experiments using two primary model configurations: the first is a case where the radiation code always sees the active water vapor tracer in the model, with radiative heating rates responding dynamically to simulated changes in specific humidity; the second is a case where the radiation code always sees a prescribed fixed specific humidity field from a hemispherically symmetric control simulation. We then apply cooling perturbations, in this case changes to the incoming solar radiation at the top of the atmosphere, in the northern hemisphere of varying strengths, and find that for a given perturbation, the latitude of the ITCZ shifts twice as far southward in the case with dynamic water vapor radiation interaction in comparison to the case without. In equivalent experiments, but with the moist convection scheme turned off, we find this increase in sensitivity remains, suggesting that the increase in sensitivity is robust to the convection parameterization used.

Though energy flux equator theory (Kang et al., 2008), differences in the latitude of the ITCZ between cases with and without the water vapor feedback with equivalent forcings can be attributed primarily to increases in the cross equatorial vertically integrated moist static energy flux. Increases in the cross equatorial energy flux can be mostly accounted for by differences in the energy budget of the atmosphere in the tropics, regardless of whether the forcing itself is imposed in the tropics or extratropics. The differences in the energy budget in the tropics can be traced back physically to the movement of water vapor with the ITCZ (and its associated longwave heating) into the southern hemisphere; this

amplifies the inter-hemispheric difference in net column heating, and thereby increases the cross equatorial energy flux (in these cases from the southern hemisphere to the northern hemisphere).

Outreach Activities: Mentor to Kemal Aziz, a high school student at the Staten Island Technical High School, on two science projects — one for the Quality of Life Innovations competition, and one for the New York City Science and Engineering Fair.

References:

Frierson, D. M. W., Held, I. M., & Zurita-Gotor, P. (2006). A Gray-Radiation Aquaplanet Moist GCM. Part I: Static Stability and Eddy Scale. Journal of the Atmospheric Sciences, 63(10), 2548–2566. https://doi.org/10.1175/JAS3753.1.

Frierson, D. M. W., Held, I. M., & Zurita-Gotor, P. (2007). A Gray-Radiation Aquaplanet Moist GCM. Part II: Energy Transports in Altered Climates. Journal of the Atmospheric Sciences, 64(5), 1680–1693. https://doi.org/10.1175/JAS3913.1.

Frierson, D. M. W. (2007). The Dynamics of Idealized Convection Schemes and Their Effect on the Zonally Averaged Tropical Circulation. Journal of the Atmospheric Sciences, 64(6), 1959–1976. https://doi.org/10.1175/JAS3935.1.

Frierson, D. M. W., & Hwang, Y.-T. (2011). Extratropical Influence on ITCZ Shifts in Slab Ocean Simulations of Global Warming. Journal of Climate, 25(2), 720–733. https://doi.org/10.1175/JCLI-D-11-00116.1.

Hwang, Y.-T., Frierson, D. M. W., & Kang, S. M. (2013). Anthropogenic sulfate aerosol and the southward shift of tropical precipitation in the late 20th century: AEROSOLS AND TROPICAL RAIN BELT SHIFTS. Geophysical Research Letters, 40(11), 2845–2850. https://doi.org/10.1002/grl.50502.

Kang, S. M., Held, I. M., Frierson, D. M. W., & Zhao, M. (2008). The Response of the ITCZ to Extratropical Thermal Forcing: Idealized Slab-Ocean Experiments with a GCM. Journal of Climate, 21(14), 3521–3532. https://doi.org/10.1175/2007JCLI2146.1.

Ming, Y., & Ramaswamy, V. (2011). A Model Investigation of Aerosol-Induced Changes in Tropical Circulation. Journal of Climate, 24, 5125–5133.

Paynter, D., & Ramaswamy, V. (2014). Investigating the impact of the shortwave water vapor continuum upon climate simulations using GFDL global models. Journal of Geophysical Research: Atmospheres, 119(18), 2014JD021881. https://doi.org/10.1002/2014JD021881.

Voigt, A., Stevens, B., Bader, J., & Mauritsen, T. (2013). Compensation of Hemispheric Albedo Asymmetries by Shifts of the ITCZ and Tropical Clouds. Journal of Climate, 27(3), 1029–1045. https://doi.org/10.1175/JCLI-D-13-00205.1.

Publications:

Clark, S. K., Ward, D. S., and Mahowald, N. M. “Parameterization-based uncertainty in future lightning flash density.” Geophysical Research Letters, In press (2017).

Presentations:

Clark, S. K., Ming, Y., and Held, I. M. “The role of water vapor in the ITCZ response to hemispherically asymmetric forcings.” AGU Fall Meeting, San Francisco, CA, December 2016. Poster Presentation.

Clark, S. K., Ming, Y., and Held, I. M. “The role of water vapor in the ITCZ response to hemispherically asymmetric forcings.” WCRP Model Hierarchies Workshop, Princeton, NJ, November 2016. Poster Presentation.

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)

Other Participating Researchers: Michael Oppenheimer (Princeton), Robert Socolow (Princeton), David Keith (Harvard)

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). An additional project aims to explore the policy implications of stratospheric aerosol albedo modification.

Methods and Results/Accomplishments:

My research explores the physical connections between free tropospheric cloud amount, humidity, and circulation in an idealized model. I use the Held-Suarez dynamic core (Held and Suarez 1994) with two different moisture representations: a passive water tracer in a saturation adjustment scheme (after Galewsky, et al. 2005) and a cloud scheme from a comprehensive climate model (as in Zhao, et al. 2009). Comparison of the saturation adjustment and cloud microphysical schemes highlight the role of cloud processes in redistributing atmospheric moisture. Sensitivity studies within the model's explicit treatment of cloud microphysics reveal the key role of re-evaporation of hydrometeors in moistening the lower troposphere. The magnitude and location of the extratropical cloud maxima is tightly connected to the sub-grid-scale relative humidity distribution assumed by the cloud scheme. Cloud formation in the extratropics interrupts the isentropic transport of moisture from the tropics, drying the polar upper troposphere. Simple alterations to the general circulation in the model demonstrate that details of changes in the temperature gradient and the location of the eddy-driven jet are essential for understanding the simulated cloud response to climate change. I am currently further exploring the utility of the idealized model for exploring cloud processes while pursuing further implications of these results.

Additionally, as part of a PEI-STEP fellowship, advised by Michael Oppenheimer and Rob Socolow and in collaboration with David Keith, I am using GCMs to consider the regional climate impacts of stratospheric aerosol albedo modification (SAAM), a proposed form of geoengineering aimed at reducing the amount of solar radiation reaching the earth. The goal of this project is to reduce the uncertainty of risks and benefits surrounding SAAM and consider the policy implications for international governance.

Outreach Activities: I tutored a high school student bi-weekly through Princeton's PACE Center Community House SAT Prep program. Additionally, with Michael Oppenheimer, I am co-supervising undergraduate Scott Bechler on his senior thesis in the Princeton Geosciences department.

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.

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

Presentations:

Frazer, M. E., Y. Ming, and I. M. Held. Modeling Water Vapor and Clouds in an Idealized GCM? Poster presentation, Model Hierarchies Workshop, November 2016.

Frazer, M. E., Y. Ming, and I. M. Held. Understanding Cloud Process with an Idealized model. Poster presentation, AGU Fall Meeting, December 2016.

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)

Other Participating Researchers: Andrew Barton (Scripps)

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 focused on the predictability of short term changes in marine Net Primary Production (NPP), from monthly to seasonal scales, using statistical methods. The focus on NPP predictability reflects its central role in marine ecosystem functioning and in the global carbon cycle, and it is a key aspect to improve the management of living marine resources. The analysis was extended to estimate the predictability of sea surface temperature (SST), in order to assess the hypothesis that ecosystem feedbacks can lead biogeochemical variables to be more predictable than the physical environment (Séférian et al. 2014). We estimated potential predictability by fitting a set of reduced dimension, linear Dynamic SpatioTemporal Models (rDSTM, Cressie & Wikle 2011) to monthly NPP and SST anomaly series derived from 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). We identified areas of enhanced NPP predictability matching the location of oligotrophic gyres and transition regions between ocean biomes, where fluctuations in biome boundaries generate large biogeochemical perturbations that leave lasting imprints on NPP. In these areas, the predictability horizon for NPP was longer than for SST, although SST was more predictable over large areas of the equatorial and northeast Pacific. Our results support the potential for extending seasonal to inter-annual physical climate predictions to predict ocean productivity. Preliminary results were presented at Ocean Sciences Meeting 2016 and we have submitted a manuscript currently under review.

A second effort focused on the assessment of surface winds from three widely used atmospheric reanalysis products (NCEP/NCAR, ERA-Interim and JRA-55) and their corresponding ocean forcing datasets (CORE v2.1, DFS v5.2 and JRA-55do), which include *ad hoc* corrections for use in ocean simulations. We compared wind patterns most relevant to ocean circulation (surface wind stress, its curl

and estimates of vertical upwelling velocity) across global and regional scales, with added emphasis on the main Eastern Boundary Upwelling Ecosystems (EBUEs). Biased winds impact key biogeochemical processes by altering nutrient fluxes and biological production, and contribute to biases ocean circulation and transport like the warm bias in eastern boundary current regions (Richter 2015). The analysis highlighted a continued improvement in the quality of wind data sets with increases in atmospheric model resolution, further enhanced by *ad hoc* corrections. It also suggested a reduced fidelity for derived quantities involving the calculation of spatial derivatives, like wind stress curl and Ekman pumping, which suggests the need to develop better correction strategies across ocean-relevant wind properties. Taken together, our results suggest the need to incorporate uncertainties in wind forcing into ocean simulation experiments and retrospective analysis, favoring the use of reanalysis products already adjusted for large scale biases.

Outreach Activities: Teaching of the course *Global Change Biology* within the International Master of Science "Marine Biodiversity and Conservation" (www.embcplus.org) offered by a consortium of six European universities, including University of Oviedo (3 ECTS/29h theory).

References:

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

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

Séférian, R., Bopp, L., Gehlen, M., Swingedouw, D., Mignot, J., Guilyardi, E. & Servonnat, J. (2014). Multiyear predictability of tropical marine productivity. Proceedings of the National Academy of Sciences, 111, 11646–11651.

Spalding, M.D., Agostini, V.N., Rice, J. & Grant, S.M. (2012). Pelagic provinces of the world: A biogeographic classification of the world's surface pelagic waters. Ocean & Coastal Management, 60, 19–30.

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.

Wentz, F.J., Scott, J., Hoffman, R., Leidner, M., Atlas, R. & Ardizzone, J. (2015). Remote sensing systems cross-calibrated multi-platform (CCMP) 6-hourly ocean vector wind analysis product on 0.25 deg grid, version 2.0.

Publications:

Barton, A. D., F. González Taboada, A. Atkinson, C. E. Widdicombe, Ch. Stock (submitted). Integration of environmental variation by the marine plankton community.

González-Gil, R., F. González Taboada, C. Cáceres, J. Largier, R. Anadón. (submitted). Winter mixing preconditioning of the spring phytoplankton bloom in the Bay of Biscay.

González Taboada F., A. Barton, Ch. Stock, J. Dunne, J. G. John. (submitted). Seasonal to interannual predictability of oceanic net primary production inferred from satellite observations

González Taboada F., Ch. Stock et al. (in preparation). Surface winds from atmospheric reanalysis lead to contrasting oceanic forcing and coastal upwelling patterns.

Petrik, C., F. González Taboada, Ch. Stock (in preparation). The influence of fish life history traits on recruitment variability.

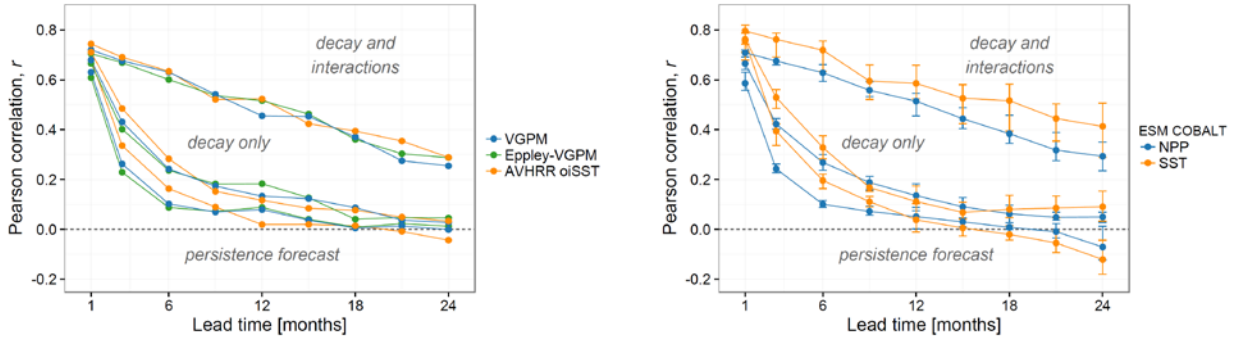


Figure 1. Potential predictability of monthly anomalies of net primary productivity (NPP) and sea surface temperature (SST) at different lead times for remote sensing data (left) and for simulations of ESM COBALT (right). Predictability was estimated as the mean anomaly correlation coefficient between NPP or SST monthly anomalies and within sample, one step ahead predictions based on (i) the full reduced dimension model, (ii) a model considering only the local decay of major modes, and (iii) the persistence forecast (i.e. a prediction based on the anomaly recorded.

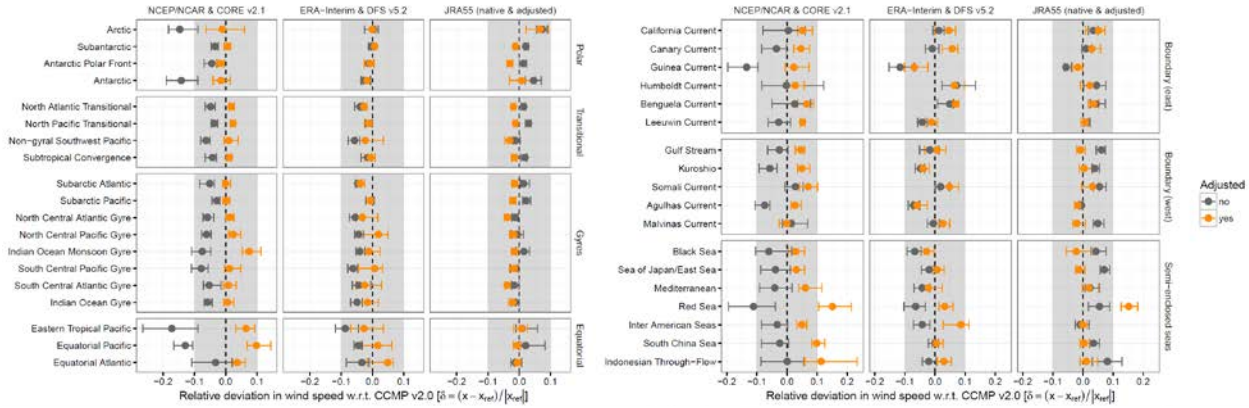


Figure 2. Regional summaries of the relative deviation in wind speed, using CCMP v2.0 (Wentz et al., 2015) as a reference. Different panels present the median and 50% interquantile range for local level relative deviations over each of Spalding et al.'s (2012) pelagic provinces of the world, which were further grouped by biome and between large open ocean areas (*left*) and ocean boundary systems and marginal seas (*right*). Within each panel, color indicate whether the statistics correspond to native (*dark grey*) or *ad hoc* adjusted (*orange*) products designed for ocean model forcing experiments. The grey ribbon in the background corresponds to a relative -error range of ±0.10. Positive (negative) values indicate a predominance of values larger (smaller) than those in the reference dataset.

Progress Report Title: **Understanding and Quantifying Tropical Air-Sea Interaction**

Principal Investigator: Jie He (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Gabriel A. Vecchi (GFDL), Michael Winton (GFDL)

Other Participating Researchers: Clara Deser (NCAR)

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 is to quantify the sea surface temperature forcing and atmospheric feedback processes in the tropics and form a simple framework for understanding tropical air-sea interaction and its changes from anthropogenic forcing.

Methods and Results/Accomplishments:

A long-standing challenge in understanding the tropical air-sea interaction is to separate the oceanic forcing and atmospheric forcing, both of which occur simultaneously in a coupled system. I approached this issue by using atmosphere-only simulations, which provide an ideal opportunity to study the oceanic forcing and atmospheric forcing in isolation. Based on the atmosphere-only simulations, I quantified various processes in tropical air-sea coupling in the form of feedback parameters. These feedback parameters built a simple framework for understanding the basic nature of air-sea interaction and its future changes and for identifying the key processes that cause model biases, much like the radiative feedback parameters in global warming studies.

One of the important findings so far is that the SST forcing of convection is a monotonically increasing function of the base SST. Observational studies expected the SST forcing to be weak for very high base SSTs. However, I found that simultaneous SST-rainfall relationships in any coupled system, including observations, are inadequate for quantifying the SST forcing. The monotonically increasing SST forcing with base SST can be physically explained using a simple moist static energy model.

Outreach Activities: Invited talk at NCAR, Columbia Univ., Zhejiang Univ. (China) and Georgia Tech.

Publications:

He, J., C. Deser and B. J. Soden (2016), Atmospheric and oceanic origins of tropical precipitation variability. J. Climate, doi:10.1175/JCLI-D-16-0714.1.

He, J., M. Winton, G. Vecchi, L. Jia, and M. Rugenstein (2016), Transient climate sensitivity depends on base climate ocean circulation. J. Climate, 30(4), 1493–1504, doi:10.1175/JCLI-D-16-0581.1.

Ma, J., G. Foltz, B. J. Soden, Huang, G., He, J., and Dong, C. (2016), Will surface winds weaken in response to global warming?, Environ. Res. Lett., 11, 124012.

He, J., and B. J. Soden (2016), A re-examination of the projected subtropical precipitation decline. Nature Climate Change, doi:10.1038/nclimate3157.

