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Cooperative Institute for Climate Science 
Princeton University 

Annual Progress Report under cooperative agreement NA14OAR4320106 

For the period April 1, 2017 – March 31, 2018 

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. 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.

CICS Research Internships

CICS research internships, a program initiated in 2016, are 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. A total of 7 candidates were selected for CICS funding, comprising 5 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 broader GFDL community. Students, home institutions, and titles of research presentations are listed below.

2017 CICS Summer Interns: (L to R) Caroline Cardinale, Katie Boaggio, Mick Lee, Daniel Lloveras, Sarah Nickford, Stephanie Lin & Haylie Mikulak

Caroline Cardinale, Hun School: Automated Dimensional Consistency Checking in MOM6.
Katie Boaggio, College of New Jersey: Tracking and Analyzing Extratropical Cyclones with fvGFS.
Mick Lee, University of Maryland: CPMIP Metrics.
Daniel Lloveras, University of Miami: Evaluating the Predictability of Summertime Precipitation in the United States.
Sarah Nickford, Stonybrook University: Turbulence and Mixing in the Orkney Passage.
Stephanie Lin, Cornell University: Understanding and Predicting the Global Monsoon Precipitation.
Haylie Mikulak, University of Nebraska: Examining the Impact of Temperature on Shipping Days for Corn, Soybeans, and Wheat.
CICS, AOS, and GFDL scientists joined forces with fellow scientists and environmentalists from around the state during the fourteenth annual celebration of Ocean Fun Days at the Jersey Shore to advance knowledge and stewardship for New Jersey’s marine and coastal environments. The free, two-day event was held on Saturday, May 20th at Island Beach State Park and May 21st at the New Jersey Sea Grant Consortium (NJSGC) on Sandy Hook.

CICS Associate Director Sonya Legg, who coordinated the outreach effort at Princeton, was joined by AOS Faculty Member Steve Griffies, Bing Pu (CICS/AOS), Angel Adames-Carraliza (UCAR), Tsung-Lin Hsieh (CICS/AOS), Jane Smyth (AOS) and Shiv Priyam Raghuraman (AOS) at the CICS/AOS exhibit to lead hands-on experiments demonstrating iceberg melting and ocean acidification. The group of volunteers was one of over 50 exhibitors presenting at the 2017 event, which drew thousands to the Jersey Shore for a weekend of interactive exploration and education.

With a record number of exhibitors and display tables jam-packed with children and families eager to try their hand at tabletop scientific inquiry, 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 the booths and exhibits, the NJSGC headquarters location, in the historic Fort Hancock section of Sandy Hook, included guided tours of many of Sandy Hook’s historic sites and an open house at the NOAA/James J. Howard Science Laboratory. New in 2017 at Island Beach State Park, visitors joined students and faculty from Project Terrapin and the Marine Academy of Technology and Environmental Science (MATES) as they released young diamondback turtles back into their natural habitat.

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, National Park Service and the National Oceanic and Atmospheric Administration.
Summer Institute in Weather and Climate

“It is food for a teacher’s soul to come and be revitalized,” said a participating teacher of the QUEST summer institute held at Princeton University from July 10-14, 2017. The Cooperative Institute for Climate Science (CICS) co-sponsored the longstanding institute, a summer professional development program designed for teachers of grades K-8 to deepen their content knowledge in science through self-directed investigation and hands-on laboratory experiments.

Led by content experts Steve Carson, a middle school teacher and former Geophysical Fluid Dynamics Laboratory (GFDL) researcher, and Danielle Schmitt, manager of the Princeton Geosciences undergraduate lab, teachers learned about the many important roles the ocean plays in our climate and how to translate the science for their classrooms in line with the Next Generation Science Standards (NGSS), newly adopted in New Jersey. Participants performed experiments as well as discussed pedagogy and underlying content with colleagues and the faculty, developing skills for instructing inquiry-based science.

Teachers explored isotope fractionation and the rainout effect, using fossils in sediment cores as a climate proxy, and the greenhouse effect, according to Anne Catena, director of professional development initiatives in Princeton’s Program in Teacher Preparation. Together, they worked to better understand the effect of warming ocean temperatures on organisms and ecosystems; the ocean’s role in mediating the climate; heat transfer and thermal expansion of the ocean; and atmospheric and oceanic circulation and their impact on climate. The teachers also planned NGSS aligned lessons and engaged in practices of science, including developing and using models; analyzing and interpreting data; and engaging in argument from evidence.

The week-long institute, which was co-facilitated by elementary and high school lead teachers from two local districts, drew 14 teachers from seven New Jersey school districts, including Burlington Township, Hillsborough Township, Hopewell Valley, Manalapan Englishtown, Ocean City, Trenton, and West-Windsor Plainsboro, as well as three private schools. The institute provided the resources and knowledge teachers need to generate new and exciting standards-based science lessons to approximately 1700 students throughout New Jersey, among them historically underserved student populations.
Following the institute, feedback from the participants was overwhelmingly positive, according to Catena, as was the response to guest speakers SOCCOM Project Manager Roberta Hotinski and Greta Shum, formerly of Climate Central and now a digital media specialist at the Andlinger Center for Energy and the Environment, who gave an overview of the research project and its adopt-a-float program that pairs researchers at sea with classrooms on land. Participating teachers are able to return to their classrooms in the fall with confidence in their enhanced content knowledge and renewed enthusiasm for science instruction, a win-win proposition for both students and teachers.

The institute was made possible by funding from CICS, with additional support from the Program in Teacher Preparation.

**Summer Schools**

During the summer of 2017, CICS supported AOS Graduate Students Chiung-Yin (Jenny) Chang’s and Elizabeth Yankovsky’s participation in a summer school program on “Fundamental Aspects of Turbulent Flows in Climate Dynamics” at the École de Physique des Houches from July 3–August 25, 2017. CICS also sponsored AOS Graduate Student Jane Baldwin’s participation in the “Advanced Climate Dynamic Courses (ACDC)” summer school held in Rondane National Park, Norway.
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

Princeton Environmental Institute (PEI)
Director, Michael Celia

Task II: Cooperative Research Projects and Education
managed by CICS Associate Director Sonya Legg

Center for Biocomplexity (CBC)

Energy Group

Center for Environmental BioInorganic Chemistry (CEBIC)

Task III: Individual Research Projects
managed by CICS Director Jorge L. Sarmiento

Princeton Climate Center (PCC)
Jorge L. Sarmiento, Director
Research Portion of CICS to be managed within PCC
Task III

Cooperative Institute for Climate Science Structure

CICS Executive Committee

Cooperative Institute for Climate Science (CICS)
Jorge L. Sarmiento, Director
Sonya Legg, Assoc. Director

Task II: Cooperative Research Projects and Education
managed by CICS Associate Director Sonya Legg

Task III: Individual Research Projects
managed by CICS Director Jorge L. Sarmiento

Task I: Administrative Activities
managed by Jorge L. Sarmiento
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
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.

Atmospheric Model Development

A major achievement completed in the past year, involving both GFDL and CICS scientists, has been the development of the AM4.0 atmospheric model, which forms the atmospheric component of GFDL’s new coupled climate model CM4. Two recent publications (Zhao et al, 2018a,b) describe the characteristics of AM4.0 simulations, and the model development and tuning strategy, with CICS co-authors V. Balaji, Xi Chen, Pu Lin, Sergey Malyshev, Fabien Paulot, Zhaoyi Shen, and Levi Silvers. This model includes state-of-the-art representations of aerosols and clouds, at a resolution suitable for long climate integrations, and CICS researchers have contributed many different aspects, from the dynamical core discretization to the examination of stratospheric dynamics and cloud processes.

While AM4.0 is now “frozen” for the purpose of ongoing climate model simulations, research into better representations of physical processes for implementation in future atmospheric model versions continues, much involving CICS researchers. Many aspects of both climate and weather are sensitive to atmospheric convection, which can be explicitly simulated at very high model resolution. However, in the intermediate 1-100km range achieved by current global atmospheric models, convective motion is neither well-resolved nor well represented by parameterizations. CICS postdoctoral research associate Nadir Jeevanjee has explored the use of the GFDD FV3 model at varying resolutions and with variable physics to identify the requirements for adequately simulating convective motion in this "gray zone". Aerosols are important physical components of the atmosphere, which play an important role in the radiation budget. CICS graduate student Zhaoyi Shen has focused on the fast response of European land surface temperatures to aerosol forcing, using observations to constrain the modeled effect of the aerosols. CICS postdoctoral research associate Alexandra Jones has developed a benchmark code framework for diagnosing the errors in climate model radiative forcing parameterizations of the aerosol indirect effect. CICS associate research scholar Bing Pu has focused on climate model predictions of atmospheric dust, which has significant local impacts on human activities. Key results include identification of climatic causes of past changes in dustiness in the Southwestern USA and Great Plains, and projected increases in dust activity in the Southern Great Plains under future climate scenarios associated with increased greenhouse gases. Many particulate aerosols are a hazard to health: CICS postdoctoral research associate Jordon Schnell has used the new AM4.0 atmospheric model to simulate the influence of meteorological conditions on these particulates in the Indian subcontinent, demonstrating improved prediction skill compared to previous atmospheric models.
Characterizing the Role of Multi-Scale Heterogeneity in the Earth System

CICS Postdoc, Nathaniel Chaney led a pioneering study to examine how the ever-growing data sets of the terrestrial environment could be harnessed via a novel clustering approach to improve the representation of land heterogeneity in the GFDL land model. A prototype study showed that it takes ~300 sub-grid land tiles to represent the macroscale behavior of a fully distributed model. The assembly of a model with subgrid tiles led to significant differences in model predictions, for example, dampening macro scale extremes; and it facilitated the comparison of macro-scale model simulations with the much higher resolution of field observations. The new tiling scheme has already been implemented globally. CICS scientists Sergey Malyshev and Marjolein Van Huijgevoort participated in the study.

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.

Climate and Weather Extremes

An important application of earth system models is in understanding how extreme weather events, such as heat waves, extreme precipitation, droughts, will change in frequency, intensity, and distribution in a changing climate. Several CICS researchers have been applying GFDL’s earth system modeling capability to understand the dependence of these societally costly phenomena on the underlying climate. CICS scientist Lakshmi Krishnamurthy found that extreme rainfall events like that responsible for the 2015 Chennai flood are more likely when the Bay of Bengal sea surface is anomalously warm. CICS associate research scholar Salvatore Pascale has examined the impact of increasing CO2 on the North American monsoon and the extreme precipitation associated with Gulf of California moisture surges. CICS graduate student Jane Baldwin has focused on heat waves, and by applying a new heat wave metric to GFDL climate model projections, shows that hot days that closely follow prior hot days will constitute a greater proportion of heat wave hazard as the climate warms. CICS associate research scholar Nathaniel Johnson analyzed simulations from the GFDL FLOR model covering the recent period of global warming slowdown to show that the dominant sources of wintertime cold and summertime warm extreme temperatures are naturally occurring large-scale climate patterns, distinct from the dominant sources of global mean temperature variability. By contrast, CICS postdoctoral research associate Jonghun Kam used multiple climate models to show that the extreme warming in the 2016 November-December Arctic would most likely not have occurred without anthropogenic global warming.

Global Marine Biogeochemistry Prediction

A significant result in the area of Marine biogeochemistry, was a study led by CICS postdoc Jongyeon Park on the predictability of annual fish catch in the California Current Large Marine Ecosystem. This project involved first developing an improved simulation of the biogeochemistry, which was accomplished primarily by modifying the biogeochemistry initialization to avoid the degradation of the simulation due to excessive upwelling of nutrients in the equatorial region. Data on fish catch from the Sea Around Us Project database were then used to show that fish catch in the California Current Large Marine Ecosystem can be estimated from chlorophyll and temperature observations with a correlation coefficient of 0.85 at 0-1 year time scales, and 0.82 at 1-2 year time scales. Publications are in preparation, and planning is underway to improve the prediction skill.
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 Administrators. 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, 2017 – March 31, 2018, Princeton received funds in the amount of $6,418,565 for Task II and Task III research projects (see details in CICS FY’18 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

- CICS Research Internships
- Ocean Fun Days 2017
- Summer Institute in Weather and Climate
- Summer Schools

Earth System Modeling and Analysis Projects

- Hybrid Ocean Model Development (Alistair Adcroft)
- Flexible Modeling System (FMS) (V. Balaji)
- Evaluation of Tropical Cyclone Track and Intensity Prediction in GFDL’s FV3 Dynamical Core (Morris Bender)
- Impacts of Cryosphere-Aerosol Interactions on Hydroclimate Variability over High Mountain Asia (Hoi Ga Chan)
- Characterizing the Role of Multi-Scale Heterogeneity in the Earth System (Nathaniel Chaney)
- Rhines Scale and Eddy Diffusivity Scalings for Poleward Heat Transport (Chiung-Yin Chang)
- Investigation of Physical Mechanisms and Model Biases of Mesoscale Convective Systems in the Central United States (Shawn Cheeks)
- Development of GFDL Cubed-Sphere Dynamical Core for the NGGPS Project (Xi Chen)
- Marine Ecosystem Tipping Points: Climate Downscaling for California Current Marine Ecosystem Impacts (Enrique Curchitser/Charles Stock)
- Crystallization of Sodium Chloride in Supersaturated Aqueous Solutions (Pablo G. Debenedetti/Athanassios Z. Panagiotopoulos)
- Parameterizing the Melting of Icebergs in GCMs (Anna FitzMaurice)
- Advancing Mechanistic Representation of Photosynthesis and Respiration in the GFDL Land Model LM3-PPA and the Next Generation of the GFDL Earth System Model (Paul PG Gauthier/Stephen W. Pacala)
- Reflection of Rossby Waves by Shear Zones (Matthew Gliatto)
- The Dynamics of Ice Shelves and Ice Streams (Marianne Haseloff)
- The Land Phosphorous Cycle: Interactions with Carbon and Nitrogen across Neotropical Ecosystems (Lars Hedin)
- A Moist Quasi-Steady Baroclinic Eddy with Hypohydrostatic Convection (Tsung-Lin Hsieh)
- An Examination of the Radiative Forcing and Feedback in the GFDL Models (Yi Huang)
- GFDL Model Hierarchies and Idealized Cloud-Resolving Modeling (Nadir Jeevanjee)
- Aerosol Instantaneous Radiative Forcing Component of the RFMIP (Alexandra Jones)
- CLIMIP5 Model-based Assessment of Anthropogenic Influence on Highly Anomalous Arctic Warmth during November-December (Jonghun Kam)
- Impacts of Variability in Iron Supply on Marine Biogeochemistry (Charlotte Laufkötter)
Earth System Modeling and Analysis Projects continued

- Responses of the Global Land Nitrogen Cycle to Anthropogenic Land Use and Climate Changes (Minjin Lee)
- Ocean Mixing Processes and Parameterization (Sonya Legg)
- Understanding the Decline of Arctic Sea Ice and Its Influence on Mid-Latitude Weather (Dawei Li)
- Simulating Stratospheric Circulations in a Changing Climate (Pu Lin)
- Modeling the Responses and Feedback of Coastal Marine Ecosystems to Global Change (Xiao Liu)
- Data Assimilation System for Seasonal to Decadal Climate Prediction (Feiyu Lu)
- Modeling Ice Shelf/Ocean Interactions (Gustavo Marques)
- Cross-timescale Interactions, Diagnostics for Coupled Circulation Models, and Applications (Ángel Muñoz)
- Internal Wave Mixing in Continental Slope Canyons (Robert Nazarian)
- Regional Changes in Aerosol Radiative Forcings: Mechanisms and Implications (Fabien Paulot)
- Interactions between the Atmospheric Energy Budget and the Tropical Large-Scale Circulation (Max Popp)
- Detection and Attribution of Dust Sources to Understand Dust Effects on Climate and Air Quality (Bing Pu)
- Understanding Tropical Pacific Biases in Climate Simulations and Initialized Predictions (Sulagna Ray)
- Langmuir Turbulence and its Impact on the Coupled Climate System (Brandon Reichl)
- Exploring the Relationship between Surface $\text{PM}_{2.5}$ and Meteorology in Northern India (Jordan Schnell)
- Development of an Ice-Sheet Model, its Iceberg Component, and Coupling with Other Climate-Model Components (Olga Sergienko)
- Improvements to the Modular Ocean Model’s Neutral Mixing Physics, Diagnostic Output, and Offline Capabilities (Andrew Shao)
- Probing Interactions between Clouds and the Large-Scale Circulation (Levi G. Silvers)
- Exchange Mechanisms in the Urban Boundary Layer (Alexander Smits/Elie Bou-Zeid)
- Characterizing South American Monsoon Variability with the Moist Static Energy Budget (Jane Smyth)
- Next-Generation Carbon and Nitrogen Cycling in the GFDL Land Model (Benjamin Sulman)
- Emissions from Fires: Interactions and Impacts in the Coupled Land-Atmosphere (Daniel Ward)
- Understanding Multi-Decadal Natural Climate Variability and its Potential Role in Explaining Observed Climate Changes (Xiaoqin Yan)
- Symmetric and Baroclinic Instability in Dense Shelf Overflows (Elizabeth Yankovsky)
- Eddy Momentum Flux Parametrization in Ocean Models (Laure Zanna)
- Implement Time-Varying Reservoir in GFDL Land Model (Yujin Zeng)
- Understanding the Controlling Factors of Tropical Precipitation Distribution (Yi Zhang)
- Cloud-Resolving Model Development and Application (Linjiong Zhou)
Earth System Model Applications Projects