He, J., and B. J. Soden (2016), The impact of SST biases on projections of anthropogenic climate change: a greater role for atmosphere-only models?, Geophys. Res. Lett., 43(14), 2016GL069803, doi:10.1002/2016GL069803.

He, J., G. Vecchi, N. Johnson, B. Kirtman and L. Jia, Tropical air-sea interaction. Part I: a model-based theory, in prep.

He, J., G. Vecchi, N. Johnson, B. Kirtman and L. Jia, Tropical air-sea interaction. Part II: changes from anthropogenic forcing, in prep.

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

Principal Investigator: Nathaniel Johnson (Princeton Associate Research Scholar)

CICS/GFDL Collaborators: Gabriel Vecchi (GFDL), Andrew Wittenberg (GFDL), Lakshmi Krishnamurthy (Princeton), Sarah Kapnick (GFDL), Jie He (Princeton), Angel Munoz (Princeton), Salvatore Pascale (Princeton), Baoqiang Xiang (GFDL)

Other Participating Researchers: 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), Qinghua Ding (UCSB), Neven Fuckar (BSC-CNS), Xichen Li (Institute of Atmospheric Physics), Changhyun Yoo (Ewha Womans University), Chueh-Hsin Chang (National Taiwan University), Tyler Janoski (Rutgers), Tony Broccoli (Rutgers)

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%)

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 investigated 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 (SST) biases are responsible for these differences. Most surprisingly, I have determined that North Atlantic SST biases have a more significant effect on U.S. precipitation biases than North Pacific SST biases. I currently am writing up these results in a manuscript.

I also have been engaged in several other projects related to subseasonal-to-seasonal climate prediction. I have been supervising a postdoctoral scientist, Dr. Jiaxin Black, in a collaborative project with the NOAA Climate Prediction Center and Penn State. We have completed a study and submitted a manuscript on the subseasonal prediction of Northern Hemisphere teleconnection pattern indices. With collaborators at BSC-CNS, UCSB, NOAA CPC, and the University of Washington, I have contributed to two studies on the prediction and multidecadal variability of Arctic sea ice. I am working with collaborators from Ewha Womans University and National Taiwan University to study the subseasonal predictability and to develop subseasonal prediction tools for East Asian climate. With Dr. Sarah

Kapnick, I have co-mentored Mr. Tyler Janoski on a project focusing on the changes in eastern U.S. blizzards under climate change, as determined through simulations with the GFDL FLOR climate model.

Outreach Activities:

Co-mentor of Mr. Tyler Janoski during his undergraduate internship with the Hollings Scholar Program at GFDL in the summer of 2016

Publications:

Ding, Q., A. Schweiger, M. L'Heureux, D. S. Battisti, S. Po-Chedley, N. C. Johnson, E. B. Wrigglesworth, K. Harnos, Q. Zhang, R. Eastman, and E. J. Steig, 2017: Influence of high-latitude atmospheric circulation changes on summertime Arctic sea ice. Nature Climate Change, 7, 289–295, doi:10.1038/nclimate3241.

Wang, G., L. Wu, N. C. Johnson, and Z. Ling, 2016: Observed three-dimensional structure of ocean cooling induced by Pacific tropical cyclones. Geophysical Research Letters, 43:7632-7638.

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, 47:3737-3764.

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, 47:1527-1543.

Fučkar N. S., V. Guemas, N. C. Johnson, and F. J. Dobas-Reyes, 2016: Dynamical prediction of Arctic sea ice modes of variability. Climate Dynamics, in review.

Black, J., N. C. Johnson, S. Baxter, S. B. Feldstein, D. S. Harnos, and M. L'Heureux, 2017: The predictors and forecast skill of Northern Hemisphere teleconnection patterns for lead times of 3-4 weeks. Monthly Weather Review, under revision.

Presentations:

Johnson, N. C. (December 2016). The impact of sea surface temperature biases on North American precipitation biases and drought variability in a GFDL climate model. 2016 AGU Fall Meeting.

Johnson, N. C. (November 2016). Increasing occurrence of cold and warm extremes during the recent global warming slowdown. Seminar series at Ewha Womans University in Seoul, Korea (Invited).

Johnson, N. C. (November 2016). Increasing occurrence of cold and warm extremes during the recent global warming slowdown. Seminar series at Seoul National University in Seoul, Korea (Invited).

Johnson, N. C. (November 2016). Increasing occurrence of cold and warm extremes during the recent global warming slowdown. Seminar series at National Taiwan University in Taipei, Taiwan (Invited).

Johnson, N. C. (November 2016). Prospects of subseasonal climate prediction for lead times beyond two weeks. Seminar at Central Weather Bureau in Taipei, Taiwan (Invited).

Johnson, N. C. (September 2016). Statistical approaches for diagnosing and applying sources of forecast skill to subseasonal predictions. EMS 16th Annual Meeting.

Progress Report Title: **Climate Variability and Predictability**

Principal Investigator: Lakshmi Krishnamurthy (Princeton Climate Prediction Specialist)

CICS/GFDL Collaborator: Gabriel A. Vecchi (GFDL), Xiaosong Yang (UCAR/GFDL), V. Balaji (Princeton), Sarah Kapnick (GFDL), Ángel G. Muñoz (Princeton), Andrew Wittenberg (GFDL), Bill Stern (GFDL), Fanrong Zeng (GFDL), Seth Underwood (GFDL), Liwei Jia (Princeton), Karin van der Wiel (Princeton)

Other Participating Researchers: Rym Msadek (CNRS/CERFACS), Karen Paffendorf

Theme: Earth System Model Applications

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

Objectives: Performing real time seasonal forecasting every month by running and analyzing state-of-the-art coupled climate models on supercomputers; Analyzing seasonal predictability based on forecasts; Attribution of extreme Chennai flood of 2015; Assessment of forecast skill in GFDL high-resolution models in the Intra-Americas Sea relevant for stakeholders

Methods and Results/Accomplishments

The main goal of this project is to perform real time seasonal forecasting every month by running and analyzing state-of-the-art coupled climate models on supercomputers. To achieve this goal, I perform the following: a) Retrieving real-time observational data, quality control the data and post-process in the format compatible with GFDL models; b) Execute a data-assimilation run to prepare atmosphere and ocean initial conditions for CM2.1 forecasts and ocean initial conditions for FLOR forecasts; c) Execute AMIP runs and prepare atmospheric initial conditions for FLOR forecasts; d) Perform real-time forecast using CM2.1 and FLOR models; and e) Post-process the forecast data in a format required by NMME, quality control the data and upload data to FTP server.

In addition, I also work on climate variability and predictability. Attribution study of extreme flood over Chennai in 2015 was performed. A suite of model simulations from GFDL high-resolution coupled climate models were used to investigate the odds of occurrence of an extreme flood event over Chennai and the role of radiative forcing and/or large-scale SST forcing in enhancing the probability of such an event in future. Climate of 20th century experiments with large ensembles suggest that the radiative forcing may not enhance the probability of occurrence of extreme flood events over Chennai. Doubling of CO_2 also show lack of evidence of increase in probability of such events in global warming scenario. Further, the role of large-scale SST forcing from the Indian and Pacific Oceans on the odds of occurrence of floods over Chennai was also explored. It is shown that the probability of occurrence of an extreme flood event over Chennai neither favors an El Niño nor La Niña in the tropical Pacific. However, warm Bay of Bengal SSTs tend to increase the odds of occurrence of extreme flood event over Chennai. The atmospheric conditions such as low SLP and north easterlies favoring transport of moisture from warm Bay of Bengal are conducive for intense flooding. Knowing that the probability of occurrence of intense flood events over Chennai increases during years with warm Bay of Bengal SSTs, will help decision makers in developing adaption and mitigation strategies for future risks and disaster posed by such an event.

Further, forecast skill in GFDL high-resolution models is analyzed in the Intra-America Seas region that is relevant for stakeholders. Skill in coupled and uncoupled versions of low- resolution CM2.1 and high-resolution FLOR models is analyzed by applying model-output statistics (MOS). It is shown that the skill in the Intra-America Seas is improved after applying MOS in comparison to raw data.

Publications:

Krishnamurthy, L., V. Krishnamurthy, 2016: Indian monsoon's relation with the decadal part of PDO in observations and NCAR CCSM4 Int. J. Climatol., DOI:10.1002/joc.4815.

Krishnamurthy, L., Gabriel A. Vecchi, Xiaosong Yang, Karin van der Wiel, V. Balaji, Sarah Kapnick, Liwei Jia, Fanrong Zeng, Karen Paffendorf, Seth Underwood: Causes of 2015 Extreme Chennai Flood event (in preparation).

Krishanmurthy, L., Ángel G. Muñoz, Gabriel A. Vecchi, Rym Msadek, Andrew Wittenberg, Bill Stern, Fanrong Zeng: Assessment of forecast skill in GFDL high- resolution models in the Caribbean region relevant for stakeholders (in preparation).

Presentations:

Krishnamurthy, L., Poster presented at GFDL poster EXPO on February 2017, Impact of Strong ENSO events on regional tropical cyclone activity in a high-resolution climate model.

Krishnamurthy, L., 97th AMS Annual meeting in Seattle January 2017. Presented poster, The Seasonality of the Great Plains Low-Level Jet and ENSO Relationship.

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

Principal Investigator: Meiyun Lin (Princeton Research Scholar)

CICS/GFDL Collaborator: Larry Horowitz (GFDL)

Other Participating Researchers: R. Payton and G. Tonnesen (US EPA), A.M. Fiore (Columbia/LDEO)

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

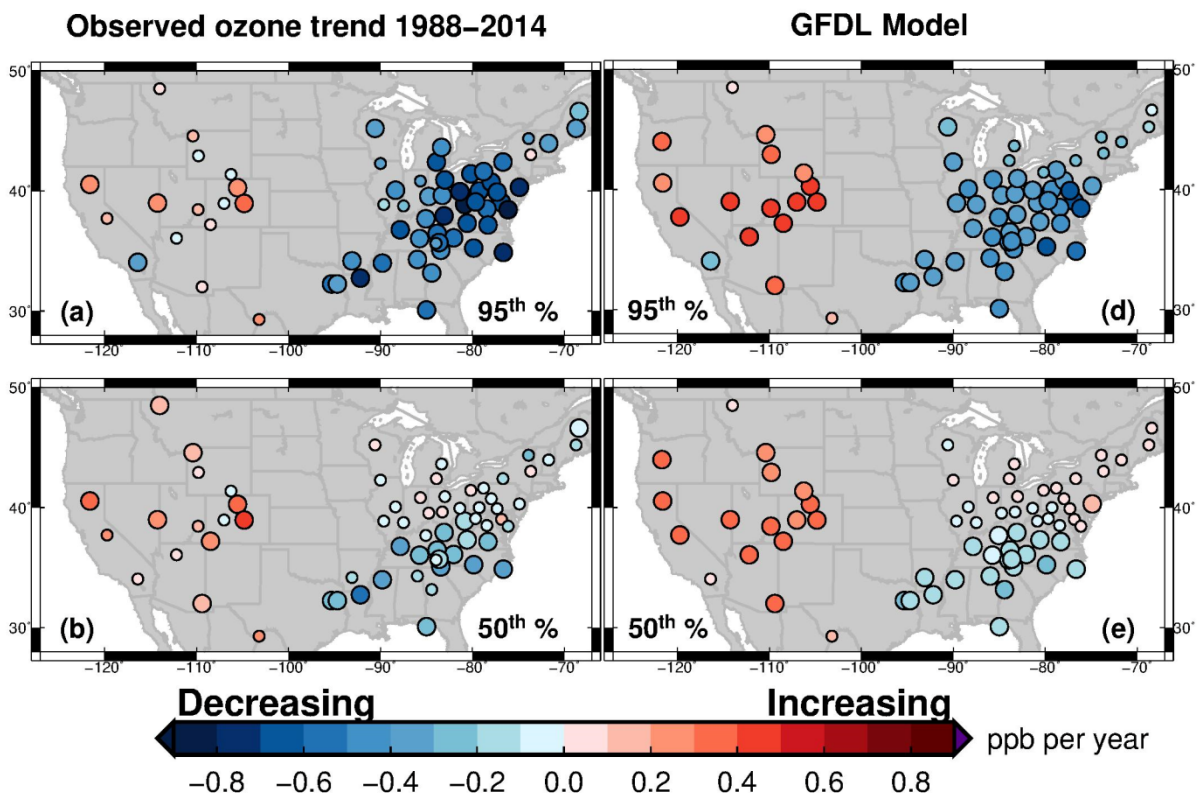
Objectives: Systemically investigate how surface ozone means and extremes across the continental US respond to increases in Asian anthropogenic emissions, North American emission controls, rising global methane, wildfire emissions, regional heat waves and droughts over the course of 35 years from 1980 to 2014.

Methods and Results/Accomplishments:

US surface O_3 responds to varying global-to-regional precursor emissions, climate, and extreme weather, with implications for designing effective air quality control policies. We examine these conjoined processes with observations and global chemistry-climate model (GFDL-AM3) hindcasts over 1980-2014. The model captures the salient features of observed trends in daily maximum 8-hour average O_3: (1) increases over East Asia (up to 2 ppb yr^{-1}), (2) springtime increases at western US (WUS) rural sites (0.2-0.5 ppb yr^{-1}) with a baseline sampling approach, (3) summertime decreases, largest at the 95th percentile, and wintertime increases in the 50th to 5th percentiles over the eastern US (EUS). Asian NO_x emissions tripled since 1990, contributing as much as 65% to modeled springtime background O_3 increases (0.3-0.5 ppb yr^{-1}) over the WUS, outpacing O_3 decreases attained via 50% US NO_x emission controls. Methane increases over this period contribute only 15% of the WUS background O_3 increase. Springtime O_3 observed in Denver has increased at a rate similar to remote rural sites. During summer, increasing Asian emissions approximately offset the benefits of US emission reductions, leading to weak or insignificant observed O_3 trends at WUS rural sites. Mean springtime WUS O_3 is projected to increase by ~10 ppb from 2010 to 2030 under the RCP8.5 global change scenario. While historical wildfire emissions can enhance summertime monthly mean O_3 at individual sites by 2-8 ppb, high temperatures and the associated buildup of O_3 produced from regional anthropogenic emissions contribute most to elevating observed summertime O_3 throughout the USA. GFDL-AM3 captures the observed interannual variability of summertime EUS O_3. However, O_3 deposition sink to vegetation must be reduced by 35% for the model to accurately simulate observed high-O_3 anomalies during the severe drought of 1988. Regional NO_x reductions alleviated the O_3 buildup during the recent heat waves of 2011 and 2012 relative to earlier heat waves (e.g., 1988; 1999). The O_3 decreases driven by NO_x controls were more pronounced in the Southeast US, where the seasonal onset of biogenic isoprene emissions and NO_x-sensitive O_3 production occurs earlier than in the Northeast. Without emission controls, the 95th percentile

summertime O_3 in the EUS would have increased by 0.2-0.4 ppb yr^{-1} over 1988-2014 due to more frequent hot extremes and rising biogenic isoprene emissions.

The above key findings were published in a peer-reviewed article in Atmospheric Chemistry and Physics (Lin et al., 2017). The paper was featured in Princeton News and NOAA Research, and received a lot of media coverage, including by E&E News, National Public Radio (NPR), Southern California Public Radio (SCPR), The Weather Channel, and USA TODAY.



Surface-level ozone, also known as smog, has increased at western U.S. rural sites during spring, partly due to rising Asian pollution, while smog has decreased in the eastern U.S. Smog results from human-made emissions of smog-precursor chemicals such as nitrogen oxides (NO_x), which are produced by cars, power plants and other industrial sources. Shown are the 1988-2014 trends in springtime ozone levels on days that were very smoggy (top panel) and on average (bottom panel) from observations (left) and from a model built by the Geophysical Fluid Dynamics Laboratory (GFDL, right). Larger circles indicate sites where there is greater certainty about the ozone trend. On a smoggy day (top panel), ozone levels has declined over the past several decades in the east, as indicated by the blue circles, while the ozone level has increased in the west, as indicated by the red circles, despite a 50 percent reduction in U.S. NO_x emissions. Credit: Lin et al. (ACP, 2017)

Publications:

Lin, Meiyun, W. Horowitz, R. Payton, A.M. Fiore, G. Tonnesen (2017). US surface ozone trends and extremes over 1980-2014: Quantifying the roles of rising Asian emissions, domestic controls, wildfires, and climate. Atmos. Chem. Phys., doi:10.5194/acp-17-2943-2017.

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Shen, Zhaoyi; Yi Ming; Larry W. Horowitz; V. Ramaswamy; Lin, Meiyun (2017). On the Seasonality of Arctic Black Carbon. J. of Climate, in press.

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Sun, L., Xue, L., Wang, T., Gao, J., Ding, A., Cooper, O. R., Lin, Meiyun, et al.: Significant increase of summertime ozone at Mount Tai in Central Eastern China, Atmos. Chem. Phys., 16, 10637-10650, doi:10.5194/acp-16-10637-2016, 2016.

L. E. Ott, B. N. Duncan, Anne M. Thompson, Glenn Diskin, Zachary Fasnacht, Andrew O. Langford, M.Y. Lin, Andrea M. Molod, J. Eric Nielsen, Sally E. Pusede, Andrew J. Weinheimer, Yasuko Yoshida (2016), Frequency and Impact of Summertime Stratospheric Intrusions over Maryland during DISCOVER-AQ (2011): New Evidence from NASA's GEOS-5 Simulations, J. Geophys. Res., doi:10.1002/2015JD024052.

F. Paulot, P. Ginoux, W. F. Cooke, L. J. Donner, S. Fan, M.Y. 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(3), DOI:10.5194/acp-16-1459-2016.

Presentations:

Lin, Meiyun, Oct 31, 2016, University of Toronto Noble Seminar Series: Linking climate variability to surface ozone trends and extremes (Invited).

Lin, Meiyun, Sep 30, 2016, Poster presentation at International Global Atmospheric Chemistry (IGAC) Project 2016 Science Conference.

Lin, Meiyun, Apr-11, 2016, MIT Atmospheric Science Seminar: Climate versus emission drivers of ozone pollution trends and extremes (Invited).