- Orographic Controls on the Hydroclimate of Asia, and Temporal Compounding of Heat Wave Events (Jane Baldwin)
- Investigating the Intertropical Convergence Zone and Monsoons in an Idealized Moist Model with Full Radiative Transfer (Spencer Clark)
- Understanding Controlling Factors of Humidity Extratropical Clouds with an Idealized Model (Michelle Frazer)
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- Climate Variability and Predictability (Lakshmi Krishnamurthy)
- Air quality, Ecosystem-Atmosphere Interactions, and Climate (Meiyun Lin)
- Impact of Mountains on Tropical Circulation in Two Earth System Models (Sergey Malyshev)
- The Impact of Climate Change on the Transmission and Incidence of Directly-Transmitted Childhood Diseases (C. Jessica E. Metcalf)
- GFDL Curator System and Data Portal Infrastructure and CMIP6 (Serguei Nikonov)
- Global Marine Biogeochemistry Prediction (Jongyeon Park)
- Present and Future Hydroclimate of the North American Monsoon and Other Semiarid Regions (Salvatore Pascale)
- Understanding the Super Greenhouse Effect through ENSO Events (Shiv Priyam Raghuraman)
- Using Models to Improve our Ability to Monitor Ocean Uptake of Anthropogenic Carbon and Ecosystem Stressors (Keith Rodgers)
- Seasonal Prediction of Estuarine Water Quality (Andrew Ross)
- Constraining Aerosol Forcing from Land Surface Air Temperature Records (Zhaoyi Shen)
- Potential Sources for Extended Weather Predictability (Yongqiang Sun)
- The Impact of Large Phytoplankton on Biogeochemical Modeling of Primary Production and Response to Climate-Induced Ecosystem Changes (Bess Ward)
- Geoengineering Outlet Glaciers and Ice Streams (Michael Wolovick)
- Understanding 2014-2016 Record Warm Global Mean Surface Temperatures (Jianjun Yin)
- Variability and Predictability of North American Climate Arising from the Tropics (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

Education/Outreach Projects

- CICS Research Internships
- Ocean Fun Days 2017
- Summer Institute in Weather and Climate
- Summer Schools

Earth System Modeling and Analysis Projects

Ocean and Ice processes

- Hybrid Ocean Model Development (Alistair Adcroft)
- Parameterizing the Melting of Icebergs in GCMs (Anna FitzMaurice)
- The Dynamics of Ice Shelves and Ice Streams (Marianne Haseloff)
- Ocean Mixing Processes and Parameterization (Sonya Legg)
- Modeling Ice Shelf/Ocean Interactions (Gustavo Marques)
- Internal Wave Mixing in Continental Slope Canyons (Robert Nazarian)
- Langmuir Turbulence and its Impact on the Coupled Climate System (Brandon Reichl)
- Development of an Ice-Sheet Model, its Iceberg Component, and Coupling with Other Climate-Model Components (Olga Sergienko)
- Improvements to the Modular Ocean Model’s Neutral Mixing Physics, Diagnostic Output, and Offline Capabilities (Andrew Shao)
- Symmetric and Baroclinic Instability in Dense Shelf Overflows (Elizabeth Yankovsky)
- Eddy Momentum Flux Parametrization in Ocean Models (Laure Zanna)

Atmospheric Processes

- Impacts of Cryosphere-Aerosol Interactions on Hydroclimate Variability over High Mountain Asia (Hoi Ga Chan)
- Investigation of Physical Mechanisms and Model Biases of Mesoscale Convective Systems in the Central United States (Shawn Cheeks)
- Development of GFDL Cubed-Sphere Dynamical Core for the NGGPS Project (Xi Chen)
- Crystallization of Sodium Chloride in Supersaturated Aqueous Solutions (Pablo G. Debenedetti/Anastissios Z. Panagiotopoulos)
- Reflection of Rossby Waves by Shear Zones (Matthew Gliatto)
- A Moist Quasi-Steady Baroclinic Eddy with Hypohydrostatic Convection (Tsung-Lin Hsieh)
- An Examination of the Radiative Forcing and Feedback in the GFDL Models (Yi Huang)
Earth System Modeling and Analysis Projects continued

- GFDL Model Hierarchies and Idealized Cloud-Resolving Modeling (Nadir Jeevanjee)
- Aerosol Instantaneous Radiative Forcing Component of the RFMIP (Alexandra Jones)
- Regional Changes in Aerosol Radiative Forcings: Mechanisms and Implications (Fabien Paulot)
- Interactions between the Atmospheric Energy Budget and the Tropical Large-Scale Circulation (Max Popp)
- Detection and Attribution of Dust Sources to Understand Dust Effects on Climate and Air Quality (Bing Pu)
- Probing Interactions between Clouds and the Large-Scale Circulation (Levi G. Silvers)
- Exchange Mechanisms in the Urban Boundary Layer (Alexander Smits/Elie Bou-Zeid)
- Cloud-Resolving Model Development and Application (Linjiong Zhou)

High-Performance Computing and Architecture

- Flexible Modeling System (FMS) (V. Balaji)

Weather and Climate Extremes

- Evaluation of Tropical Cyclone Track and Intensity Prediction in GFDL’s FV3 Dynamical Core (Morris Bender)
- CIMIP5 Model-based Assessment of Anthropogenic Influence on Highly Anomalous Arctic Warmth during November-December (Jonghun Kam)
- Exploring the Relationship between Surface PM$_{2.5}$ and Meteorology in Northern India (Jordan Schnell)

Earth-System Science

- Characterizing the Role of Multi-Scale Heterogeneity in the Earth System (Nathaniel Chaney)
- Marine Ecosystem Tipping Points: Climate Downscaling for California Current Marine Ecosystem Impacts (Enrique Curchitser/Charles Stock)
- Advancing Mechanistic Representation of Photosynthesis and Respiration in the GFDL Land Model LM3-PPA and the Next Generation of the GFDL Earth System Model (Paul PG Gauthier/Stephen W. Pacala)
- The Land Phosphorous Cycle: Interactions with Carbon and Nitrogen across Neotropical Ecosystems (Lars Hedin)
- Impacts of Variability in Iron Supply on Marine Biogeochemistry (Charlotte Laufkötter)
- Responses of the Global Land Nitrogen Cycle to Anthropogenic Land Use and Climate Changes (Minjin Lee)
- Modeling the Responses and Feedback of Coastal Marine Ecosystems to Global Change (Xiao Liu)
- Next-Generation Carbon and Nitrogen Cycling in the GFDL Land Model (Benjamin Sulman)
- Emissions from Fires: Interactions and Impacts in the Coupled Land-Atmosphere (Daniel Ward)
- Implement Time-Varying Reservoir in GFDL Land Model (Yujin Zeng)
Earth System Modeling and Analysis Projects continued

Climate Change and Variability

- Rhines Scale and Eddy Diffusivity Scalings for Poleward Heat Transport (Chiung-Yin Chang)
- Understanding the Decline of Arctic Sea Ice and Its Influence on Mid-Latitude Weather (Dawei Li)
- Simulating Stratospheric Circulations in a Changing Climate (Pu Lin)
- Data Assimilation System for Seasonal to Decadal Climate Prediction (Feiyu Lu)
- Cross-timescale Interactions, Diagnostics for Coupled Circulation Models, and Applications (Ángel Muñoz)
- Understanding Tropical Pacific Biases in Climate Simulations and Initialized Predictions (Sulagna Ray)
- Characterizing South American Monsoon Variability with the Moist Static Energy Budget (Jane Smyth)
- Understanding Multi-Decadal Natural Climate Variability and its Potential Role in Explaining Observed Climate Changes (Xiaoqin Yan)
- Understanding the Controlling Factors of Tropical Precipitation Distribution (Yi Zhang)

Earth System Model Applications Projects

Climate Change and Variability

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**Earth-System Science**

- Long Term Variability of Marine Ecosystems in Earth System Models (Fernando González Taboada)
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**High-Performance Computing and Architecture**

- GFDL Curator System and Data Portal Infrastructure and CMIP6 (Serguei Nikonov)

**Ocean and Ice Processes**

- Geoengineering Outlet Glaciers and Ice Streams (Michael Wolovick)
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), Gustavo Marques (Princeton), Brandon Reichl (Princeton), Olga Sergienko (Princeton), Andrew Shao (Princeton)

Other Participating Researchers: Anders Damsgaard (Princeton), Sina Khani (Princeton), Alon Stern (Princeton), Malte Jansen (U. Chicago), 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:
Weather-Ready Nation Goal: Society is Prepared for and Responds to Weather-Related Events (10%)
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts (70%)
Resilient Coastal Communities and Economies Goal: Coastal and Great Lakes Communities are Environmentally and Economically Sustainable (20%)

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

Methods and Results/Accomplishments:
Finalizing OM4, the $\frac{1}{4}^\circ$ ice-ocean component of CM4, has taken up most of my time. The ocean configuration was settled in Spring of 2017 and a long coupled control run conducted over the summer (which developed major polynyas) followed by a re-run in the Fall (with corrected glacier albedos) and is considered acceptable in many metrics. The corresponding OMIP CORE2-IAF experiment ran in the Fall and based on cursory analysis also looks very respectable. One bug in the forcing, and several deviations from the OMIP protocol, have been uncovered and so the final run to be analyzed and submitted is currently being prepared but we are confident these will incur small only effects.

The virtual planet (“Neverland”) project, with post-doc Sina Khani and collaborator Malte Jansen, for evaluating eddy-parameterizations is yielding both expected and challenging results: we are finding regions of PV homogenization, regions of APE reduction (GM), a strong role for standing eddies depending on the regime, but none of the coded parameterizations work well in all regimes.

Development of a Lagrangian sea-ice model started with post-doc Anders Damsgaard who is prototyping ideas in a stand-alone Julia code. He has already demonstrated the viability of reduced physics (reduced complexity) by showing that dynamic jamming can occur in a model with floe-floe cohesion instead of tangential friction. This work is submitted in Damsgaard et al. (2018).

Development of the tabular-iceberg model wrapped up with post-doc Alon Stern and colleague Olga Sergienko. The point-particle model of icebergs (Stern et al., 2016) includes 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. This work is published in Stern et al. (2017).
**Outreach Activities:** Working with two undergraduate interns on analysis software for MOM6 output and datasets.

**References:**


**Publications:**


**Presentations:**

**Progress Report: Flexible Modeling System**

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

**CICS/GFDL Collaborator:** Alistair Adcroft (Princeton), Stephan Fueglistaler (Princeton), Sergey Nikonov (Princeton), Rusty Benson (GFDL), Jeff Durachta (GFDL), Isaac Held (GFDL), Larry Horowitz (GFDL), John Krasting (GFDL), Zhi Liang (GFDL), Shian-Jiann Lin (GFDL), Sarah Kapnick (GFDL), Ming Zhao (GFDL)

**Other Participating Researchers:** Laure Resplandy (Princeton), Gabriel Vecchi (Princeton), Giovanni Aloisio (CMCC), Luca Cinquini (JPL), Cecelia Deluca (NOAA/ESRL), Veronika Eyring (DLR), Andrew Gettelman (NCAR), Chris Golaz (LLNL), Frederic Hourdin (IPSL), Bryan Lawrence (Reading), Eric Maisonnave (CERFACS), Thorsten Mauritsen (MPI-M, Hamburg), Anna Michalak (Stanford), Eva Sinha (Stanford), Karl Taylor (PCMDI), 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.

As co-chair of 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.

Significant accomplishments in the period 2017-2018 include a paper in *Science*, showing the role of precipitation in amplifying eutrophication under climate change; delivery of a production software infrastructure for CM4, GFDL’s flagship model for CMIP6; a first prototype of a system for distributing climate model output on the cloud, under DOE funding (DREAM Project); awards for cloud credits from Google Inc. to explore running climate simulations on Google Cloud, and distributing climate model output data via Google Cloud; and six refereed publications, 1 lead-author, 1 in *Science*.

**Workshops organized:** The 7th Annual ESGF Face 2 Face Meeting, San Francisco, 4-8 December 2017; the Vulcan Philanthropies Joint Climate Science-Computing Workshop, Princeton University, 10-12 April 2017; and the Fourth Workshop on Coupling Technologies for Earth System Models, Princeton University, 20-22 March 2017.

Service on several major review boards: Science Advisory Board for the Max Planck Institut for Meteorology, Hamburg; NCAR Computing and Informations System Lab Scientific Advisory Panel Chair; NCAR Scientific Advisory Panel; DOE ACME Project; and Barcelona Supercomputing Centre Earth Science Division (BSC-ES).

Publications:


Progress Report Title: Evaluation of Tropical Cyclone Track and Intensity Prediction in GFDL’s FV3 Dynamical Core

Principal Investigator: Morris A. Bender (Princeton Research Professional)

CICS/GFDL Collaborators: Shian-Jiann Lin (GFDL)

Other Participating Researchers: Andrew Hazelton (Princeton), Isaac Ginis (University of Rhode Island)

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: Evaluate Tropical Cyclones (TCs) in the GFDL FV3 model. Particular focus was placed on the tropical cyclone track and intensity forecast skill both for the 13km global version and a 3km nested version of the model that is being developed and has been run in near-real time in 2017.

Methods and Results/Accomplishments:

The GFDL FV3 dynamical core was selected by the National Weather Service (NWS) as the backbone for the Next Generation Global Prediction System (NGGPS), replacing the NWS current global prediction system (GFS). Since the GFS provides valuable guidance for forecasting of TCs worldwide, as the GFDL FV3 (fvGFS) is transitioned to the NWS, accurate prediction of TC activity, particularly track and intensity is essential. Drawing upon decades of experience in the modeling of tropical cyclones, Bender was tasked to assist in the evaluation of the fvGFS skill in TC prediction, and assist in the evaluation of the model performance as improvements were made and incorporated into 2 versions of the model (i.e. 13 km global, and 3 km nested version) run in near-real time. Focusing on a 3-year sample of TCs in all ocean basins, Bender has made extensive evaluation of the skill of the fvGFS in TC prediction, and compared the skill with other top models used for TC prediction. He has found that the fvGFS consistently is exhibiting impressive skill both for track and intensity prediction. The track skill is found to be slightly improved compared to the current operational GFS, with much improved intensity prediction worldwide. He has shown that the greatest improvement in the intensity skill was likely due to the GFDL micro-physics added into fvGFS model, which significantly reduced the model’s positive intensity bias. These results have been presented in several conferences and are being summarized in a formal publication under preparation which Bender is the lead author. In addition, during the extremely active 2017 Atlantic hurricane season, Bender was asked to provide regular updates to upper-level OAR/NOAA management, on the performance of the fvGFS for the 3 high-profile storms that severely impacted the USA in 2017 (e.g., Harvey, Irma and Maria).

In collaboration with Andrew Hazelton, a Princeton University Post-Doc, a high-resolution version of the fvGFS was developed for hurricane applications, using the nesting capability of the FV3 dynamic core. This modeling system was run in near-real time, for most of the 2017 Atlantic Hurricane season. The nested version of the fvGFS is showing great promise in TC intensity prediction and is comparable to the best hurricane models available. Results of this study have been summarized in a formal publication that Bender is second author on.