Lin, Meiyun, Apr-8, 2016, Harvard University Atmospheric Science Seminar: The roles of climate variability on U.S. surface ozone trends and extremes (Invited).

Progress Report Title: **Exploring Future Biogeophysical Signal of Land Use and its Uncertainties**

Principal Investigator: Sergey Malyshev (Princeton Professional Specialist)

CICS/GFDL Collaborator: Elena Shevliakova (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 (50%)
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts (50%)

Objectives: To understand possible future climate change due to biogeophysical effects of human land use activity, and its uncertainty under different scenarios

Methods and Results/Accomplishments:

Human land use is one of the important factors that affects near-surface climate in present day. It has large effect on the carbon balance of the Earth, influencing present-day and future climate change through the concentrations of greenhouse gases in the atmosphere. It also has significant direct effect on climate, since land use disturbances modify the land surface properties important for its interaction with the atmosphere, including its roughness length, reflectance, and vegetation properties related to evapotranspiration.

This study focuses on direct (biogeophysical) effect of the land use in the future, and its uncertainties due to differences in projected scenarios of the future land use activities, as well as model dependence of simulated response.

Jones et al. (2013) found that the assumptions about anthropogenic activity in the future may result in large differences in biogeophysical effect of land use. Even if the total greenhouse gas emissions are the same, depending on whether universal carbon tax (UCT) of fossil fuel carbon tax (FFICT) are assumed, by the year 2100 the difference between scenarios in their study can be as large as 0.4K globally, with much larger deforestation in FFICT scenario resulting in colder climate. Simulated regional effects of differences in land use are larger yet. To quantify the model-related and scenario-related uncertainty of the response, we performed an ensemble of numerical experiments using the same scenarios, but with GFDL's ESM2Mb model. Our results indicate the same sign of the response, but the magnitude of differences between FFICT and UCT scenarios in noticeably smaller in ESM2Mb (Figure 1).

Figure 2 shows the annual-mean near-surface temperature difference between the two scenarios in CESM (Jones at al., 2013) and ESM2Mb. Both models show similar geographical patterns of the land use signal over the land, with relative cooling in high latitudes in FFICT scenario due to more extensive land use and albedo feedback. However, the signal in ESM2Mb is weaker. This can be partially explained by the differences in climate sensitivity between the models: 1.8°K for CESM and 1.3°K for ESM2Mb. Seasonal patterns indicate that the largest land use effect in ESM2Mb occurs in March-April-May, due to combination of albedo effect (larger snow overlap on deforested area) and insolation.

We have also analyzed the difference in temperature between croplands (the areas most affected by the human land use activities) and natural vegetation, following methodology of Malyshev et al. (2015).

Interestingly, this local difference appears to be unaffected by the difference in the land use intensity between FFICT and UCT scenarios.

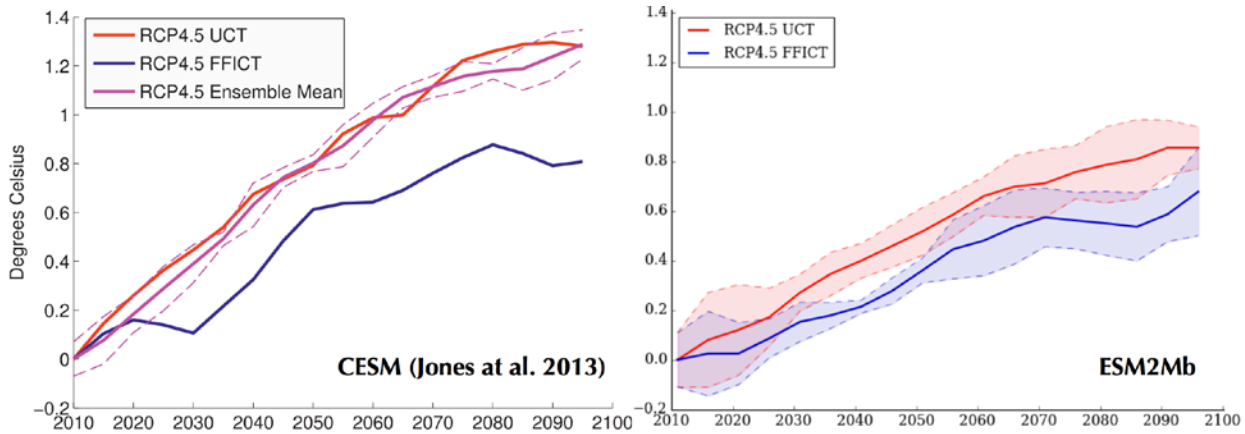

Figure 1. Global mean near-surface air temperature relative to the first decade of each simulation (2005-2104) in CESM (left) and ESM2Mb (right).

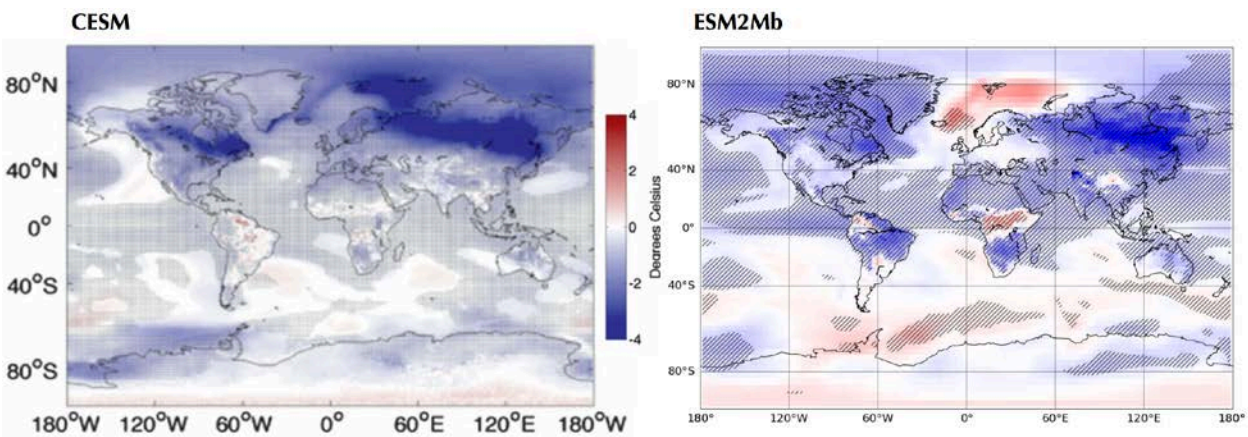

Figure 2. RCP4.5 FFICT-UCT annual mean near-surface air temperature differences, averaged over the last decade of simulations (2090-2099); Right is CESM (Jones et al. 2013), left is ESM2Mb. Hatching indicate statistical significance with 95% confidence.

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S. Malyshev, E. Shevliakova, R. J. Stouffer, and S. W. Pacala (2015): Contrasting Local versus Regional Effects of Land-Use-Change-Induced Heterogeneity on Historical Climate: Analysis with the GFDL Earth System Model. Journal of Climate, 28, No.13, 5448–5469, doi:10.1175/JCLI-D-14-00586.1.

Publications:

S. Malyshev, E. Shevliakova (2016): Exploring Future Biogeophysical Signal of Land Use and its Uncertainties. Global Land Project, 3rd Open Science Meeting, Beijing, China, October 24-27.

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/Arable Inc.)

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 biological habitats

Methods and Results/Accomplishments:

During 2016, we completed a spatial disaggregation framework which predicts surface temperature and surface salinity throughout the Chesapeake Bay, based on air temperature and precipitation over the Bay area and Susquehanna River watershed. A water balance model, corrected for wind-induced snow under-catch, converts watershed precipitation and air temperature to Susquehanna River flow into the Chesapeake Bay. In addition, a simple non-linear model predicts surface water temperature at the Thomas Point buoy from lagged air temperature. These non-spatial variables are then converted to spatial predictions across the Bay using model trees.

Modeled values of surface temperature and salinity in the Chesapeake Bay from the model trees agree well with historical observations from CTD casts (**Fig. 1**). Warmer air temperatures over the Bay lead to warmer surface water temperatures, and higher Susquehanna River outflows lead to down-bay movements of isohalines, and fresher conditions throughout most of the Bay. We can thus have some confidence that the statistical framework developed for recent historical conditions can be used to project future conditions in the Chesapeake Bay on longer time-scales.

When applied to statistically downscaled outputs from four general circulation models (GCMs), our framework projected future surface temperature increases for Chesapeake Bay of 2.0 – 5.5°C by the end of the 21st century, under RCP8.5. Salinity projections were more variable, but increased slightly in winter – spring in the wetter GCMs (e.g. GFDL-CM3), and decreased in the drier GCMs (e.g. IPSL-CM5A-LR) (**Fig. 2**).

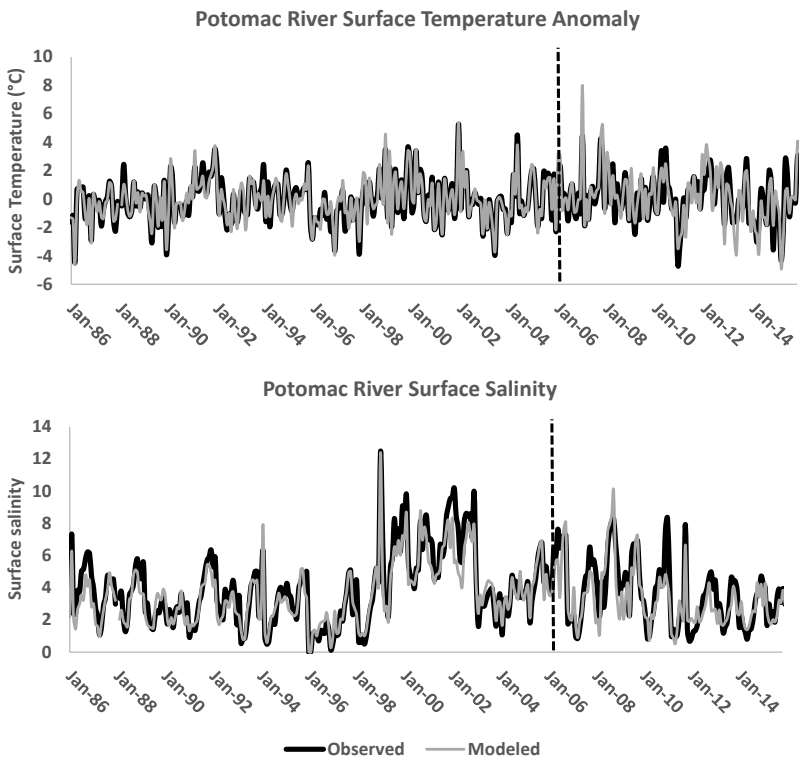

Fig 1: Observed and modeled monthly surface temperature anomaly and surface salinity in the Potomac River, 1986 - 2015. Time series and R^2 statistics are shown for the dataset used to train the models (1986 – 2005), and the out-of-sample "test" dataset (2006 – 2015)

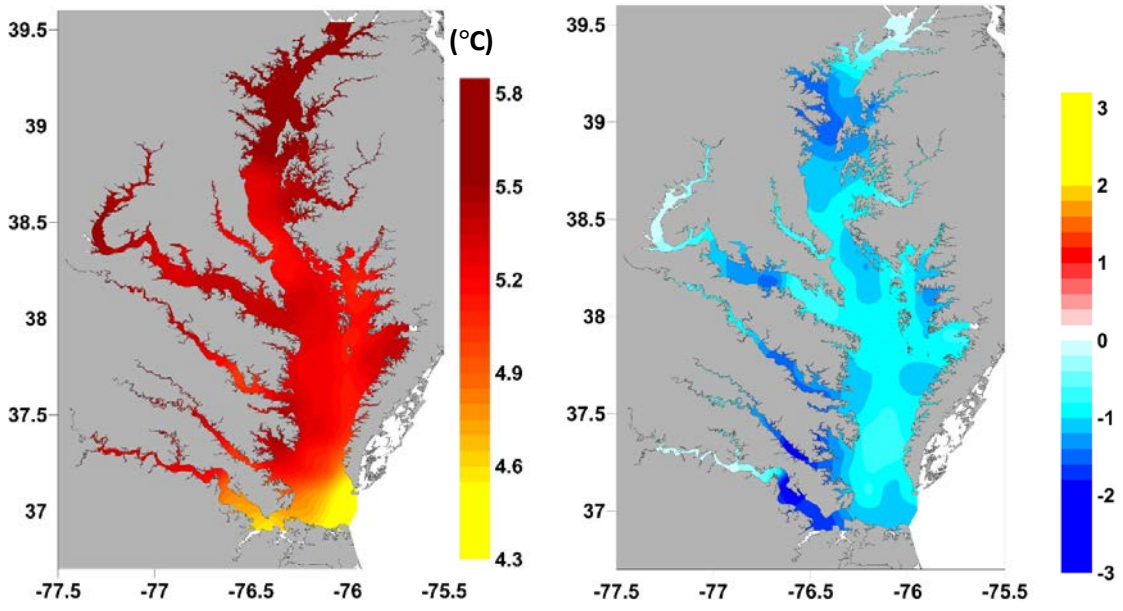

Figure 2: Projected changes in summer surface temperature (left) and winter surface salinity (right) in the Chesapeake Bay from the GFDL-CM3 model: 2071-2100 minus 1970-1999, averaged across all statistical downscaling methods. GFDL-CM3 showed particularly strong warming, and strong precipitation increase, out of a suite of 26 GCMs considered.

The choice of statistical downscaling method was less influential than choice of GCM in our particular study. This was mostly due to our selection of widely diverging GCMs, and statistical downscaling techniques from that same general family of methods. However, the downscaling methods were most different at very warm temperatures, where they were required to extrapolate beyond the range of currently observed values (**Fig. 3**).

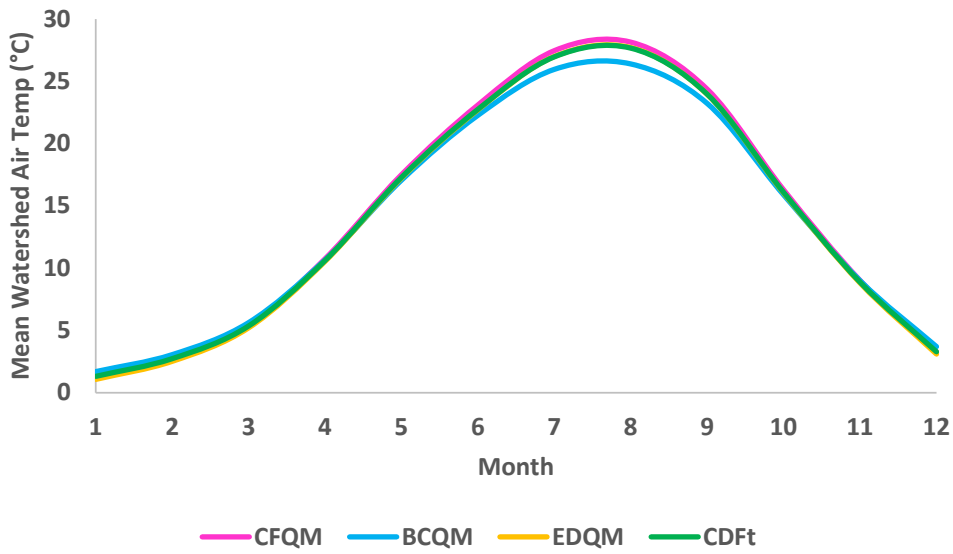

Figure 3: Mean 2m air temperature in the Susquehanna River watershed 2001-2100, from the four statistical downscaling methods applied to the GFDL-CM3 model, averaged across months.

Projections from the framework could potentially be used for a number of living marine resource applications. In collaboration with scientists at NOAA-NCCOS, we developed a simple case study to highlight the utility of our downscaled projections. We focused on the occurrence of *Vibrio* species in the Chesapeake Bay. *Vibrios* are naturally-occurring bacteria responsible for human illness, both from seafood contamination and environmental contact (e.g. swimming). They are more prevalent under certain temperature and salinity conditions, which vary among species.

By using existing habitat suitability models, we projected the future change in probability of occurrence of three *Vibrio* species (*V. vulnificus*, *V. cholerae* and *V. parahaemolyticus*) in the Chesapeake Bay by the end of the 21st century. Results suggested a widespread increase in suitable conditions for *V. vulnificus*, primarily due to increasing water temperatures. In contrast, habitat suitability for *V. cholerae* increased only in lower salinity portions of the Bay and tributaries, due to this species' affinity with low salinity environments (**Fig. 4**).

A manuscript describing the spatial disaggregation framework is currently in review at Estuaries and Coasts. A manuscript describing the *Vibrio* projections is also in the final stages of preparation for initial submission.