Publications:


Presentations:


Hazelton, A. T. and M.A. Bender, 2018: Global and Nested fvGFS Performance on Tropical Cyclones, HFIP Weekly Telecon.

Progress Report Title: Impacts of Cryosphere-Aerosol Interactions on Hydroclimate Variability over High Mountain Asia

Principal Investigator: Hoi Ga Chan (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Sarah Kapnick (GFDL), Paul Ginoux (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: Quantify the impacts of aerosol deposition on snow to surface energy budget and hydrological cycle by including darkening due to aerosol deposition as well as the evolution of optical and physical properties of snow

Methods and Results/Accomplishments:

Processed snow water equivalent data as part of the model validation for aerosol deposition.

Used radiative transfer model to identify and prioritize the parameters that are critical for improving the parameterization of snow. From those sensitivity studies, major parameters are identified, 1) grain size; 2) concentration of light-absorbing impurities; and 3) elevation of the surface. The new snow parameterization should include 1) evolution of grain size as a function of temperature and time; 2) absorption due to dust, black carbon and organic matters assuming they are externally mixed within the snow; and 3) should separate the albedo into black-sky and white-sky albedo in order to factor in the elevation of the snow surface. Other parameters such as the shape of the snow grain and the mixing scheme of the light-absorbing impurities needs to be investigated in future sensitivity studies.

Offline assessment of the potential impacts of dust and black carbon deposition on radiative forcing were also carried using radiative transfer model with the amount of aerosols deposition estimated by GCM. The estimated radiative forcing follows the same trend as the field measurement.
Progress Report Title: Characterizing the Role of Multi-Scale Heterogeneity in the Earth System

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

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

Other Participating Researchers: Martyn Clark (NCAR), 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 petabytes of environmental data to improve the representation of spatial heterogeneity in the GFDL land model. This updated model is being used to understand the role of multi-scale spatial heterogeneity in the Earth system through multi-decadal land-atmosphere coupled simulations.

Methods and Results/Accomplishments:
The continual growth in the availability, detail, and wealth of environmental data provides an invaluable asset to improve the characterization of land heterogeneity in Earth System models. As a proof of concept, over this past year, I completed a study that explores how to effectively and efficiently harness these data in the GFDL land model over a 1/4 degree grid cell in the western foothills of the Sierra Nevada in Central California. First, a novel hierarchical multivariate clustering approach (HMC) was developed that summarizes the high dimensional environmental data space into hydrologically interconnected representative clusters (i.e., tiles). These tiles and their associated properties are then used to parameterize the sub-grid heterogeneity of the Geophysical Fluid Dynamics Laboratory (GFDL) LM4-HB land model. To assess how this clustering approach impacts the simulated water, energy, and carbon cycles, model experiments were run using a series of different tile configurations assembled using HMC. The results over the test domain show that: 1) the observed similarity over the landscape makes it possible to converge on the macroscale response of the fully distributed model with around 300 sub-grid land model tiles; 2) assembling the sub-grid tiles from observed data leads at times to noticeable differences in the macroscale states and fluxes of the water, energy, and carbon cycles; for example, explicit subsurface interactions between the tiles leads to a dampening of macroscale extremes; 3) connecting the fine-scale grid to the model tiles via HMC enables circumventing the classic scale discrepancies between the macroscale and field-scale estimates; this has potentially significant implications for the evaluation and application of Earth System models. This new tiling scheme has now been implemented globally using a C96 and C384 grid.

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

Figure 1. As an exploratory simulation, the LM4-HB model is run between 2002 and 2014 using 14 tiles assembled via HMC. The tile simulated daily evapotranspiration (ET) values for June 16th, 2005 are mapped out onto the 30-meter fully distributed grid using the HMC-assembled fine-scale map of tiles. This provides an approach to take highly efficient model simulations and create field-scale representations for novel model application and validation methods.
**Progress Report Title:** Rhines Scale and Eddy Diffusivity Scalings for Poleward Heat Transport

**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 better understand the dynamical processes that determine the equator-to-pole temperature gradient by studying eddy diffusivity scaling theories in an idealized general circulation model

**Methods and Results/Accomplishments:**

A fundamental question of Earth’s climate is what sets the equator-to-pole temperature gradient in the atmosphere, and the answer to this question largely resides in our understanding of poleward eddy heat transport and the associated eddy diffusivity scaling. Recently, two of these scaling theories have been developed to explain comprehensive global climate models by Barry et al. (2002; hereafter BCT) and Frierson et al. (2006; hereafter FHZ). They both employed the Rhines scale as the mixing length for diffusivity, but the theories differ in other respects. In the attempt to reconcile them, we have revisited an earlier theory proposed by Held and Larichev (1996; hereafter HL). By breaking HL theory into multiple parts, we showed that under quasigeostrophic approximation the scaling theories of FHZ and BCT are equivalent to the theory of HL with some extra assumptions. When applying to full non-quasigeostrophic numerical simulations in comprehensive models, lack of agreement with the scaling theories can result from ambiguities associated with the complex spatial structure of the mean fields. To enable the validation of HL theory while avoiding this issue, we considered the scaling expressions based on Rhines scale and eddy energetics, and we used them to study a simpler idealized dry GCM. (Held and Suarez 1994). In our simulations, we consistently found Rhines scale as a good predictor for mixing length. Supplemental analysis on velocity scalings confirmed that Rhines scale may be qualitatively attributed to either the unstable baroclinic wavelength or the cascade-halting scale, depending on whether the model resides in a quasi-linear or fully turbulent regime. In some of the simulations a breakdown of the theory is observed as neither the turbulence nor quasi-linear argument explains the simulated eddy energy level. These limitations of the theory are to some extent an analog to the discrepancies reported in HL’s two-layer QG simulations. It suggests there are likely some inherent problems with the theory itself or Rhines scale is relevant to mixing length for other physical reasons. In either case, our results point to the need of returning to lower complexity models for a better understanding of these theories.

**References:**


Publications:

**Figure 1.** Diffusivity scaling results for varying meridional temperature gradient at radiative equilibrium ($\Delta_y$) (blue) and planetary rotation rate ($\Omega$) (red) simulations: the log-log plots of the simulated diffusivity ($D$) versus the scaling predictions by planetary vorticity gradient ($\beta$) and three simulated variables, including globally averaged eddy kinetic energy ($EKE$), globally averaged eddy available potential energy ($EAPE$), and globally averaged kinetic energy dissipation by surface drag ($\epsilon_d$). All the predicted values are multiplied by a constant ($c$) such that the prediction for the control simulation (black filled) equals to $D$. 
Progress Report Title:  Investigation of Physical Mechanisms and Model Biases of Mesoscale Convective Systems in the Central United States

Principal Investigator:  Shawn Cheeks (Princeton Graduate Student)

CICS/GFDL Collaborator:  Stephen Garner (GFDL), Stephan Fueglistaler (Princeton), Leo 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:
Weather-Ready Nation Goal:  Society is Prepared for and Responds to Weather-Related Events

Objectives:  Utilizing GOES-class satellite imagery and modern image processing algorithms, develop a climatology of mesoscale convective systems in the central United States – identifying patterns in season, location, time of day, and precipitation impacts. Using this observational record as a baseline, experiments will be conducted on ZETAC and FV3 models to evaluate model representation of these observed patterns.

Methods and Results/Accomplishments:
Thus far, the observational dataset has been produced for a twenty-year climatology (1996-2015) of mesoscale convective systems in the Central United States. This dataset is currently being evaluated for patterns of statistical significance, which will be submitted for publishing. Once completed, corresponding datasets will be produced from the default ZETAC and FV3 model settings and compared against the observational record. This analysis will inform future modeling experiments to identify physical mechanisms and biases in these models.

Outreach Activities:  Regular visits to 8th grade math classes at Village Charter School (Trenton, NJ) to support STEM classroom activities. Facilitated cooperation between Fall River Elementary School (Roderfield, WV) and the SOCCOM Adopt-a-Float program. Accompanied SOCCOM-affiliated scientist to Fall River Elementary School to introduce students to climate science.

Publications:
Investigation of Observed Climatological Patterns of Mesoscale Convective Systems in the Central United States, in preparation.
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), Lucas Harris (GFDL), Linjiong Zhou (Princeton)

Other Participating Researchers: Cheng Li (Caltech/JPL), Jan-Huey Chen (UCAR)

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: Preparing FV3 implementation into NOAA/NWS Global Forecast System. Exploring FV3 as a driver of the globally cloud resolving capability at the resolution of 3km. Develop a “Low Mach number Approximate Riemann Solver (LMARS)” based dynamical core.

Methods and Results/Accomplishments:
2017-2018 is a critical year for FV3 development to both NOAA's NGGPS implementation and GFDL's AM4/CM4 finalization. The grid-staggering choice of FV3 has been challenged (see references of Randall 1994, Skamarock 2008, Konor and Randall 2017 and the discussion) that the D-Grid staggering is inferior due to poor dispersion properties. I have led the research that enables the classic von Neumann analysis to be performed on high-order numerical discretization, which better represents the numerical properties of real-world applications. Our work demonstrates two important conclusions: 1. Both the pros and cons due to grid staggering choices diminish with high-order discretization; 2. The C-Grid results in non-stationary noise, which forms low-frequency aliasing to the solutions. This work is preparing for submission. Our work on the fvGFS variable-resolution 10-day forecast is completed and submitted to BAMS. Our work on FV3 development is featured in a report published in Science magazine, I have contributed content to this work, in Fig. 1. In GFDL, the development of the AM4 model is approaching finalization, I have contributed to this project by creating a new 33-level and 49-level vertical hybrid coordinates for the climate simulation and the application with full chemistry features. The new coordinates provide better resolution near the surface, which lead to significant improvement to the simulated 2-meter temperature. The AM4 model results are published in JAMES.
Fig. 1. A figure featured on the Science magazine that demonstrates FV3 applications in different scales

More recent FV3 development is focusing on 3 km resolution development. With such fine resolution, many traditionally considered "under-resolved" processes can start being explicitly resolved. Fig. 2 is a demonstration of the OLR field at the end of a 40-day 3km FV3 simulation. With deep-convection parameterization turned off, the tropical convections are now directly powered by the dynamical processes. We can observe such convection processes in high fidelity in this animation.

Fig. 2. The Outgoing Longwave Radiation field of FV3 3-km resolution run at the end of 40-day simulation

My collaborator at Caltech is working with me to create a new dynamical core based on my Low Mach-number Approximate Riemann Solver (LMARS, Chen et al., 2013). Owing to the unique properties of this solver, the new model has the following features: 1. The total energy is the prognostic variable; 2. No explicit diffusion is required; 3. Moisture process is rewritten from scratch, which takes full advantage that the total energy is the prognostic variable. 4. This model is universal that can be used for both earth
and other planetary atmospheric research. Some preliminary results are demonstrated in Fig. 3., which
show the Jupiter atmospheric convection of both ammonium cloud (brown) and water cloud (grey)
convection. The publication of this work is in preparation.

I also have some other research activities during the year. I have participated in the Dynamical
Cores Model Inter-comparison Project (DCMIP 2016) as the FV3 tutor. We have published the overview
paper on GMD, and a series publication of the results are under preparation. We have also submitted the
idealized Modon tests paper, which is an important test to validate the model's ability to resolve vortices.
This paper is published on JAMES. I have also presented my research results and FV3 group's results in
several conferences, such as AGU, AMS annual meetings. In particular, I represented FV3 group to
demonstrate our work in NCAR's AMWG meeting. During the last Nor'easter snow storm, I was quoted in
a news piece from Observer.

Fig. 3. A double periodic simulation of both ammonium and water clouds convection in the Jupiter
atmospheric environment from a LMARS-based model

References:
Geoscientific Model Development Discussions, 1–58.

Press Coverage:

**Publications:**

**Presentations:**


Progress Report Title: Marine Ecosystem Tipping Points: Climate Downscaling for California Current Marine Ecosystem Impacts

Principal Investigator: Enrique Curchitser (Rutgers Associate Professor)

CICS/GFDL Collaborator: Charles Stock (GFDL)

Other Participating Researchers: Raphael Dussin (Rutgers), Shuwen Zhang (Rutgers)

Award Number: NA14OAR4320106

Task III: Individual Projects

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Healthy Oceans Goal: Marine fisheries, habitats, and biodiversity are sustained within healthy and productive ecosystems (50%)
Resilient Coastal Communities and Economies Goal: Coastal and Great Lakes communities are environmentally and economically sustainable (50%)

Objectives: To develop a framework for Earth System model integrations across scales with an emphasis on biogeochemical cycles in coastal regions

Methods and Results/Accomplishments:
Understanding and quantitative projection of credible future Earth system scenarios requires a modeling framework that represents the numerous components, the feedbacks between them, and resolves the scales important to variability within each sub-system. In the ocean, coupled physical-biogeochemical models have recently matured both in global and regional implementations. However, little work exists with a holistic view that links global and coastal models. The thrust of our current work under this award is to implement the NOAA-GFDL biogeochemistry model, COBALT, in a regional, high-resolution model, ROMS, and perform downscaling studies for coastal regions with a consistent biogeochemistry model across the spatial scales. A further benefit of our approach is the ability to test features of the global Earth System model at high-resolution in a computationally affordable way.

With the newly developed, consistent, downscaling capability we have been carrying out coupled ocean-biogeochemistry simulations in the California Current System and the Northeast US Shelf. Figure 1 shows a transect of both temperature and chlorophyll for both ESM2M and the downscaled ROMS-COBALT model. Though the high-resolution downscaled model significantly improves the coastal representation of temperature and chlorophyll in the upwelling system, chlorophyll values are still lower than observations (left panel). This has led to the addition of a coastal diatom class in COBALT, which shows the model is able to represent the range of scales (high-coastal to oligotrophic interior) seen in the observations (Van Oostende et al, 2018). The coupled model is also showing significant skill in representing coastal hypoxia (Dussin et al, 2018). A recently published paper focuses on the role of anticyclonic eddies in the NO3 on the US Northeast Shelf (Zhang et al, 2018) and a paper in preparation is focusing on the shelf nitrogen budget.

Further work is planned using our model framework to carry out a small ensemble of projections for future ecosystem states in the two coastal regions.
Figure 1: Cross-shelf transect from the downscaled California Current coupled bio-physical model (ESM2M to ROMS). On the left, the model with 2-phytoplankton classes, on the right the corresponding model with the addition of coastal diatoms (Van Oostende et al, 2018). Dashed lines are sea surface temperature, solid lines are chlorophyll.

Publications:

Presentations:
**Progress Report Title:** Crystallization of Sodium Chloride in Supersaturated Aqueous Solutions

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

**CICS/GFDL Collaborator:** Yi Ming (GFDL), Hao Jiang (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:** Crystallized salt particles in sea-salt aerosols can efficiently induce heterogeneous ice nucleation, and are crucial for the microphysics of marine clouds. The objective of this work is to improve our understanding of the crystallization of salt particles by applying molecular simulation methods to study homogeneous nucleation of sodium chloride (NaCl), the most widely present salt species in sea-salt aerosols, in supersaturated solutions.

**Methods and Results/Accomplishments:**

Ice nucleation, especially the heterogeneous nucleation of ice in sea-salt aerosols, is crucial in Earth System Models (ESM). The hydrated crystallized NaCl particle, formed when a NaCl solution is exposed to low relative humidity resulting in a supersaturation, is found to efficiently induce depositional heterogeneous ice nucleation. One of the important questions regarding such process is how Na⁺ and Cl⁻ ions nucleate into crystals in a supersaturated solution, and what is the nucleation rate for the crystallization. It is, however, extremely challenging to address these questions directly in experiments due to the insufficient spatiotemporal resolution of the existing experimental techniques. A consensus about the mechanism of NaCl nucleation has not yet been reached, and whether the nucleation process can be described by the classical nucleation theory is subject to debate. However, the classical nucleation theory is constantly used, regardless its validity, for estimation of the NaCl nucleation rates in prior experimental or simulation studies.