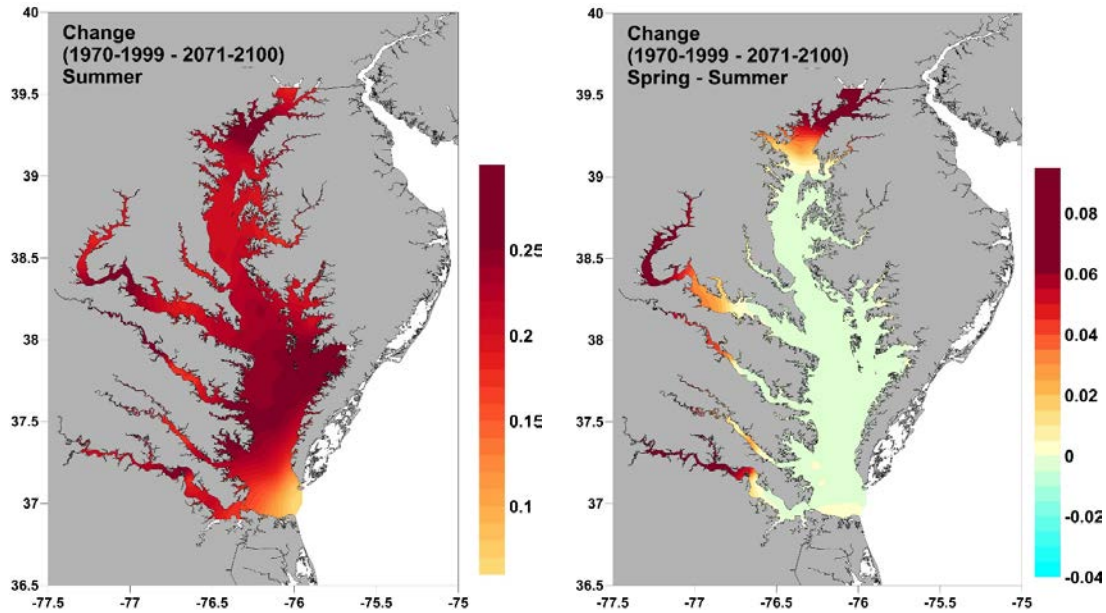

Figure 4: Difference between projections of historical (1970 – 1999) and future (2071 – 2100) probability of *V. vulnificus* (left) and *V. cholerae* (right) occurrence in the Chesapeake Bay, from statistically downscaled outputs from the GFDL-CM3 model. Differences are calculated as future (2071 – 2100) minus historical (1970 – 1999) probabilities of occurrence, with red showing a future increase, and blue showing a future decrease.

Publications:

Muhling, B.A., Jacobs, J., Stock, C.A., Gaitan, C.F., Saba, V.S. (in prep) Projections of the future occurrence, distribution, and seasonality of three Vibrio species under climate change in the Chesapeake Bay. EcoHealth.

Muhling, B.A., Gaitan, C.F., Stock, C.A., Saba, V.S., Tommasi, D., Dixon, K.W. (in review) Potential temperature and salinity futures for Chesapeake Bay using a statistical downscaling framework. Estuaries and Coasts.

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Muhling, B.A., Brill, R., Lamkin, J.T., Roffer, M.A., Lee, S.K., Liu, Y., Muller-Karger, F. (2016) Projections of future habitat use by Atlantic bluefin tuna from a mechanistic vs. a correlative distribution model. ICES Journal of Marine Science doi:10.1093/icesjms/fsw215.

Presentations:

Muhling, B.A., Gaitan, C.F., Stock, C.A., Saba, V.S., Tommasi, D., Dixon, K.W. (2016) Downscaling climate models for ecological forecasting in northeast US estuaries. NOAA ecological Forecasting Meeting, Silver Spring, MD, April 2016.

Muhling, B.A., Lamkin, J.T., Ingram Jr., G.W., Walter, J.F., Lee, S.K., Liu, Y., Domingues, R., Roffer, M.A., Muller-Karger, F.E., Quattro, J., Lindo Atichati, D. (2016) Ecology and management of Atlantic bluefin tuna under climate variability and change. PICES Annual Meeting, San Diego, CA, October 2016.

Progress Report Title: **The Nonlinearity of Rainfall Response to ENSO in East Asia**

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 recognize the existence of a nonlinear behavior of precipitation to ENSO in certain regions and seasons, so that rainfall increases during both the warm and cold phases compared to Neutral; Attempt is made to understand the mechanisms behind this phenomenon, which will be useful in improving prediction of the climate influences of ENSO

Methods and Results/Accomplishments:

Rainfall behavior in several observational datasets are studied, and we show that while El Nino and La Nina are frequently considered as mirror images of each other, this perspective does not hold with regard to certain aspects of the climate system and in certain regions. In particular, during the late fall/early winter season in the southeastern coast of China, mean rainfall increases during both El Nino and La Nina compared to Neutral. Methodology to diagnose the nonlinearity, which involves fitting a quasi-linear model to the data, is introduced. Rainfall anomalies are shown to be statistically significant at the 99% level in several datasets using a bootstrap test on the signal-to-noise ratio. Additionally, this nonlinear response is captured in the FLOR nudged-SST model simulations, and is again statistically significant at the 99% level. However, this is not captured in the LOAR model.

Several attempts have been made to explain this nonlinear behavior. Much time was spent in conducting a moisture budget analysis of the models and trying to understand the response of the various terms in the budget, namely the large-scale moisture flux, evaporation term and transient eddies. Unfortunately, we faced difficulties in this decomposition because we lacked high-frequency 3D model data to estimate the large-scale circulation based on moisture fluxes. Thus, the decomposition involved much interpolation and was done in coarse temporal scales. While the large-scale moisture flux calculated in this way indeed exhibits a nonlinear response to ENSO as does precipitation, the magnitudes of the responses do not match, especially during La Nina. In another way, the decomposition involved errors (which are exploited as transient eddies) with magnitudes as large as the transport itself, therefore rendering the decomposition results more questionable. Recently, a new hypothesis regarding the nonlocal effects in time on the rainfall behavior is being examined. We hope to spend at most a few more weeks on this hypothesis; if we are unable to establish its validity then a short diagnostic paper about the nonlinear response will be produced, leaving the mechanisms as future work. We will then move on to another topic (the next chapters of my thesis), which could be on the (nonlinear) impacts of the annual cycle on ENSO development, persistence and strength.

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Yatagai, A., and Coauthors, 2012: APHRODITE: Constructing a long-term daily gridded precipitation dataset for Asia based on a dense network of rain gauges, B. Am. Meteor. Soc. , 93, 1401-1415, doi:10.1175/BAMS-D-11-00122.1.

Progress Report Title: **Preparation GFDL Data Publishing Infrastructure to CMIP6**

Principal Investigator: Serguei Nikonov (Princeton Earth System Modeler)

CICS/GFDL Collaborator: V. Balaji (Princeton), Aparna Radhakrishnan (GFDL/Engility), Hans Valhenkamp (GFDL/NCAR)

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: Preparation of GFDL data publishing infrastructure to CMIP6 project which included Curator system adaptation to new architecture of data model, participating in MIPs data requests elaboration, and efforts estimation burdened on scientific community

Methods and Results/Accomplishments:

CMIP6 is going to be a major effort of the world climate community during next two years. In conjunction with this, it is of vital importance to assess the resources required for the project's fulfilment as accurately as possible. These investigations were done globally -- among the world community, and locally -- in GFDL. The results were reported at the Earth System Grid Federation Conference (Washington, DC) and used by the CMIP6 Steering Committee for project tuning.

Another substantial constituent was technical work for the adaptation of the Curator system to comprehend the cardinally redesigned CMIP6 data model. According to this, the Curator database has gotten a new variables relational structure, and the correspondent counterparts program modules were modified. Among them, the system core - SQL/XML mapper and publishing module - fremetar (FRE metadata rewriter) with accompanying tools. Currently, the system is under final review and testing to be ready for publishing the first CMIP6 runs.

CMIP6 preparation didn't stop routine efforts for publishing small GFDL projects (MDTF, FLOR). For such projects, a simple website was developed by summer intern Daniele Schneider under my direction. It's going to be simple data distribution tool for small projects and limited communities.

Presentations:

CMIP6 "Impact" on scientific community. S. Nikonov, V. Balaji, E. Mason, A. Radhakrishnan, N. Sharadjaya, H. Vahlenkamp. 6th Annual ESGF F2F Conference. Dec 6-9, 2016. Washington, DC.

Earth System Model Development and Analysis using FRE-Curator and Live Access Servers: On-demand analysis of climate model output with data provenance. A. Radhakrishnan, V. Balaji, R. Schweitzer, S. Nikonov, K. O'Brien, H. Vahlenkamp, E. Burger. AGU 2016 Fall Meeting. Dec 12-16, 2016. San Francisco, Ca.

Progress Report Title: **Observational Constrains on the Photochemistry of SO_2**

Principal Investigator: Fabien Paulot (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Larry Horowitz (GFDL), Songmiao Fan (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: Sulfate is an important contributor to surface air pollution and aerosol forcing. However its photochemical sources remain poorly constrained. Here, we show that observed changes in the seasonality of sulfate in the US can help better constrain the relative importance of the different photochemical sources of sulfate.

Methods and Results/Accomplishments:

Stringent controls have reduced U.S. SO_2 emissions by over 60% since the late 1990s. Observations from the U.S. EPA CASTNET network show that these controls have successfully reduced sulfate aerosols, an important component of fine particulate matter, in summer. However much less reduction has been observed in winter and at many locations sulfate concentrations are now greater in winter than in summer.

Using the Geophysical Fluid Dynamics Laboratory AM3 chemistry-climate model, we show that the change in the seasonality of sulfate provides a powerful constrain on the representation of SO_2 photochemistry in models. In particular oxidant limitation during winter causes winter sulfate concentration to be sensitive to primary sulfate emissions (at high SO_2 emissions), in-cloud titration of H_2O_2, and in-cloud oxidation by O_3 (at low SO_2 emissions). The increase in the ratio of winter to summer sulfate in the last decade is best explained by the O_3 reaction, whose rate coefficient has increased over the past decades because of increasing NH_3 emissions and decreasing SO_2 emissions, both of which lower cloud water acidity. We show that in the absence of anthropogenic NH_3, cloud pH would remain too acidic for ozone to oxidize SO_2. This suggests that NH_3 contributes to poor air quality in winter both directly (via ammonium nitrate) and indirectly (via enhanced sulfate production). Our model further suggests that O_3 reaction rate coefficient will keep increasing in coming decades reducing the efficiency of SO_2 emission controls.

We also compare the observed change in the seasonality of sulfate with that simulated by 11 models that participated in Coupled Model Intercomparison Project 5. Only five models qualitatively capture the change in the seasonality of sulfate. This suggests that a better representation of cloud pH is needed to improve sulfate simulations.

Publications:

Paulot, F., S. Fan, and L. W. Horowitz *(*2017*)*, Contrasting seasonal responses of sulfate aerosols to declining SO_2 emissions in the Eastern U.S.: Implications for the efficacy of SO_2 emission controls, Geophys. Res. Lett., 44, 455–464, doi:10.1002/2016GL070695.

Presentations:

Paulot, F., Invited speaker at IGAC: Impact of natural and anthropogenic surface heterogeneities on N deposition and NH_4NO_3.

Paulot, F., Poster presentation at AGU Contrasting seasonal responses of sulfate aerosols to declining SO_2 emissions in the Eastern U.S.: Implications for the efficacy of SO_2 emission controls.

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: Sources of uncertainties in 21st century projections of potential ocean ecosystem stressors

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 (Rodgers et al., 2015), and second (Frölicher et al., 2016) results of this research have now been published. These studies address the timescales over which anthropogenic changes in ecosystem stressors can be expected to emerge above the natural background variability. This study of Frölicher et al. (2016) was conducted through collaboration with Charles Stock at GFDL.

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. This work is being pursued through collaboration with GFDL scientists Delworth, Zhang, and Dunne.

An extension of the work with the large ensemble simulations has been pursued through collaboration with Brendan Carter (NOAA-PMEL/U. Washington). For this work, the large ensemble suite of 30 runs with ESM2M was used to assess the detectability of biogeochemical aspects of ocean acidification (OA) on the marine alkalinity distribution from decadally repeated hydrographic measurements such as those produced by the Global Ship-Based Hydrographic Investigations Program (GO-SHIP). This work resulted in the publication of the study of Carter et al. (2016). Further collaboration with Brendan Carter focused on changes in carbon storage and acidification in the North Pacific, and resulted in the publication Carter et al. (2017).

Work has also been conducted on quantifying the rate and patterns and mechanisms regulating the spread of anthropogenic carbon in the ocean, and thereby pathways of ocean acidification. This has resulted in the publication of Iudicone et al. (2016). This work identified pathways and mechanisms controlling the uptake of perturbations carbon by the ocean, and serves as the basis for continuing efforts to interpret GO-SHIP carbon measurements.

Outreach Activities: A summer undergraduate intern was hosted last summer, Erin McCabe (Princeton U., funded by the Princeton Environmental Institute). The work pursued by Erin has continued through into a Junior Project at Princeton, where NOAA's MOM5-TOPAZ model is being used to interpret GO-SHIP measurements.

Publications:

Carter, B.R., T.L. Frölicher, J.P Dunne, K.B. Rodgers, R.D. Slater, and J.L. Sarmiento (2016), When can ocean acidification impacts be detected from decadal alkalinity measurements?, Global Biogeochem. Cycles, 30, doi:10.1002/2015GB005308.

Carter, B.R., R.A. Feely, S. Mecking, J.N. Cross, A.M. Macdonald, S.A. Siedlecki, L.D. Talley, C.L. Sabine, F.J. Millero, J.H. Swift, A.G. Dickson, and K.B. Rodgers (2017), Two decades of Pacific anthropogenic carbon storage and ocean acidification along Global Ocean Ship-based Hydrographic Investigations Program sections P16 and P02, Global Biogeochem. Cycles, 31, doi:10.1002/2016GB005485.

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, Global Biogeochemical Cycles, 30(8), doi:10.1002/2015GB005338.

Iudicone, D., K.B. Rodgers, Y. Plancherel, O. Aumont, T. Ito, R.M. Key, G. Madec, and M. Ishii (2016), The formation of the ocean's anthropogenic carbon reservoir, Scientific Reports, 6, 35473, doi:10.1038/srep35473.

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

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

CICS/GFDL Collaborator: Gabriel Vecchi (GFDL)

Other Participating Researchers: 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 the tropical North Atlantic

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 a combination of the Geophysical Fluid Dynamics Laboratory (GFDL) Coupled Model CM2.1 (Delworth et al., 2007) and 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 CM2.5-FLOR'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 over an additional 100 years. Using the climate state at predetermined years, as initialization, we create several 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 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 and calculating the model ensemble average.

Changes in dust atmospheric concentration lead to direct radiative responses from the top of the atmosphere (ToA) through to the surface along with regional hydrologic and thermodynamic responses, depending crucially on the amount of aerosol absorption versus scattering. There are large anomalies in the West African monsoon due to moist enthalpy changes throughout the atmospheric column over West Africa. In the tropical North Atlantic, there are significant responses in the upper ocean heat budget arising from the wind stress curl response to a shift in the Atlantic Intertropical Convergence Zone and associated mixed layer depth anomalies.

Simultaneously, there are changes in tropical cyclone activity across the North Atlantic Ocean with the largest response occurring in the most absorbing and scattering optical regimes. There are also non-negligible anomalies in the North Pacific and Indian Oceans. A relationship between accumulated cyclone energy and ToA radiative flux anomalies is found to explain the North Atlantic anomalies while several known climate variations are theorized to explain the far-field response to the dust forcing.

Changing the optical regime of dust alone is found to lead to radiative anomalies larger than simply adding dust. As dust becomes more scattering, there is a net global cooling focused in the Northern Hemisphere and a general equatorward shift of tropical precipitation and the mid-latitude atmospheric jets. This leads to a preferential negative phase of the North Atlantic Oscillation, a decrease in the Atlantic Meridional Overturning Circulation, and associated changes to the global meridional heat transport.

Using the above methods, I graduated with a PhD from the Princeton University Atmospheric and Oceanic Sciences Program in August of 2016.

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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.

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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.

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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, 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, 2016: The climatological effect of perturbations in atmospheric burden and optical properties of Saharan dust. Proceedings, AGU Fall Meeting, San Francisco, CA.

Strong, J. D. O., August 2016: The Climatological Effect of Perturbations in Atmospheric Burden and Optical Properties of Saharan Dust, Ph.D. thesis, Princeton University.

Strong, J. D. O., G. A. Vecchi, and P. Ginoux, 2017: The climatological effect of Saharan dust on global tropical cyclones in a fully coupled GCM. in prep.

Strong, J. D. O., G. A. Vecchi, and P. Ginoux, 2017: Sensitivity of climate simulations to choice of dust aerosol optical properties. in prep.

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 (GFDL), Gabriel Vecchi (GFDL), Tom Delworth (GFDL), Anthony Rosati (GFDL), Xiaosong Yang (GFDL)

Other Participating Researchers: 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), 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:

Fish populations 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 (Tommasi et al. 2017a). 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 suggests that current seasonal sea surface temperature forecasts can enable managers to more proactively adjust fishing levels to changing environmental conditions, increasing catch during favorable periods while protecting the stock from collapse during unfavorable conditions, leading to more

effective catch targets.

This work is part of a larger body of research that involves scientists from across NOAA at NOAA Research, including GFDL, ESRL, and PMEL, NOAA Fisheries, NOAA's National Weather Service, and NOAA's National Ocean Service. The aim of this broad research effort is to apply advances in seasonal to decadal forecasting to NOAA's mission. To foster use of these forecasts within NOAA and the larger scientific community, we published a review paper (Tommasi et al. 2017b) establishing a common understanding of the prospects and challenges associated with the application of seasonal to decadal scale forecasts in a fisheries management context and how to meet them. This paper synthesizes talks and discussions from a workshop on the Application of Seasonal to Decadal Climate Predictions for Marine Resource Management we organized at Princeton University on June 3-5 2015. In addition to seasonal forecasts, the workshop identified multi-annual forecasts as of potential value to marine resources decisions. Currently, Dr. Tommasi is leading a paper assessing multi-annual SST anomaly forecast skill in coastal systems (Tommasi et al., in prep).

Outreach Activities: Co-supervised a Princeton University Senior Thesis Project (in collaboration with Rebecca Asch); PICES member of the Scientific Steering Committee for the ICES/PICES 6th Zooplankton Production Symposium in May 2016 in Bergen, Norway; Co-convener of session on "Seasonal to Decadal Prediction of Marine Systems: Opportunities, Approaches and Applications" at the 2016 ICES Annual Science Conference; Q&A interview with NOAA, available at <http://research.noaa.gov/News/NewsArchive/LatestNews/TabId/684/ArtMID/1768/ArticleID/12076/Meet-D233sir233e-Tommasi-Pioneer-in-new-field-of-fish-forecasting.aspx>.

Publications:

Tommasi, D., Alexander, M., Delworth, T., Yang, X., Rosati, T., Vecchi, G. (in prep). Multi-annual climate predictions for fisheries: a case for optimism. To be submitted to Frontiers in Marine Science.