As reported in our recently-published paper in *The Journal of Chemical Physics*, we used a path sampling molecular-based computer simulation technique known as forward flux sampling to directly compute the nucleation rates of NaCl crystallization at different solution supersaturations. We employed the SPC/E water and Joung-Cheatham force fields, which have been shown to give reasonable prediction for a series of thermodynamic (e.g. salt solubility) properties of aqueous NaCl solution. We calculate the nucleation rates directly from simulation without invoking the classical nucleation theory, and the nucleation rates are found to span over 40 orders of magnitude at salt concentrations from 8 mol/kg to 14 mol/kg. It is also found that the SPC/E and Joung-Cheatham force fields underestimate nucleation rates when compared to available experimental data, possibly due to the overestimation of crystal/solution interfacial tensions from the force fields. By analyzing the nucleation pathway, we find that ions aggregate directly into a crystal with rock-salt structure, which is the most thermodynamically stable state of solid NaCl, suggesting the nucleation process is more consistent with classical nucleation theory than with the two-step Ostwald rule. Additionally, our simulations indicate that the solvation water around a crystalline ionic nucleus impacts significantly the nucleation process, as a small crystalline nucleus with more solvation water is less likely to grow and overcome the nucleation barrier.
Outreach Activities: Prof. Panagiotopoulos and his group have been regular participants at the “Nano-Day” event organized in partnership with the Princeton Public Library, most recently on Oct. 28, 2017. Over 500 young children and their families participated in activities and demonstrations – in our case, we displayed molecular conformations and simulations of complex fluids.

References:

Publications:
**Progress Report Title:** Parameterizing the Melting of Icebergs in GCMs

**Principal Investigator:** Anna FitzMaurice (Princeton Graduate Student)

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

**Other Participating Researchers:** Claudia Cenedese (WHOI), Alon Stern (Princeton)

**Award Number:** NA14OAR4320106

**Task II:** Cooperative Research Projects and Education

**NOAA Sponsor:** V. Ramaswamy (GFDL)

**Theme:** Earth System Modeling and Analysis

**NOAA Goals:**

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

**Objectives:** To improve the representation of iceberg meltwater fluxes in GCMs

**Methods and Results/Accomplishments:**

With rising global temperatures, there has been an observed increase in the discharge of ice from the Antarctic and Greenland ice sheets. This trend has motivated a focus on the study of icebergs, which act as conduits for transporting freshwater from the ice sheet margins to the ocean as they are carried away from their sources and melt. Accurately modeling this freshwater flux is important to both physical and biological oceanography, but current iceberg parameterizations are rudimentary, with icebergs typically being represented as levitating point particles in GCMs.

We consider the influence of icebergs that occupy physical space on the ocean, with a view to answering the question of how the melting of icebergs and subsequent distribution of meltwater in the water column might be accurately parameterized in climate models. Iceberg melt is analyzed by comparing in-situ melt rates calculated via the three-equation parameterization, which was developed for application under ice shelves, with the commonly used bulk parameterization of iceberg basal melt. Our results suggest an updated velocity-independent version of the basal melt parameterization for tabular icebergs for use in calculating the basal melt rate of icebergs that are large (relative to the deformation radius), to account for the changes in ocean properties caused by the physical presence of a large iceberg in the ocean.

**Publications:**

- FitzMaurice, A. and Stern, A. Parameterizing the basal melt of tabular icebergs. Ocean Modelling, Submitted.


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 P.G. Gauthier (Princeton Associate Research Scholar), Stephen W. Pacala (Princeton Professor)

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

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 and nitrogen cycles in the GFDL LM4 and ESM4 models by improving the representation of plant photosynthesis and respiration and nitrogen partitioning

Methods and Results/Accomplishments:

Plant carbon is characterized by two main and opposed metabolic rates: photosynthesis (P) and respiration (R). The definition of photosynthesis in LM3 has now been improved by including a light limitation component, a more realistic temperature response and an inhibition of leaf respiration in the light (Kok effect). The light limitation led to the implementation of a new mechanistic control for Leaf Area Index (LAI). Historically, GFDL ESM was largely overestimating LAI and this overestimation was more obvious in the Northern hemisphere (Anav et al 2013). LAI is estimated as a function of biomass that is itself controlled by productivity, so the ratio P:R. This parameterization resulted into the constant production of leaves if the ratio P:R was none null. In fact, this overproduction of leaves resulted from two artefacts of the parameterization: (1) the constant relationship between $V_{\text{cmax}}$ and respiration and (2) the lack of control of maximum LAI. Because LAI is a function of the ratio P:R, leaf productivity is dependent of the irradiance reaching each layer of the canopy. When irradiance reaches zero, then leaves would be unproductive and LAI should stop expanding. While the reduction of LAI impacts directly the carbon cycle, it is also likely to affect the nitrogen cycle. This parameterization has been implemented successfully into GFDL LM3 and in LM4-PPA as a way to estimate LAImax. The result of this parameterization is a reduction of maximum LAI in Boreal and Tropical regions (figure 1B). In these regions at the grid cell, LAI was reduced by 19%. In addition, to maximize leaf carbon uptake, mitochondrial respiration has been shown to decrease under high irradiance leading to the empirical observation of the Kok effect (Kok, 1948). Because this parameterization allows for more plasticity in the acquisition of carbon by plants under limited conditions (when photosynthesis rate is low) and it has been ignored in most land models, the Kok effect has been implemented into GFDL-LM4. A direct consequence of this parameterization is a slight increase in LAI by 4% (figure 1C). Nevertheless, when combined with light limitation, LAI was reduced by 17% in the regions of interest. While this effect improves the realistic representation of vegetation in tropical and boreal regions, the impact in the Arctic is still moderate (figure 2). This moderate impact on LAI for tundra or circumpolar regions, where modelled LAI is still ~5, is a direct consequence of the misrepresentation of the decoupled response of respiration and photosynthesis to...
temperature and to nitrogen limitation. A corrected representation of this response has been implemented and showed significant climate sensitivity in ESM4.

The initial effort in this project has been concentrated on implementing these new parameterizations into the new advanced GFDL model LM4. In parallel to this effort, another CICS team implemented CORPSE (Sulman et al 2017) module, that include nitrogen parameterizations, into LM4. At this stage, both parameterizations are now fully operational in LM4 and are currently compared to further improve the control of ecosystem productivity through Carbon and Nitrogen cycles. The consequences of these two implementations on Net and Gross primary production under current climate and future scenarios are particularly investigated.

**Figure 2. Annual maximum leaf area index for pre-industrial potential vegetation**

**Figure 3. Annual Maximum leaf area Index for pre-industrial potential vegetation from 60 to 90N**

**References:**


Publications:

Presentations:

Progress Report Title: Reflection of Rossby Waves by Shear Zones

Principal Investigator: Matthew Gliatto (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:
Weather-Ready Nation Goal: Society is Prepared for and Responds to Weather-Related Events

Objectives: The goal is to determine whether or not a Rossby wave generated in the midlatitudes will propagate into the tropics. We modeled the system as a two-layer QG model with a critical latitude in only the lower layer.

Methods and Results/Accomplishments:

We want to determine whether a Rossby wave generated in the midlatitudes will successfully propagate into the tropics or be absorbed or reflected before it gets there. In the atmosphere, the mean zonal winds are more westerly at higher latitudes. To deal with this gradient, we used a two-layer model with a mean zonal wind profile $U(y)$ in both layers. The two profiles are separated only by a constant, which represents the vertical wind shear.

We used a scattering problem — discretizing a differential equation and making use of boundary conditions — to calculate both the coefficients and the momentum fluxes of reflection and of transmission for the wave. MATLAB was the only software used. We found that the wave is almost completely absorbed except for over a certain range of values of the vertical wind shear. This range is, after nondimensionalizing the shear, always larger than 2. Over this range of values, there is a large amount of transmission. Thus, the wave can successfully propagate into the tropics only if the nondimensionalized wind shear is larger than 2.

References:


**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:** The objective of this project is to improve our understanding of the ice sheet contribution to sea level rise by improved modeling of marine ice sheets and ice streams.

**Methods and Results/Accomplishments:**

Ice shelves form when ice sheets grounded below sea level begin to float. They transmit ocean forcing (e.g. variations in basal melt rates) inland by changing the stress balance at the grounding line, the contact line between floating ice shelves and grounded ice sheets. Observations suggest that changes in ice shelf geometry can lead to the loss of grounded ice, which contributes to sea level rise. My work in collaboration with Olga Sergienko has focused on understanding these dynamics by extending a recently-developed boundary layer approach to calculate analytically how the ice flux at the grounding line changes for different ice shelf conditions. This allowed us to identify calving (that is, the breaking off of icebergs at the ice shelf front) as a major control on the position and stability of the grounding line (Haseloff & Sergienko, in press). This result implies that current simulations of marine ice sheet dynamics may be significantly less certain than previously anticipated, as no complete mathematical description of calving processes yet exists.