Tommasi, D., Stock, C., Pegion, K., Vecchi, G., Methot, R.D., Alexander, M., and Checkley, D. (2017a). Improved management of small pelagic fisheries through seasonal climate prediction. Ecological Applications 27, 378-388.

Tommasi, D., Stock, C., Hobday, A.J., Methot, R., Kaplan, I.C., et al. (2017b). Managing marine resources in a dynamic environment: the role of seasonal to decadal climate forecasts. Progress in Oceanography 152, 15-49.

Tommasi, D., Jacox, M.G., Alexander, M.A., Siedlecki, S., Werner, F.E., Stock, C.A., Bond, N.A. (2017c). Seasonal forecasts of ocean conditions in the California Current Large Marine Ecosystem. US CLIVAR Variations Newsletter 15, 41-46.

Presentations:

Tommasi, D., Stock. C., Pegion, K., Vecchi, G., Methot, R.D., Alexander, M., and Checkley, D. (2017). Seasonal Climate Predictions to Improve Fisheries Management Decisions. Oral Presentation at the 2017 ICES/PICES Drivers of Dynamics of Small Pelagic Fish Resources Symposium in Victoria, BC, Canada.

Tommasi, D., Stock. C. (2016). Value of ocean prediction to fisheries management. Oral Presentation at the 2016 ICES Annual Science Meeting in Riga, Latvia.

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.

Progress Report Title: **U.S. Extreme Precipitation and River Flooding in Global Coupled Models**

Principal Investigator: Karin van der Wiel (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Gabriel Vecchi and Sarah Kapnick (GFDL)

Other Participating Researchers: James Smith (Princeton)

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 (40%)
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts (60%)

Objectives: To investigate the representation of extreme precipitation in high-resolution global climate models; to use these models for analysis of the causes of Mississippi flooding and the attribution of the extreme events

Methods and Results/Accomplishments:

Extreme meteorological events strongly impact society. Predicting extreme events with strong impacts is and understanding changes in a changing climate is therefore of large importance. I have started by investigating daily precipitation extremes over the contiguous U.S. I have found that the high-resolution GFDL models (FLOR and HiFLOR) significantly improve the simulation of these extremes compared to lower resolution models. Based on these findings, I used these models for two further studies: (1) In August 2016 a stationary low pressure system caused heavy precipitation over south Louisiana. The rain led to devastating flooding over a large area, destroying many thousands homes, killing thirteen people. Together with an international team of scientists I worked on an attribution study, in which it was concluded such heavy rain events are now 1.4 times more likely than at the beginning of the 20th century. The results were picked up by many media outlets. (2) Using the full coupled model, including the river routing module in its land component, I further studied the full complexity of Mississippi river flooding. The largest Mississippi floods are caused by an anomalous amount of snow melt in combination with above normal precipitation. The importance of snow melt indicates there is some predictability of these floods possible, based on snow pack in the catchment. Finally, due to decline of snow fall and snow pack in a warmer future, the largest Mississippi floods decrease in intensity.

Finally, I worked on a side project not related to extreme precipitation. I used the high-resolution model to investigate the distribution of mild weather now and changes of mild weather in the future. Mild weather is the weather we hope for when planning outdoor activity. It doesn't cause immediate large societal impacts, but we argue it is important nevertheless. The results were met with large media interest.

Outreach Activities: I volunteer as a scientist in the 'Letters to a Pre-Scientist' program (more details at www.prescientist.org).

Publications:

K van der Wiel, SB Kapnick, GA Vecchi, WF Cooke, TL Delworth, L Jia, H Murakami, S

Underwood, F Zeng (2016): The resolution dependence of contiguous U.S. precipitation extremes in response to CO2 forcing. Journal of Climate, 29, pp. 7991-8012.

K van der Wiel, SB Kapnick, GA Vecchi (2017): Shifting patterns of mild weather in response to projected radiative forcing. Climatic Change, 140, pp. 649-658.

K van der Wiel, SB Kapnick, GJ van Oldenborgh, K Whan, S Philip, GA Vecchi, RK Singh, J Aright, H Cullen (2017): Rapid attribution of the August 2016 flood-inducing extreme precipitation in south Louisiana to climate change. Hydrology and Earth System Sciences, 21, pp. 897-921. Highlighted article.

K van der Wiel, SB Kapnick, GA Vecchi, JA Smith: Characteristics of great Mississippi flooding events in a coupled climate model (in preparation).

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

Principal Investigator: Bess Ward (Princeton Professor)

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

Other Participating Researchers: Nicolas Van Oostende (Princeton), Enrique. Curchister (Rutgers), Raphael Dussin (Rutgers)

Award Number: NA14OAR4320106

Task III: Individual Projects

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: 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 (chla >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-running 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, which is grazed only by large zooplankton. 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 and aggregation susceptibility. We then adapted the model configuration to adjust the implicit size characteristics of the three non-diazotrophic phytoplankton size 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 were implemented in a new version of the COBALT model.

These modifications to the COBALT model address one of the two main hypotheses about why current models fail to represent the full dynamic range observed in chlorophyll concentrations – the importance of phytoplankton community composition and trophic decoupling. The second main hypothesis is that low resolution in the physical models in which COBALT is imbedded effectively average out the very high observed chla concentrations. We addressed this possibility using the very recent development of a Regional Ocean Modeling System (ROMS) implementation of COBALT by Raphael Dussin and Enrique Curchitser (Rutgers) applied to the California Current System. Thus we were able 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). We found, by implementing and comparing the existing 1° and 1/10° COBALT model configuration with the even higher resolution ROMS (i.e. control climatology), that refinements in the physical representation of the system did indeed slightly improve the high chla representation. Addition of the improved ecological/biogeochemical configurations in the ROMS implementation of COBALT was used to assess mechanisms of acute high chla accumulation. Runs of 11 years perturbations were 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.

The main findings are: The ROMS/COBALT models combined to greatly improve the modeled range and median level of chla relative to previous models, and to much more closely simulate satellite observations, especially in the productive coastal regions of interest. The highest chla was adjacent to the coast with an offshore gradient much more realistic than previous models with only 2 phytoplankton groups. The new model also simulated aggregation loss and resulted in simulated near bottom oxygen concentrations that accurately represent observations of nearshore hypoxia. Again, the range of O_2 concentrations, as well as their geographical representation, was much improved in the high resolution model with three phytoplankton groups. A manuscript is being readied for submission (see below).

Outreach Activities: Two undergraduate students, one GEO major and one CEE major, performed JP or ST work in the lab on projects related to CICS project. They grew diatom cultures and performed nutrient uptake experiments in order to determine growth and nutrient kinetic parameters for future use in ecosystem models. Both students met regularly with Ward and Van Oostende and were advised in the lab by Van Oostende. Van Oostende also collaborated with Danielle Schmitt to implement a new laboratory module (measuring phytoplankton traits and growth as a function of light limitation) in GEO 202, the science major track of Introductory Oceanography. Student evaluations listed this module as their favorite, because of the hands on experience and the opportunity to general real data.

References:

Armstrong RA (2003) A hybrid spectral representation of phytoplankton growth and zooplankton response: The “control rod” model of plankton interaction. Deep Sea Research Part II: Topical Studies in Oceanography 50:2895-2916.

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Stock CA, Dunne JP, John JG (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.

Taylor AG, Goericke R, Landry MR, Selph KE, Wick DA, Roadman MJ (2012) Sharp gradients in phytoplankton community structure across a frontal zone in the California Current Ecosystem. J Plankton Res 34:778-789.

Thingstad TF (1998) A theoretical approach to structuring mechanisms in the pelagic food web. Eutrophication in Planktonic Ecosystems: Food Web Dynamics and Elemental Cycling. Springer.

Van Oostende N, Dunne JP, Fawcett SE, Ward BB (2015) Phytoplankton succession explains size-partitioning of new production following upwelling-induced blooms. Journal of Marine Systems.

Venrick EL (2002) Floral patterns in the California current system off southern California: 1990 1996. Journal of Marine Research 60:171-189.

Publications:

Van Oostende, N., R. Dussin, C. A. Stock, A. D. Barton, E. Curchister, J. P. Dunne and B. B. Ward (to be submited to *Progress in Oceanography*). Simulating the dynamic range of chlorophyll concentration from the oligotrophic ocean gyres to coastal upwelling systems.

Van Oostende, N., R. Dussin, C. A. Stock, A. D. Barton, E. Curchister, J. P. Dunne and B. B. Ward. Simulating the dynamic range of chlorophyll concentration from the oligotrophic ocean gyres to coastal upwelling systems (ASLO presentation, February 2017).

Progress Report Title: **Geoengineering Outlet Glaciers and Ice Streams**

Principal Investigator: Michael Wolovick (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 Model Applications

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

Objectives: To explore the possibility that mass loss and associated sea level rise from marine-terminating outlet glaciers and ice streams could be delayed through the construction of an artificial sill to block access of warm water to the grounding line

Methods and Results/Accomplishments:

Mass loss from Greenland and Antarctica is highly sensitive to the presence of warm ocean water that drives melting of ice shelves and marine terminated glaciers. This warm water resides offshore at depth and accesses the grounding line through deep but narrow troughs and fjords. In this project, I investigate the possibility of blocking warm water transport through these choke points with an artificial sill and I explore whether grounding line retreat and ice sheet mass loss can be delayed or prevented by artificially reducing submarine melt.

In this project, I use a simple width-averaged model of ice stream flow coupled to a buoyant-plume model of submarine melt. The model is based on a flowline model that I previously developed for my thesis. During my past year at Princeton, I have done further model development to adapt the model to the present problem I am trying to address. I added the following major features to the core model: variable flowband width to parameterize the cross-flow dimension, movable grounding lines with subgrid interpolation, the Shallow Shelf Approximation (SSA) version of the governing equations, and a turbulent plume model of submarine melt. In addition, I developed the following capabilities around the model: code and procedures for transforming gridded data representing real glaciers into an along-flow width-averaged coordinate system, and an inverse model to infer basal boundary conditions from observed width-averaged velocity data. The latter two pieces of development were necessary to produce model input files that accurately represent real, as opposed to idealized, glaciers in a width-averaged sense.

Using this new version of the model, I find that grounding line retreat and sea level rise can be delayed or reversed for hundreds of years if warm water is prevented from accessing outlet glaciers and ice-shelf cavities. Glaciers with a floating shelf exhibit a strong response to the presence of the artificial sill regardless of the choice of calving law, while tidewater glaciers require a strong linkage between submarine melt and iceberg calving for the artificial sill to have an effect. As a result of this difference and as a result of differing degrees of overdeepening in the basal topography, Antarctica and Greenland present very different societal cost-benefit analyses. Intervention in Greenland would be low-cost and low-reward: the volume of the artificial sill is comparable to existing large public works projects such as the Dubai Islands or the Suez Canal, but the magnitude of averted sea-level rise is small, the success of the intervention depends on the choice of calving law, and the glaciers return to their non-geoengineered trajectories within one to two centuries. Intervention in Antarctica, on the other hand, would be high-cost

and high-reward: the volume of the artificial sill is one to two orders of magnitude greater, but the averted sea level rise is much larger, the intervention is successful regardless of the choice of calving law, and the ice streams remain far from their non-geoengineered trajectories throughout the 1000 year duration of the model runs. In both cases, an artificial sill cannot save the glaciers forever if the climate continues to warm and surface melt continues to increase, but glacial geoengineering may offer society a way to delay irreversible grounding line retreat and thus buy time while emissions reduction and carbon removal efforts are underway.

Publications:

Wolovick, M. J., and T. T. Creyts (2016), Overturned folds in ice sheets: Insights from a kinematic model of traveling sticky patches and comparisons with observations, J. Geophys. Res. Earth Surf., 121, doi:10.1002/2015JF003698.

Presentations:

Wolovick, M., Sergienko, O. (2016), Geoengineering Glacial Fjords, Abstract C21B-0681 presented at 2016 Fall Meeting, AGU, San Francisco, CA, 12-16 December.

Wolovick, M., Sergienko, O. (2016), Geoengineering Ice Streams with Artificial Sills, presented at WAIS Workshop, Sterling, VA, 3-6 October.

Wolovick, M., Sergienko, O. (2016), Geoengineering Glacial Fjords, presented at IGS International Symposium on Interactions of Ice Sheets and Glaciers with the Ocean, La Jolla, CA, 10-15 July.

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 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 investigate polynya signal transport mechanisms in the deep and abyssal oceans and the timescales on which these mechanisms act

Methods and Results/Accomplishments:

We use GFDL CM2G, a coupled climate model with an isopycnal ocean (GOLD; *Adcroft and Hallberg 2006*) to explore polynya signal transport mechanisms. Polynyas are periodically forced every 29 years via increased diapycnal diffusivity in a region of the Weddell Sea. Dye tracer is added to each polynya in order to determine where the polynya water spreads. A total of 63 polynyas are forced during the length of the simulation, and composites of the events are used to examine the polynya signal in the deep and abyssal oceans, following *Zanowski et al., 2015*.

We find that polynya signals are transported via two dynamical mechanisms that act on different timescales and spread at different rates: 1) large-scale waves such as Kelvin and planetary and topographic Rossby waves that on interannual-to-decadal timescales and 2) advection that acts on decadal-to-centennial timescales. The polynya advective signal spreads globally and generally follows the pathways of Antarctic Bottom Water (Fig. 1). Wave signals are also present globally, and manifest themselves as isopycnal depth displacements, or interface height anomalies (Fig. 2). Both waves and advection give rise to temperature anomalies on isobaths. We attempt to quantify the wave and advective contributions to these temperature changes by constructing an advective cooling field and comparing this to the total minimum cooling from the composite polynya (Fig. 3). The advective cooling field is constructed by scaling the tracer field by the mean cooling in the polynya (-0.2˚C). In most locations, waves dominate the contribution to the cooling, as advection can explain less than half of the total cooling.

Recently, we have moved away from polynya research to examine ocean ventilation. In this second project, we have developed a new ideal age tracer, λ-age, that addresses some of the problems associated with traditional ideal age tracer in models. λ-age is equivalent to ideal age, but with the addition of a decay rate λ that allows this new tracer to equilibrate in the interior ocean faster than traditional ideal age. Preliminary results indicate that λ-age is appropriate for determining thermocline water ventilation ages, and it may also be applicable in the deep ocean, but further work is required to verify this.

Finally, all of the research described above is part of my dissertation (*Zanowski 2017*) that I successfully defended on December 2, 2016.

Outreach Activities: PPPL Young Women's Conference, Princeton Prison Teaching Initiative, Science Advisor for ACCESS: Artists and Scientist Collaborations at the New York Hall of Science

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: 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., 2017. The influence of Antarctic open-ocean polynyas on the abyssal ocean. Ph.D. Dissertation, Princeton University, Proquest Dissertations Publishing 10248291.

Zanowski, H., R. Hallberg, and J.L. Sarmiento, 2017: Weddell polynya pathways in the global abyssal oceans (In prep to be submitted to Journal of Physical Oceanography).

Zanowski, H., A. Shao, and R. Hallberg, 2017: A new ideal age tracer. (In prep).

Figures:

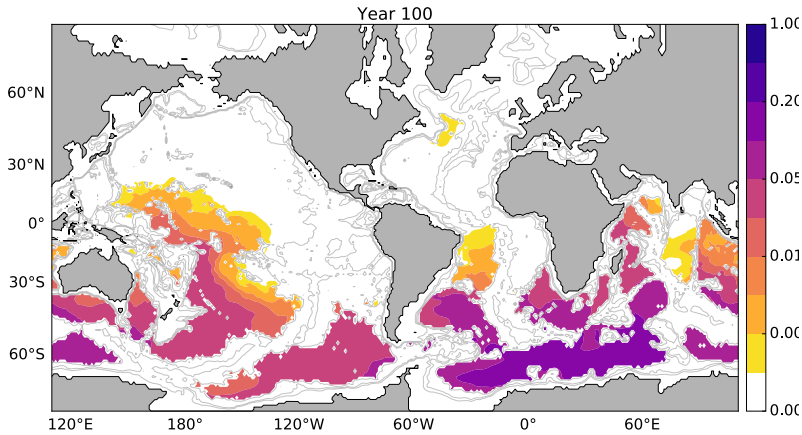

Figure 1. Composite tracer mass fraction (kg kg^{-1}) at 4200 m after 100 years.

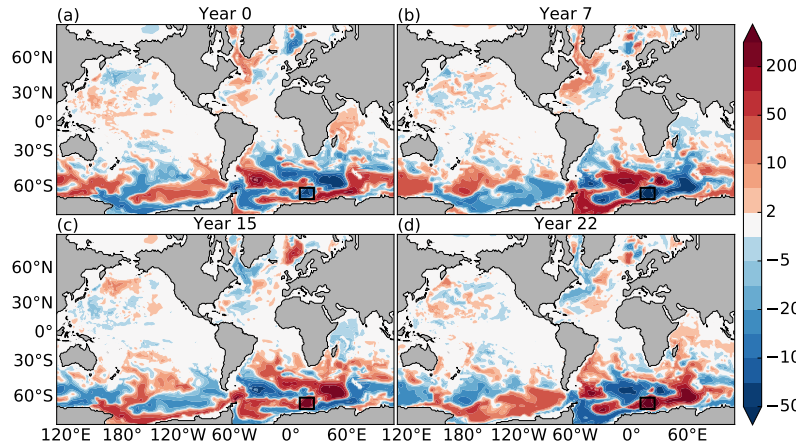

Figure 2. Bandpassed composite interface height anomalies (m) on σ_2=36.99 kg m^{-3} at (a) 0, (b) 7, (c) 15, and (d) 22 years relative to the polynya start year. Black boxes mark the polynya region.

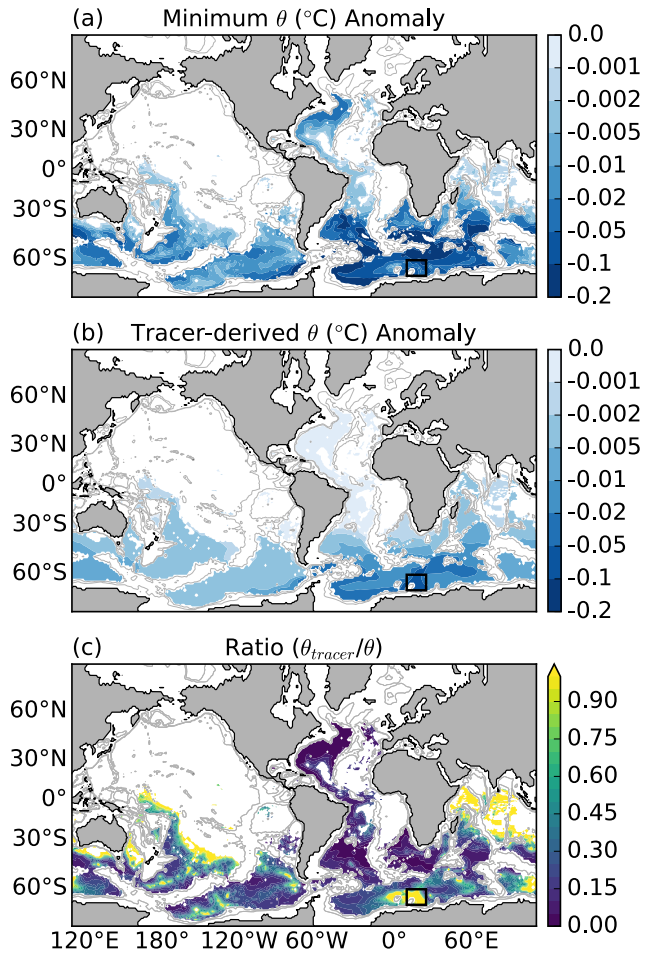

Figure 3. Composite 3900 m (a) total minimum cooling (˚C), (b) constructed advective cooling (˚C), and (c) the ratio of (b) to (a). The total minimum cooling is calculated by taking the composite minimum temperature anomaly at each point over the 29-year polynya period. The advective cooling field is constructed by multiplying the average cooling in the polynya region (-0.2˚C) by the composite maximum tracer field. Ratios above 0.5 indicate that advection likely causes the majority of the cooling, while ratios below 0.5 indicate that large-scale waves likely cause the majority of the cooling. Black boxes mark the polynya region

Progress Report Title: **Decadal Detectability of Anthropogenic Hydroclimate Changes on Regional and Global 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 project aims to assess the decadal shifts of hydroclimate mean state caused by anthropogenic forcing in near-term projections.

Methods and Results/Accomplishments:

Future changes in hydroclimate resulting from anthropogenic forcing consist of shifts in mean state and possible changes in internal variability. Considering the inherently limited predictability of internal variability owing to the chaotic nature of climate system, our confidence in projections of future hydroclimate changes on decadal and longer time scales relies on a faithful assessment of shifts in mean state. Previous studies assessing the mean state shifts focused on long-term projections (e.g., end of current century) because of both the low signal to noise ratio and the lack of systematic data required to resolve internal variability in near-term projections. However, near-term projections of hydroclimate changes are more relevant to adaptation and mitigation planning.

Here we assess the near-term shifts of hydroclimate (precipitation minus evaporation) mean state caused by anthropogenic forcing, using three long preindustrial simulations and three large ensembles of historical-to-future experiments from two state-of-the-art climate models developed at GFDL and NCAR, respectively. This large volume of simulations enables us to estimate the decadal evolution of hydroclimate mean state. Focusing first on projections of regional hydroclimate changes over North America, we find consistent results between the two models despite their many differences. Specifically, anthropogenic forcing will cause significant shifts in hydroclimate mean state over large parts of North American land and surrounding oceans by 2050 relative to the 1950~1999 mean state, with earlier shifts towards moistening in high latitudes and drying in subtropics. During cold seasons, northeastern and southwestern North America will experience the earliest significant anthropogenic moistening and drying, respectively, while during warm seasons, central North America will experience the earliest significant drying. In few regions without significant shifts in hydroclimate mean state, the lack of detectable anthropogenic signal is due to a combination of weak hydroclimate changes and large uncertainty from internal decadal variability, the latter of which arises mostly from unpredictable atmospheric internal dynamics.

In addition to North America, we extend our analysis to the whole globe and find robust results between the two models. The earliest shifts in hydroclimate mean state caused by anthropogenic forcing occur in high latitudes, tropical Pacific, eastern basins of subtropical Pacific and Atlantic and over parts of land such as southeastern South America (during local summer) and northern Eurasia (during local

winter). These model results highlight the role of anthropogenic forcing in the near-term hydroclimate changes and have implications for mitigation and adaptation planning.

Outreach Activities: (1) volunteered at the New Jersey Ocean Fun Days to conduct experiments (ice melting rate in fresh versus sea water) and explain sciences to the public, May, 2016; (2) co-mentored (with Liwei Jia) an internship student, Clair Miles, from Stanford University, June-September, 2016.

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. J. Climate, 29, 8515-8534, doi: http://dx.doi.org/10.1175/JCLI-D-16-0287.1.

Zhang, H. and T. Delworth, 2017a: Decadal Detectability of Anthropogenic Hydroclimate Changes over North America. in prep. for J. Climate.

Zhang, H. and T. Delworth, 2017b: Decadal Detectability of Global Anthropogenic Hydroclimate Changes in Near-term Projections. in prep. for GRL.

Presentations:

Zhang, H., Detection, Attribution and Projection of Regional Rainfall Changes On (Multi-) Decadal Time Scales: A Focus on Southeastern South America , CLIVAR Open Science Conference in Qingdao in September, 2016.

Zhang, H., Detection, Attribution and Projection of Regional Rainfall Changes On (Multi-) Decadal Time Scales: A Focus on Southeastern South America , AGU annual fall meeting in December, 2016.

Progress Report Title: **Decadal Climate Variability and Predictability**

Principal Investigator: Liping Zhang (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Tom Delworth (GFDL)

Other Participating Researchers: Xiaosong Yang (UCAR), Richard G. Gudgel (GFDL), Liwei Jia (Princeton), Gabriel A. Vecchi (GFDL) 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 access the decadal predictability of Southern Ocean SST and its associated climate impacts

Methods and Results/Accomplishments:

This study explores the potential predictability of the Southern Ocean (SO) climate on decadal timescales as represented in the GFDL CM2.1 (Delworth et al. 2006) model using prognostic methods. We conduct perfect model predictability experiments starting from ten different initial states, and show potentially predictable variations of Antarctic bottom water formation (AABW) rates on time scales as long as twenty years. The associated Weddell Sea (WS) subsurface temperatures and Antarctic sea ice have comparable potential predictability as the AABW cell. The predictability of sea surface temperature (SST) variations over the WS and the SO is somewhat smaller, with predictable scales out to a decade. This reduced predictability is likely associated with stronger damping from air-sea interaction. As a complement to our perfect predictability study, we also make hindcasts of SO decadal variability using the GFDL CM2.1 decadal prediction system. Significant predictive skill for SO SST on multi-year time scales is found in the hindcast system. The success of the hindcasts, especially in reproducing observed surface cooling trends, is largely due to initializing the state of the AABW cell. A weak state of the AABW cell leads to cooler surface conditions and more extensive sea ice. Although there are considerable uncertainties regarding the observational data used to initialize the hindcasts, the consistency between the perfect model experiments and the decadal hindcasts at least gives us some indication as to where and to what extent skillful decadal SO forecasts might be possible.

References:

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

Publications:

Liping Zhang, Thomas L. Delworth, Xiaosong Yang, Richard G. Gudgel, Liwei Jia, Gabriel A. Vecchi and Fanrong Zeng, 2017: Estimating decadal predictability for the Southern Ocean using the GFDL CM2.1 model. Submitted to Journal of Climate (In the first revision).

Liping Zhang, Thomas L. Delworth and Liwei Jia, 2017: Diagnosis of decadal predictability of

Southern Ocean sea surface temperature in the GFDL CM2.1 model. Submitted to Journal of Climate. (In the second revision).

Thomas L. Delworth, Fanrong Zeng, Gabriel A. Vecchi, Xiaosong Yang, Liping Zhang and Rong Zhang, 2016: The North Atlantic Oscillation as a driver of rapid climate change in the Northern Hemisphere. Nature Geoscience, 9, 509-512.

Thomas L. Delworth, Fanrong Zeng, Liping Zhang, Rong Zhang, Gabriel Vecchi, Xiaosong Yang, 2016: The central role of ocean dynamics in connecting the North Atlantic Oscillation to the extratropical component of the Atlantic Multidecadal Oscillation, Journal of Climate, in press, JCLI-D-16-0358.

Liping Zhang and Thomas L. Delworth, 2016: Impact of the Antarctic bottom water formation on the Weddell Gyre and its northward propagation characteristics in GFDL model, Journal of Geophysical Research: Oceans, 121,5825-5846.

Liping Zhang and Thomas L. Delworth, 2016: Simulated response of the Pacific decadal oscillation to climate change, Journal of climate, 24, 3971-3988.

Liping Zhang, Thomas L. Delworth and Fanrong Zeng, 2016: The impact of multidecadal Atlantic meridional overturning circulation variations on the Southern Ocean. Climate Dynamics, p1-21, doi:10.1007/s00382-016-3190-8.

Shujun Li, Liping Zhang and Lixin Wu, 2017, Decadal potential predictability of upper ocean heat content over the twentieth century, Climate Dynamics, doi 10.1007/s00382-016-3513-9.

Presentations:

Liping Zhang and Thomas L. Delworth, 2017: Simulated response of the Pacific decadal oscillation to climate change. Poster. 97th American Meteorological Society Annual Meeting, Seattle, WA.

Liping Zhang and Thomas L. Delworth, 2016: Simulated response of the Pacific decadal oscillation to climate change. Poster. NOAA/GFDL Poster Expo.

Liping Zhang and Thomas L. Delworth, 2016: Impact of the Antarctic bottom water on the Weddell Gyre and its northward propagation characteristics in GFDL model Poster. NOAA/GFDL Poster Expo.

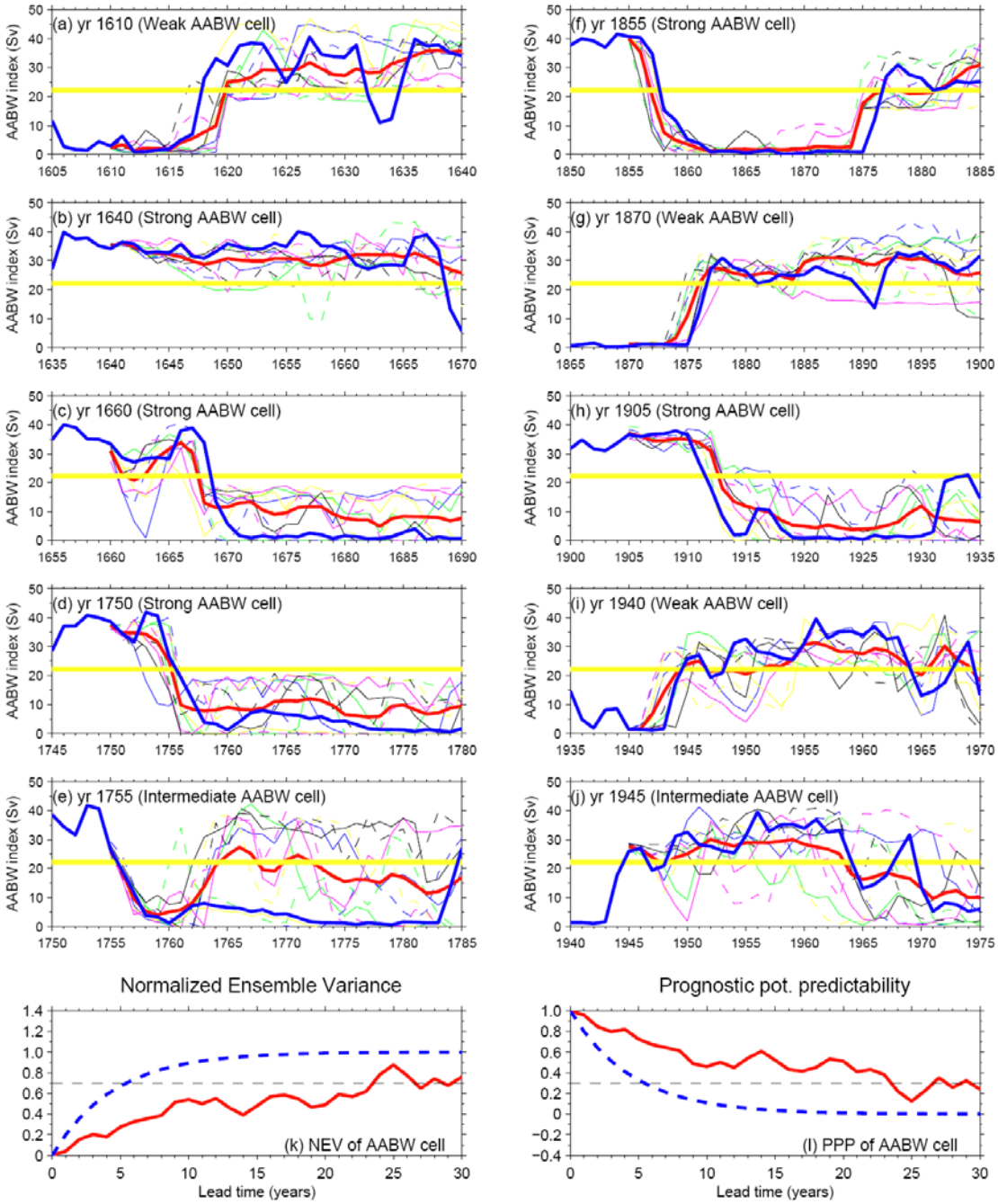

Figure 1: AABW cell index (density space) trajectories in the control run (bold blue line, starts 5 years from the beginning of the ensemble run) and in the "perfect ensemble" predictability experiments (ten thin colored lines) initialized in January 1 of year (a) 1610, (b) 1640, (c) 1660, (d) 1750, (e) 1755, (f) 1855, (g) 1870, (h) 1905, (i) 1940 and (j) 1945. The bold yellow line denotes the long term mean AABW cell index averaged in the last 500 years in the control run. Unit is Sv. (k) Normalized ensemble variance (NEV) and (l) prognostic potential predictability (PPP) averaged over ten ensemble experiments (bold red line), along with the red noise null hypothesis (dash blue line). The dashed black horizontal line denotes the 95% significance level.

	JI Lead Author			NOAA Lead Author			Other Lead Author		
	FY15	FY16	FY17	FY15	FY16	FY17	FY 15	FY16	FY17
Peer-reviewed	22	31	42	7	1	12	27	51	34
Non Peer-reviewed	60*	102*	105*	1*	2*	3*	2*	24*	15*
Chapters in books		1						1	
Ph.D. Thesis	2	3	6						

**Including Presentations*

2016-2017 Peer-Reviewed Publications

- Balaji, Maisonnave, Zadeh, Lawrence, Biercamp, Fladrich, Aloisio, Benson, Caubel, Durachta, Foujols, Lister, Mocavero, Underwood, and Wright: CPMIP: measurements of real computational performance of Earth system models in CMIP6. Geoscientific Model Development, 10, 19–34, doi:10.5194/gmd-10-19-2017.

- Balaji, V., R. Benson, B. Wyman, and I. Held, 2016: Coarse-grained component concurrency in Earth system modeling: parallelizing atmospheric radiative transfer in the GFDL AM3 model using the Flexible Modeling System coupling framework. Geoscientific Model Development, 9, 3605–3616.

- Baldwin, J. and G. Vecchi. Influence of the Tian Shan Mountains on Arid Extratropical Asia. Journal of Climate, July 27, 2016. doi:10.1175/JCLI-D-15-0490.1.

- Barth, M. C., M. M. Bela, A. Fried, P. O. Wennberg, J. D. Crounse, J. Mao, X. Ren, and coauthors, Convective Transport and Scavenging of Peroxides by Thunderstorms Observed over the Central U.S. during DC3, Journal of Geophysical Research: Atmospheres, 121(8), 4272-4295, doi:10.1002/2015JD024570.

- Bushuk, M., R. Msadek, M. Winton, G. Vecchi, R. Gudgel, A. Rosati, X. Yang (2017), Summer enhancement of Arctic sea-ice volume anomalies in the September sea-ice zone, Journal of Climate, 30, 2341–2362, doi: 10.1175/JCLI-D-16-0470.1.

- Carter, B.R., R.A. Feely, S. Mecking, J.N. Cross, A.M. Macdonald, S.A. Siedlecki, L.D. Talley, C.L. Sabine, F.J. Millero, J.H. Swift, A.G. Dickson, and K.B. Rodgers (2017), Two decades of Pacific anthropogenic carbon storage and ocean acidification along Global Ocean Ship-based Hydrographic Investigations Program sections P16 and P02, Global Biogeochem. Cycles, 31, doi:10.1002/2016GB005485.

- Carter, B.R., T.L. Frölicher, J.P Dunne, K.B. Rodgers, R.D. Slater, and J.L. Sarmiento (2016), When can ocean acidification impacts be detected from decadal alkalinity measurements?, Global Biogeochem. Cycles, 30, doi:10.1002/2015GB005308.

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- Chou, C.B., Hedin, L.O., and S.W. Pacala. Stem and foliar responses of tropical rainforest saplings to N,P,K fertilization and light vary with functional group and species identity. Phosphorus Cycling in Terrestrial Ecosystems: Advancing our fundamental understanding through a model-data connection, DOE/ NSF/ INTERFACE workshop, Townsend, TN, May 22-25, 2016.

- Clark, S. K., Ming, Y., and Held, I. M. The role of water vapor in the ITCZ response to hemispherically asymmetric forcings. AGU Fall Meeting, San Francisco, CA, December 2016. Poster Presentation.

- Clark, S. K., Ming, Y., and Held, I. M. The role of water vapor in the ITCZ response to hemispherically asymmetric forcings. WCRP Model Hierarchies Workshop, Princeton, NJ, November 2016. Poster Presentation.

- Doss-Gollin, J, Muñoz, ÁG, Pastén, M. Physical Mechanisms and S2S Predictability of 2015/16 Paraguay River Flooding. Conference Paper. Sub-seasonal to Seasonal Workshop, Columbia University. New York. 2016.

- FitzMaurice, A., F. Straneo, C. Cenedese, M. Andres, Iceberg motion and melt from observational and laboratory studies. Talk presented at: International Symposium on Interactions of Ice Sheets and Glaciers with the Ocean; La Jolla, California, USA, July 2016**.**

- Frazer, M. E., Y. Ming, and I. M. Held. Modeling Water Vapor and Clouds in an Idealized GCM? Poster presentation, Model Hierarchies Workshop, November 2016.

- Frazer, M. E., Y. Ming, and I. M. Held. Understanding Cloud Process with an Idealized model. Poster presentation, AGU Fall Meeting, December 2016.

- Haji-Akbari A, Debenedetti PG, Computational investigation of surface freezing in a molecular model of water. APS March Meeting, Session B26: Chemical Physics of Hydrogen Bonding II. New Orleans, LA, March 13, 2017.

- Haji-Akbari A, Debenedetti PG, Kinetics and mechanism of homogeneous ice nucleation in freestanding nanofilms of supercooled water. AIChE Annual Meeting, Session on Thermodynamics at the Nanoscale. San Francisco, CA, November 17, 2016.

- Haji-Akbari A, Debenedetti PG, Direct calculation of the rate of homogeneous ice nucleation for a molecular model of water. APS March Meeting, Session S31: Ice Nucleation, Amorphous Ices and the Role of Interfaces. Baltimore, MD, March 17, 2016.

- Haseloff, M., Sergienko, O. (2016), The effect of ice shelves on the ice flux at the grounding line and implications for marine ice sheet stability, AGU Fall Meeting, San Francisco, CA, 12.12.2016-16.12.2016 (talk).

- Haseloff, M., Sergienko, O. (2016), The effect of ice shelves on the ice flux at the grounding line and implications for marine ice sheet stability, WAIS workshop, Sterling, VA, USA, 03.10.2016-06.10.2016 (talk).

- Haseloff, M., Sergienko, O. (2016), The effect of ice shelves on grounding line stability, IGS symposium, La Jolla, CA, USA, 10.07.2016-15.07.2016 (talk).

- Haseloff M. and O. Sergienko (2016) The ice flux at the grounding line in flowline models with parameterized buttressing: asymptotic solutions and implications for marine ice sheet stability. AGU Fall Meeting, San Francisco, CA 12-16 December, 2016.

- Jeevanjee, N., Vertical Velocity in the Gray Zone, invited oral presentation at American Geophysical Union Annual Meeting, Dec. 2017, San Francisco CA.

- Jia, L., Oct. 2016, National Oceanic and Atmospheric Administration's 41st Climate Diagnostics and Prediction Workshop: Seasonal Prediction Skill of Northern Extratropical Surface Temperature Driven by the Stratosphere.

- Jia, L., Oct. 2016, National Oceanic and Atmospheric Administration's 41st Climate Diagnostics and Prediction Workshop: The Roles of Radiative Forcing, Sea Surface Temperature, Atmospheric and Land Initial Conditions to U.S. Summer Warming Episodes.

- Johnson, N. C. (December 2016). The impact of sea surface temperature biases on North American precipitation biases and drought variability in a GFDL climate model. 2016 AGU Fall Meeting.

- Johnson, N. C. (November 2016). Increasing occurrence of cold and warm extremes during the recent global warming slowdown. Seminar series at Ewha Womans University in Seoul, Korea (Invited).

- Johnson, N. C. (November 2016). Increasing occurrence of cold and warm extremes during the recent global warming slowdown. Seminar series at Seoul National University in Seoul, Korea (Invited).

- Johnson, N. C. (November 2016). Increasing occurrence of cold and warm extremes during the recent global warming slowdown. Seminar series at National Taiwan University in Taipei, Taiwan (Invited).

- Johnson, N. C. (November 2016). Prospects of subseasonal climate prediction for lead times beyond two weeks. Seminar at Central Weather Bureau in Taipei, Taiwan (Invited).

- Johnson, N. C. (September 2016). Statistical approaches for diagnosing and applying sources of forecast skill to subseasonal predictions. EMS 16th Annual Meeting.

- Jones, Alexandra, D. Paynter, S. Freidenreich, D. Feldman, V. Ramaswamy, W. D. Collins, (Poster Presentation), Reducing the Spread in Modeled Aerosol Radiative Forcing with a Global, Scattering, Line-by-Line Model as Part of RFMIP, AGU Fall Meeting, Monday, December 12, 2016, San Francisco, CA.

- Kam, J., Invited Talk, Climate model assessment of changes in winter-spring streamflow timing over North America, Seoul National University, Nov. 16, 2016, Seoul, South Korea.

- Krishnamurthy, L., Poster presented at GFDL poster EXPO on February 2017, Impact of Strong ENSO events on regional tropical cyclone activity in a high-resolution climate model.

- Krishnamurthy, L., 97th AMS Annual meeting in Seattle January 2017. Presented poster, The Seasonality of the Great Plains Low-Level Jet and ENSO Relationship.

- Laufkötter, C., J.G. John, C. A. Stock, J.P. Dunne, Temperature and Oxygen effects on Remineralization of Particulate Organic Matter, OCB Meeting 2016, Woods Hole, Massachusetts (poster).

- Laufkötter, C., J.G. John, C. A. Stock, J.P. Dunne, Temperature and Oxygen effects on Remineralization of Particulate Organic Matter, Gordon Research Conference on Ocean Biogeochemistry 2016, Hong Kong (poster).

- 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).

- Lee, M., Shevliakova, E., Malyshev, S., Milly, P.C.D., Jaffe, P. Stock, C. (2017), Increased climate variability and extremes amplify risks of coastal hypoxia worldwide: Implications of enhanced basin memory effects on river dissolved nitrogen in the GFDL Earth system modeling framework, AGU Chapman Conference, San Juan, Puerto Rico, USA.

- Legg, S., Internal tide breaking at topography. 20th Australasian Fluid Mechanics conference, 2016. (Invited).

- Legg, S., and the members of the Climate Process Team on internal wave driven ocean mixing: Understanding and representing the role of ocean mixing in the climate system through use of a hierarchy of models. WCRP Model Hierarchies workshop, 2016.

- Legg, S., R. Nazarian, P. Yi, J. Klymak, M. Nikurashin, and M. Buijsman, September 23, 2016: Internal Wave Driven Mixing: Numerical Process Studies of Breaking Internal Tides. CLIVAR, Open Science Conference: Charting the Course for Climate and Ocean Research.

- Li, D., R. Zhang, and T.R. Knutson, Comparison of Low-Frequency Variability of Summer Arctic Sea Ice in Three Coupled Climate Models, AMS Annual Meeting. Seattle, WA, January 2017.

- Lin, Meiyun, Oct 31, 2016, University of Toronto Noble Seminar Series: Linking climate variability to surface ozone trends and extremes (Invited).

- Lin, Meiyun, Sep 30, 2016, Poster presentation at International Global Atmospheric Chemistry (IGAC) Project 2016 Science Conference.

- Lin, Meiyun, Apr-11, 2016, MIT Atmospheric Science Seminar: Climate versus emission drivers of ozone pollution trends and extremes (Invited).

- Lin, Meiyun, Apr-8, 2016, Harvard University Atmospheric Science Seminar: The roles of climate variability on U.S. surface ozone trends and extremes (Invited).

- Lin, P., D. Paynter, L. Polvani, G. Correa, Y. Ming and V. Ramaswamy, 2016: Circulation response to ozone depletion depends on the zonal wind climatology. Talk. AGU Fall meeting, American Geophysical Union, San Francisco, CA.

- Lin, P., and J. Wilson, 2016: Simulate QBO with interactive ozone. Talk. SPARC QBO workshop: the QBO and its global influence-past, present and future, SPARC, Oxford, United Kingdom.

- Lin, Shian-Jiann , Lucas M. Harris, Rusty Benson, Linjiong Zhou, Jan-Huey Chen, and Xi Chen. To- wards a unified prediction system from Weather to Climate time-scale. In 2017 AMS Annual Meeting, Seattle, WA, USA, Jan 24 2017.

- Malyshev, S., E. Shevliakova (2016): Exploring Future Biogeophysical Signal of Land Use and its Uncertainties. Global Land Project, 3rd Open Science Meeting, Beijing, China, October 24-27.

- Mater, B., R. Hallberg, S. Legg, A. Adcroft and J. Nycander, Internal wave driven mixing: representing the propagation and far-field dissipation of internal tides in a global climate model. CLIVAR 2016 Open science conference.

- Melet, A., R. Hallberg, S. Legg, M. Nikurashin, K. Polzin, and A. Adcroft, Internal wave driven mixing: parameterizations and climatic impacts in a climate model. CLIVAR 2016 Open science conference.

- Muhling, B.A., Gaitan, C.F., Stock, C.A., Saba, V.S., Tommasi, D., Dixon, K.W. (2016) Downscaling climate models for ecological forecasting in northeast US estuaries. NOAA ecological Forecasting Meeting, Silver Spring, MD, April 2016.

- Muhling, B.A., Lamkin, J.T., Ingram Jr., G.W., Walter, J.F., Lee, S.K., Liu, Y., Domingues, R., Roffer, M.A., Muller-Karger, F.E., Quattro, J., Lindo Atichati, D. (2016) Ecology and management of Atlantic bluefin tuna under climate variability and change. PICES Annual Meeting, San Diego, CA, October 2016.

- Muñoz, ÁG, Vecchi, GA, Yang, X, Goddard, L, Robertson, AW. Atmospheric cryptography: Using weather regimes to 'crack the code' of subseasonal-to-seasonal extreme rainfall events. Conference paper. 16th EMS/11th ECAC, European Meteorological Society. Trieste (Italy), 2016. Volume: 13: EMS2016-684.

- Muñoz, ÁG, Yang, X, Vecchi, GA, Cooke, WF. Cross-timescale Diagnostics for Coupled Circulation Models. Conference Paper. Sub-seasonal to Seasonal Workshop, Columbia University. New York. 2016. doi: 10.13140/RG.2.2.19490.84164.

- Nazarian, R. and S. Legg, Internal wave scattering in Idealized and Realistic continental slope canyons. 69th annual meeting of the American Physical Society division of fluid dynamics, 2016.

- Nikonov, S., V. Balaji, E. Mason, A. Radhakrishnan, N. Sharadjaya, H. Vahlenkamp. CMIP6 "Impact" on scientific community. 6th Annual ESGF F2F Conference. Dec 6-9, 2016. Washington, DC.

- Paulot, F., Invited speaker at IGAC: Impact of natural and anthropogenic surface heterogeneities on N deposition and NH_4NO_3.

- Paulot, F., Poster presentation at AGU Contrasting seasonal responses of sulfate aerosols to declining SO_2 emissions in the Eastern U.S.: Implications for the efficacy of SO_2 emission controls.

- Popp, Max and Levi G. Silvers, Double and single ITCZs with and without clouds, EGU General Assembly 2016, Vienna, and Austria.

- Popp, Max and Levi G. Silvers, Shifting the ITCZ with longwave and shortwave cloud-radiative effects, EGU General Assembly 2017, Vienna, Austria.

- Pu, B., and P. Ginoux, 2017: Will drought intensify dust activities in the United States? The 97th American Meteorological Society (AMS) Annual Meeting, Seattle, WA.

- Pu, B., and P. Ginoux, 2016: The impact of the Pacific Decadal Oscillation on springtime dust activity in Syria, the American Geophysical Union (AGU) Fall Meeting, San Francisco, CA.

- Radhakrishnan, A., V. Balaji, R. Schweitzer, S. Nikonov, K. O'Brien, H. Vahlenkamp, E. Burger. Earth System Model Development and Analysis using FRE-Curator and Live Access Servers: On-demand analysis of climate model output with data provenance. AGU 2016 Fall Meeting. Dec 12-16, 2016. San Francisco, Ca.

- Ray, S., and A.T. Wittenberg, 2017: Heat budget of the equatorial cold tongue in GFDL FLOR global coupled model, AMS Annual Meeting, January, 2017, Seattle, USA.

- Rees, Shannon L., Shian-Jiann Lin, Lucas M. Harris, Jan-Huey Chen, Rusty Benson, Xi Chen, Zhi Liang, Matthew Morin, and Linjiong Zhou. Improved Global Weather Prediction with GFDLs FV3 Dynamical Core. In Supercomputing Conference 2016, Salt Lake City, Utah, USA, Nov 13-18 2016.

- Rees, Shannon L., Shian-Jiann Lin, Jan-Huey Chen, Rusty Benson, Xi Chen, Lucas M. Harris, Zhi Liang, and Linjiong Zhou. FV3 and the Next Generation Global Prediction System. In 32nd Conference on Hurricanes and Tropical Meteorology, San Juan, PR, Apr 17-21 2016.

- Reichl, B. G., S. Griffies, A. Adcroft, R. Hallberg: Addition of Langmuir Turbulence in a Hierarchy of Vertical Mixing Parameterizations for Ocean Climate Modeling (poster). 20th Amer. Meteor. Soc. Conf. on Air-Sea Interaction, Aug 2016.

- 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) Impacts of the Atlantic Multidecadal Variability on North American Heat Waves, CLIVAR open conference 2016, September 2016, Qingdao (China).

- Ruprich-Robert Y., Msadek R., Castruccio F., Delworth T., Yeager S., Danabasoglu G. (poster) Impacts of the Atlantic Multidecadal Variability on the North Pacific, WCRP Hierarchy Workshop 2016, November 2016, Princeton (NJ).

- Ruprich-Robert Y., Msadek R., Castruccio F., Delworth T., Yeager S., Danabasoglu G. (talk) Impacts of the Atlantic Multidecadal Variability on the North Pacific, NOAA Climate Variability and Predictability Webinar, November 2016, USA.

- Ruprich-Robert Y., Msadek R., Castruccio F., Delworth T., Yeager S., Danabasoglu G. (poster) Impacts of the Atlantic Multidecadal Variability on the North Pacific, EGU 2017, April 2017, Vienna (Austria).

- Ruprich-Robert Y., Msadek R., Delworth T., Castruccio F., Yeager S., Danabasoglu G. (talk) Impacts of the Atlantic Multidecadal Variability on North American Heat Waves, EGU 2017, April 2017, Vienna (Austria).

- Sergienko O. The effects of basal topography on subglacial water flow. WAIS Workshop, Algonkian Regional Park, Sterling, VA, 3-6 October, 2016.

- Sergienko O., A. Adcroft, J. Amundson, J. Bassis, R. Hallberg, D. Pollard , L. Stearns and A. Stern (2016) Climate Process Team, Representing calving and iceberg dynamics in global climate models. AGU Fall Meeting, San Francisco, CA 12-16 December, 2016.

- Sergienko O. V. The effects of the flexural gravity waves on stress regime of the Ross Ice Shelf IGS Symposium on Interactions of Glaciers and Ice Sheets with the Ocean. La Jolla, CA, 10-15 July, 2016.

- Sergienko O., M. Harrison, R. Hallberg and A. Adcroft (2016). Strong coupling among Antarctic ice shelves, ocean circulation and sea ice in a global sea-ice - ocean circulation model. EGU General Assembly 2016, Vienna, Austria, 17-22, April, 2016.

- Shao, A. E., Oral presentation: Canadian Meteorological and Oceanographic Society (2016), Attenuation of surface variability by oceanic ventilation.

- Shen, Z., “The influence of aerosol absorption on the extratropical circulation”. Poster. AGU 2016 Fall Meeting, San Francisco, CA. (12/2016).

- Silvers, L.G., D. Paynter, and M. Zhao: Variability of the climate feedback parameter in AM2.1, AM3, and AM4g10r8. GFDL Lunchtime Seminar, February 8th, 2017.

- Silvers, L.G. and M. Zhao: Sea Surface Temperature Patterns and Cloud Feedbacks in an Atmospheric General Circulation Model. CFMIP/WCRP Conference on Cloud Processes, Circulation and Climate Sensitivity, International Centre for Theoretical Physics, Trieste, Italy, July, 2016.

- Silvers, L.G. and M. Popp: Cloud Radiative Effects on Single and Double ITCZs. CFMIP/WCRP Conference on Cloud Processes, Circulation and Climate Sensitivity, International Centre for Theoretical Physics, Trieste, Italy, July, 2016.

- Stern A., A. Adcroft and O. Sergienko. The effect of calving size distribution on melt patterns and sea-ice formation around Antarctica. IGS Symposium on Interactions of Glaciers and Ice Sheets with the Ocean. La Jolla, CA, 10-15 July, 2016.

- 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, 2016: The climatological effect of perturbations in atmospheric burden and optical properties of Saharan dust. Proceedings, AGU Fall Meeting, San Francisco, CA.

- Subramanian, A, C Ummenhofer, A Giannini, M M Holland, Sonya Legg, A Mahadevan, D Perovich, J Small, J Teixeira, and L Thompson, August 2016: Translating process understanding to improve climate models, A US CLIVAR white paper, Report 2016-3, DOI:10.5065/D63X851Q 48pp.

- Sulman, B. N., E. Shevliakova, S. Malyshev, S. W. Pacala, R. P. Phillips, and E. Brzostek (2016). Plant nitrogen acquisition and soil microbial activity in the GFDL land model. Nutrient limitation on land: how accurate are our global land models? Yangling, Shaanxi, China.

- Sulman, B. N., E. Shevliakova, S. Malyshev, S. Pacala, and R. P. Phillips (2016). Microbes, minerals, and roots: Next-generation soil carbon in the GFDL land model. Geophysical Fluid Dynamics Laboratory, USA.

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

- Sulman, B. N., J. Moore, C. Averill, R. Abramoff, M. Bradford, A. Classen, M. Hartman, S. Kivlin, Y. Luo, M. Mayes, E. Morrison, B. Riley, A. Salazar, J. Schimel, B. Sridhar, J. Tang, G. Wang, and W. Wieder: Key process uncertainties in soil carbon dynamics: Comparing multiple model structures and observational meta-analysis. American Geophysical Union 2016 Fall Meeting, San Francisco, CA, Dec 2016.

- Tommasi, D., Jacox, M.G., Alexander, M.A., Siedlecki, S., Werner, F.E., Stock, C.A., Bond, N.A. (2017c). Seasonal forecasts of ocean conditions in the California Current Large Marine Ecosystem. US CLIVAR Variations Newsletter 15, 41-46.

- Tommasi, D., Stock. C., Pegion, K., Vecchi, G., Methot, R.D., Alexander, M., and Checkley, D. (2017). Seasonal Climate Predictions to Improve Fisheries Management Decisions. Oral Presentation at the 2017 ICES/PICES Drivers of Dynamics of Small Pelagic Fish Resources Symposium in Victoria, BC, Canada.

- Tommasi, D., Stock. C. (2016). Value of ocean prediction to fisheries management. Oral Presentation at the 2016 ICES Annual Science Meeting in Riga, Latvia.

- 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 Huijgevoort, M.H.J., Chaney, N., Malyshev, S.L., Milly, P.C.D., Shevliakova, E., 2016, Implementation of irrigation practices in a global scale land model, Presentation at Workshop Including Water Management in Large Scale Models (GEWEX and GHP), 28-30 September 2016, Gif-sur-Yvette, France.

- Van Huijgevoort, M.H.J., Chaney, N., Malyshev, S.L., Milly, P.C.D., Shevliakova, E., 2016, Implementation of Water Management Practices in a Global Scale Land Modeling, AGU Fall Meeting, 12-16 December 2016, San Francisco, USA.

- Van Oostende, N., R. Dussin, C. A. Stock, A. D. Barton, E. Curchister, J. P. Dunne and B. B. Ward. Simulating the dynamic range of chlorophyll concentration from the oligotrophic ocean gyres to coastal upwelling systems (ASLO presentation, February 2017).

- Wolovick, M., Sergienko, O. (2016), Geoengineering Glacial Fjords, Abstract C21B-0681 presented at 2016 Fall Meeting, AGU, San Francisco, CA, 12-16 December.

- Wolovick, M., Sergienko, O. (2016), Geoengineering Ice Streams with Artificial Sills, presented at WAIS Workshop, Sterling, VA, 3-6 October.

- Wolovick, M., Sergienko, O. (2016), Geoengineering Glacial Fjords, presented at IGS International Symposium on Interactions of Ice Sheets and Glaciers with the Ocean, La Jolla, CA, 10-15 July.

- Yan, X., Oral presentation, What Are the Best Fingerprints for Detecting Anthropogenic Aerosol Cooling? AGU Fall Meeting 2016 (within the Anthropogenic aerosol forcing: Mechanisms of regional climate variability and change session).

- Yi, P., S. Legg, and R. Nazarian, August 30, 2016: "A Process Study of Tidal Mixing Over Rough Topography". International Association for Hydro-Environment Engineering and Research, Eighth International Symposium on Stratified Flows.

- Yi, Y., S. Legg and R. Nazarian, A process study of tidal mixing over rough topography. 8th International symposium on stratified flows, 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, H., Detection, Attribution and Projection of Regional Rainfall Changes On (Multi-) Decadal Time Scales: A Focus on Southeastern South America, CLIVAR Open Science Conference in Qingdao in September, 2016.

- Zhang, H., Detection, Attribution and Projection of Regional Rainfall Changes On (Multi-) Decadal Time Scales: A Focus on Southeastern South America , AGU annual fall meeting in December, 2016.

- Zhang, Liping and Thomas L. Delworth, 2017: Simulated response of the Pacific decadal oscillation to climate change. Poster. 97th American Meteorological Society Annual Meeting, Seattle, WA.

- Zhang, Liping and Thomas L. Delworth, 2016: Simulated response of the Pacific decadal oscillation to climate change. Poster. NOAA/GFDL Poster Expo.

- Zhang, Liping and Thomas L. Delworth, 2016: Impact of the Antarctic bottom water on the Weddell Gyre and its northward propagation characteristics in GFDL model Poster. NOAA/GFDL Poster Expo.

- Zhou, Linjiong, Shian-Jiann Lin, Jan-Huey Chen, Lucas M. Harris, and Xi Chen. GFDL Single-Moment Six-Class Cloud Microphysics and Its Application in NGGPS. In 2017 GFDL Winter Expo, Princeton, GFDL, USA, Feb 1 2017.

- Zhou, Linjiong, Shian-Jiann Lin, Jan-Huey Chen, Lucas M. Harris, and Xi Chen. Ten-day Weather Forecasts using a 4-45km Variable-resolution Global Model: fvGFS. In 2017 AMS Annual Meeting, Seattle, WA, USA, Jan 24 2017.

- Zhou, L., S.-J. Lin, J.-H. Chen, et al., Ten-day Weather Forecasts using a 4-45 km Variable-resolution Global Model: fvGFS, 2017 AMS Annual Meeting, Seattle, USA. Talk. (January 24th, 2017).

2016-2017 Ph.D. Theses

- Chai, Junyi, June 2016. Understanding Geostrophic Turbulence in a Hierarchy of Models, Ph.D. thesis, Princeton University.

- Hill, Spencer, A., August 2016. Energetic and Hydrological Responses of Hadley Circulations and the African Sahel to Sea Surface Temperature Perturbations, Ph.D. thesis, Princeton University.

- Mooring, Todd A., September 2016, Transit Eddies in the Martian Atmosphere: Representation in Reanalysis and Idealized Modeling, Ph.D. thesis, Princeton University

- Persad, Geeta G., May 2016. Heterogeneity of Anthropogenic Aerosol Forcing, Ph.D. thesis, Princeton University.

- Strong, Jeffrey D. O., August 2016. The Climatological Effect of Perturbations in Atmospheric Burden and Optical Properties of Saharan Dust, Ph.D. thesis, Princeton University.

- Zanowski, Hannah M., December 2017. The Influence of Antarctic Open-Ocean Polynyas on the Abyssal Ocean, Ph.D. thesis, Princeton University.

ADMINISTRATIVE STAFF

CICS Director
Jorge L. Sarmiento
Professor of Geosciences
Princeton University
Phone: 609-258-6585
Fax: 609-258-2850
jls@princeton.edu

CICS Associate Director
Sonya Legg
Senior Research Oceanographer, Atmospheric and Oceanic Sciences
Lecturer in Geosciences and Atmospheric and Oceanic Sciences
Phone: 609-452-6582
Fax: 609-987-5063
slegg@princeton.edu

CICS Administrative and Financial Contact
Laura Rossi
Manager, Program in Atmospheric and Oceanic Sciences
Princeton University
Phone: 609-258-6376
Fax: 609-258-2850
lrossi@princeton.edu

CICS Administrative Assistant
Joanne Curcio
Communications Coordinator, Program in Atmospheric and Oceanic Sciences
Phone: 609-258-6047
Fax: 609-258-2850
jcurcio@princeton.edu

Task I: Administrative Activities and Outreach Supported Personnel

Name	**Rank**
Feibush, Eliot	Visualization/Computational Scientist
Legg, Sonya	CICS Associate Director
Sarmiento, Jorge L.	CICS Director
QUEST SUMMER INSTITUTE-OUTREACH SUPPORT	
Carson, Steve	Summer QUEST Facilitator
Friend, Martha	Summer QUEST Lead Teacher
Stumm, Donna	Summer QUEST Lead Teacher
SUMMER STUDENT RESEARCH INTERNS	
Abdioskouei, Maryam	Summer Intern
Alexander, Aria	Summer Intern
Miles, Claire	Summer Intern
Morovec, Miguel	Summer Intern
Nadeau, Alice	Summer Intern
Norford, Kiera	Summer Intern
Pulido-Velosa, Maria	Summer Intern
Rodriquez-Guiterrez, Leo	Summer Intern
Stansfield, Alyssa	Summer Intern

Departures - Task II

Usama Anber – 3/5/17: Brookhaven National Laboratory
Andrew Barton – 8/22/16: UCSD-Scripps, Assistant Professor
Adrien Deroubaix – 5/31/16: Ecole Polytechnique, Palaiseau, Postdoctoral Researcher
Mitchell Bushuk – 3/11/17: UCAR, Researcher
Liwei Jia – 11/25/16: NOAA Climate Prediction Center
Jingqiu Mao – 10/31/16: University of Alaska-Fairbanks, Assistant Professor
Barbara Muhling – 11/25/16: University of California Santa Cruz, Project Scientist
Karen Paffendorf – 12/2/16 – retired
Desiree Tommasi – 3/27/17: NOAA SWSFC & University of California Santa Cruz
van der Weil, Karin – 9/30/16: Royal Netherlands Meteorological Institute, Postdoc

Departures - Task III

Amir Haji Akbari Balou – 11/30/16: Yale University, Assistant Professor
Christopher Harig – 6/30/16: University of Arizona, Assistant Professor
Di Tian – 7/31/16: Auburn University, Assistant Professor

Ph.D. Defenses

Student: Junyi Chai (June 2016)
Advisor: I. Held
Dissertation: Understanding Geostrophic Turbulence in a Hierarchy of Models
Present Affiliation: Quantitative Associate, Barclays Capital, NY

Ph.D. Defenses Continued

Student: Spencer Hill (August 2016)
Advisor: Y. Ming
Dissertation: Energetic and Hydrological Responses of Hadley Circulations and the African Sahel to Sea Surface Temperature Perturbations
Present Affiliation: Postdoc, UCLA/Caltech

Student: Geeta Persad (May 2016)
Advisor: V. Ramaswamy
Dissertation: Climate Implications of the Heterogeneity of Anthropogenic Aerosol Forcing
Present Affiliation: Postdoc, Stanford University

Student: Todd Mooring (September 2016)
Advisor: I. Held
Dissertation: Transient Eddies in the Martian Atmosphere: Representation in Reanalysis and ldealized Modeling
Present Affiliation: Postdoc, University of Chicago

Student: Jeff Strong (August 2016)
Advisor: G.Vecchi
Dissertation: The Climatological Effect of Perturbations in Atmospheric Burden and Optical Properties of Saharan Dust
Present Affiliation: Postdoc, Scripps, San Diego

Student: Hannah Zanowski (December 2016)
Advisor: R. Hallberg
Dissertation: The Influence of Antarctic Open-Ocean Polynyas on the Abyssal Ocean
Present Affiliation: Postdoc, University of Washington

Task II: Cooperative Research Projects and Education Supported Personnel

Name	**Rank**	**Host/Advisor**
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
Cheeks, Shawn	Graduate Student	Garner, Steve
Chen, Xi	Associate Research Scholar	Lin, SJ
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
Jeevanjee, Nadir	Postdoctoral Research Associate	Donner, Leo
Jia, Liwei	Associate Research Scholar	Vecchi, Gabriel
Johnson, Nathaniel	Associate Research Scholar	Vecchi, G./Wittenberg, A.
Jones, Alexandra	Postdoctoral Research Associate	Ramaswamy, V./Paynter, D.
Kam, Jonghun	Postdoctoral Research Associate	Vecchi, G./Knutson, Tom
Krishnamurthy, L.	Associate Professional Specialist	Vecchi, G./Delworth, 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, Dawei	Postdoctoral Research Associate	Zhang, Rong/Knutson, Tom
Lin, Meiyun	Research Scholar	Horowitz, Larry
Lin, Pu	Associate Research Scholar	Ming, Yi
Lutsko, Nicholas	Graduate Student	Held, Isaac
Malyshev, Sergey	Professional Specialist	Pacala, Steve
Mao, Jingqiu	Associate Research Scholar	Horowitz, Larry
Mastrorocco, Gustavo	Postdoctoral Research Associate	Hallberg, Robert
Mooring, Todd	Graduate Student	Held, Isaac
Muhling, Barbara	Associate Research Scholar	Saba, Vince/Stock, Charlie
Munoz, Angel	Postdoctoral Research Associate	Vecchi, Gabe
Nazarian, Robert	Graduate Student	Legg, Sonya
Ng, Ching Ho (Justin)	Graduate Student	Vecchi, Gabriel
Nikonov, Sergey	Professional Specialist	Balaji, V.
Paffendorf, Karen	Professional Specialist	Balaji, V.
Park, Jong-Yeon	Postdoctoral Research Associate	Dunne, John
Paulot, Fabien	Associate Research Scholar	Horowitz, Larry
Persad, Geeta	Graduate Student	Ramaswamy, V.
Popp, Max	Associate Research Scholar	Held, Isaac

Task II: Cooperative Research Projects and Education Supported Personnel CONTINUED

Name	**Rank**	**Host/Advisor**
Pu, Bing	Associate Research Scholar	Ginoux, Paul
Ray, Sulagna	Associate Research Scholar	Wittenberg, Andrew
Reichl, Brandon	Postdoctoral Research Associate	Griffies, Steve
Ruprich-Robert, Yohan	Postdoctoral Research Associate	Delworth, Tom
Schnell, Jordon	Postdoctoral Research Associate	Horowitz, Larry
Sergienko, Olga	Research Glaciologist	Hallberg, Robert
Shao, Andrew	Postdoctoral Research Associate	Hallberg, Robert
Shen, Zhaoyi	Graduate Student	Horowitz, Larry
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
van Huijgevoort, Marjolein	Postdoctoral Research Associate	Shevliakova, Elena
Ward, Daniel	Associate Research Scholar	Dunne, J./Shevliakova, E.
Wolovick, Michael	Postdoctoral Research Associate	Sergienko, Olga
Yan, Xiaoqin	Postdoctoral Research Associate	Zhang, Rong/Knutson, T.
Yankovsky, Elizabeth	Graduate Student	Legg, Sonya
Zanowski, Hannah	Graduate Student	Hallberg, Robert
Zhang, Honghai	Postdoctoral Research Associate	Delworth, Tom
Zhang, Liping	Postdoctoral Research Associate	Delworth, Tom
Zhou, Linjiong	Postdoctoral Research Associate	Lin, SJ/Harris, Lucas
Zurita-Gotor, Pablo	Visiting Research Scholar	Held, Isaac

Task III: Individual Research Projects Supported Personnel

Name	**Rank**	**Host/Advisor**
Chou, Cleo	Postdoctoral Research Associate	Hedin, Lars
Fueglistaler, Stephan	Professor	--
Gauthier, Paul	Associate Research Scholar	Shevliakova, E./Pacala, S.
Haji Akbari Balou, Amir	Postdoctoral Research Associate	Panagiotopoulos, A.
Harig, Christopher	Associate Research Scholar	Simons, Fredrik
Jing, Renzhi	Graduate Student	Lin, Ning
Lin, Meiyun	Research Scholar	Horowitz, Larry
Rodgers, Keith	Research Oceanographer	Sarmiento, Jorge
VanOostende, Nicholas	Associate Research Scholar	Ward, Bess

Personnel				
Category	Number	B.S.	M.S.	Ph.D.
Faculty	5	-	2	3
Research Scientist	5	-	-	5
Visiting Scientist	1	-	-	1
Postdoctoral Research Associate	29	-	-	29
Professional Technical Staff	6	-	1	5
Associate Research Scholar	18	-	-	18
Administrative	-	-	-	-
Total (≥ 50% support)	**50**			**50**
Undergraduates	7	-	-	-
Graduate Students	21	3	12	6
Employees that receive < 50% NOAA funding (not including graduate students)	14	-	-	14
Located at the Lab (include name of lab)	GFDL-66	7	8	51
Obtained NOAA employment within the last year	-	-	-	-

CICS FY'17 List of Awards for Institutional Award NA14OAR4320106

Amount	PI	Project Title
$ 40,746[*16]	Keith Rodgers	Using Models to improve our ability to monitor ocean uptake of anthropogenic carbon (Task III) *COD-David Legler*
$ 277,140[*17]	Jorge L. Sarmiento	CICS-YR 8 (Administration – Task I) *GFDL/V. Ramaswamy*
$ 542,857[*18]	Jorge L. Sarmiento	CICS-YR 8 (Research/Education-Task III) *GFDL/V. Ramaswamy*
$4,999,952[*19]	Jorge L. Sarmiento	CICS-YR 8 (Research/Education-Task II) *GFDL/V. Ramaswamy*
$ 5,903[*20]	Jorge L. Sarmiento	CICS-YR 8 (Administration – Task I) *GFDL/V. Ramaswamy*
$ 3,837[*21]	Jorge L. Sarmiento	CICS-YR 8 (Administration – Task I) *GFDL/V. Ramaswamy*
$ 128,335 [*22]	Jorge L. Sarmiento	CICS-YR 8 (Administration – Task II) *GFDL/V. Ramaswamy*
$ 83,421[*23]	Jorge L. Sarmiento	CICS-YR 8 (Administration – Task II) *GFDL/V. Ramaswamy*

CICS FY'17 List of Awards for Institutional Award NA14OAR4320106

Amendment No./PI	Amount	Project Title
Amendment #16 PI: Keith Rodgers	$ 40,746	Using Models to Improve our Ability to Monitor Ocean Uptake of Anthropogenic Carbon
Amendment #17 PI: Jorge L. Sarmiento	$ 277,140	Cooperative Institute for Climate Science – Task I
Amendment #18 PI: Jorge L. Sarmiento	$ 542,857	Cooperative Institute for Climate Science – Task III
Amendment #19 PI: Jorge L. Sarmiento	$4,999,952	Cooperative Institute for Climate Science – Task II
Amendment #20 PI: Jorge L. Sarmiento	$ 5,903	Cooperative Institute for Climate Science – Task I
Amendment #21 PI: Jorge L. Sarmiento	$ 3,837	Cooperative Institute for Climate Science – Task I
Amendment #22 PI: Jorge L. Sarmiento	$ 128,335	Cooperative Institute for Climate Science – Task II
Amendment #23 PI: Jorge L. Sarmiento	$ 83,421	Cooperative Institute for Climate Science – Task II