Ice streams are fast-flowing regions of ice bordered by slowly moving ice. They are the main discharge routes for ice accumulated in the interior of an ice sheet. Observations suggest that the margins of some of these ice streams can migrate over time, leading to slow-down and reactivation cycles in the ice stream and drastically altering the ice sheet's discharge. The thermo-mechanical processes that govern the migration of ice stream margins operate on length scales that are much smaller than typical grid sizes of continental-scale numerical ice sheet models. To include ice stream migration in continental-scale ice sheet models, we have derived a first parametrization of these processes by analytical and numerical means (Haseloff et al., 2018).

**Outreach Activities:** Princeton Prison Teaching Initiative

**Publications:**


Presentations:


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/GFDL), Cleo Chou (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 goals of this project are two-fold: 1) to advance biogeochemical theory on terrestrial P (and N) nutrient limitation by examining the interaction between ecological dynamics and C, N, and P cycles via a simple theoretical model parameterized by empirical datasets; and 2) to apply this knowledge in the development and implementation of a state-of-the-art dynamical plant-soil P cycle for the GFDL LM4 land model that will improve modeling of the land carbon sink.

Methods and Results/Accomplishments:
We have advanced biogeochemical theory on nutrient limitation of terrestrial ecosystems by developing a simple theoretical model that integrates the biological dynamics of forest succession after disturbance with ecosystem nutrient cycling. This model tracks C, N, and P in biomass and the soil pools and allows us to determine time periods when either N or P are limiting plant growth during succession. More specifically, it informs us of essential biological dynamics, mechanisms of nutrient limitation, as well as flexible biological responses for alleviating this limitation, to include in our design of the P cycle for LM4. We parameterized our model using a dataset of succession biomass accumulation in forest biomes globally that we gathered from the literature and found temporal differences in N and P limitation within each biome and between biomes. This work was presented at the American Geophysical Union Fall Meeting in December 2017, and we are currently preparing a manuscript for publication (Chou and Hedin in preparation). Given our results, we are working towards designing and implementing a biogeochemically advanced plant-soil P cycle for LM4 in close collaboration with Elena Shevliakova and the GFDL land working group, including associate research scholar Ben Sulman who has developed and implemented the land N cycle for LM3 and LM4.

Additionally this year, Chou published empirical research on how light availability as well as tree functional group and species identity can impact N and P nutrient limitation of tropical sapling growth (Chou, Hedin & Pacala 2018). This work supports and informs our framework that crucial ecological dynamics like forest disturbance and succession can drive nutrient limitation in ecosystems by altering environmental conditions (such as light availability), impacting tree growth rates and corresponding nutrient demand. Moreover, this work suggests that plant strategies can exacerbate or alleviate plant nutrient limitation depending on the trait or combination of traits. Chou explored this further in an analysis of both how leaf functional traits may be plastic to nutrient and light availability and how these traits can impact whole tree nutrient limitation in variable light environments. This work was presented at the international meeting of the Association for Tropical Biology and Conservation in 2017. Together, these
two empirical studies encourage us to incorporate responsive plant strategies in our dynamic plant-soil model for LM4.

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

Publications:


Presentations:


Progress Report Title: A Moist Quasi-Steady Baroclinic Eddy with Hypohydrostatic Convection

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 investigate the interaction between baroclinic eddies and moist convection, and how the intensity of the eddies respond to a warmed climate

Methods and Results/Accomplishments:
A model of a moist, quasi-steady baroclinic eddy is constructed to evaluate the hypohydrostatic rescaling. In this beta-plane channel model, an LC2 life cycle equilibrates to a quasi-steady state where the generation of available potential energy is dominated by the eddy component through latent heat release in the warm sector. In previous studies, the hypohydrostatic rescaling has been used to replace convective parameterization in models involving extratropical phenomena, but it has never been evaluated in an environment where baroclinic eddies also play a role in setting the stratification. 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. The hypohydrostatic rescaling may be more useful when applied to push the resolution out of the gray zone on phenomena where the structure of convection is important.

Outreach Activities: NJ Ocean Fun Days, May 2017

Presentations:
Hsieh, Tsung-Lin. A quasi-steady baroclinic eddy with hypohydrostatic convection, 21st Conference on Atmospheric and Oceanic Fluid Dynamics, June 2017, Portland, OR.
**Progress Report Title:** An Examination of the Radiative Forcing and Feedback in the GFDL Models

**Principal Investigator:** Yi Huang (Princeton Visiting Faculty)

**CICS/GFDL Collaborator:** V. Ramaswamy (GFDL), David Paynter (GFDL)

**Award Number:** NA14OAR4320106

**Task II:** Cooperative Research Projects and Education

**NOAA Sponsor:** V. Ramaswamy (GFDL)

**Theme:** Earth System Modeling and Analysis

**NOAA Goals:**

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

**Objectives:** We analyze the radiative forcing and feedbacks in the GFDL GCMs against satellite observations.

**Methods and Results/Accomplishments:**

The uncertainty in climate feedback, especially that due to clouds, has been an enduring problem that impedes our ability of climate modeling and projection. Here we conduct a collaborative investigation of the radiative feedback from a few new angles. In this investigation, we extend radiative feedback analysis from TOA to surface and atmospheric budgets. This research is based on the kernel method and a set of radiative sensitivity kernels that we have newly developed at McGill. The kernel method [Soden & Held 2006] is a diagnostic method that quantifies the radiative feedback of a variable, where the kernel is pre-calculated and can then be multiplied with model-simulated climate response to quantify the radiative impact of this response. The feedback analyses have been mostly focused on the TOA radiation budget, although similar analysis on surface and atmospheric budgets would provide especially valuable energetic constraints for understanding such problems as PET and precipitation changes [e.g., Previdi 2010]. Towards that goal, we have developed a new set of TOA and surface radiation sensitivity kernels, based on the ERA-interim atmosphere [Dee et al. 2012] and using the RRTM. The reanalysis-based kernels especially suit the analysis of the observational counterparts of the feedback that can be compared to the modeling results. I am interested in applying these kernel sets to validating the feedbacks in all available historical simulations of the GFDL models.
**Progress Report Title:** GFDL Model Hierarchies and Idealized Cloud-Resolving Modeling

**Principal Investigator:** Nadir Jeevanjee (Princeton Postdoctoral Research Associate)

**CICS/GFDL Collaborator:** Leo J. Donner (GFDL), V. Balaji (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:** Objectives are two-fold: 1) critically examine the use of model hierarchies in understanding both observed and simulated climate 2) 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 such as GFDL's FV3 are now able to partially resolve convective clouds, but it is uncertain how aspects of the model configuration (resolution, hydrostatic approximation, diffusion) impact the representation of these convective motions, and in particular the simulated vertical velocity \( w \).

We have developed some basic theory that suggests that \( w \) will only converge at grid spacings finer than \( \sim 1 \) km, and that at these resolutions a hydrostatic model will overestimate \( w \) by a factor of about 3. Furthermore, idealized, limited-area simulations with FV3 confirm these predictions (Fig. 1, from Jeevanjee 2017). We also found that model diffusion parameters have a surprisingly large impact on the organization of convection and hence the simulated climate; see Anber 2018.

Finally, we took a critical look at how idealized simulations such as these help us understand more complex simulations, and ultimately the real Earth system. We described this ‘model hierarchy' as a Cartesian product of model components (Fig. 2), and took stock of progress that has and has not been made over the last decade in filling out missing rungs in the hierarchy. See Jeevanjee et al. (2017).


**Publications:**


Presentations:

Jeevanjee, Nadir. Vertical Velocity in the Gray Zone, poster presentation at WGNE workshop on systematic errors in weather and climate models, June 2017, Montreal, Canada.

Jeevanjee, Nadir. Vertical Velocity in the Gray Zone, oral presentation at AMS Atmosphere and Ocean Fluid Dynamics conference, June 2017, Portland, OR.

![Figure 4: Normalized convective vertical velocity $w_c$ as a function of resolution, with and without the hydrostatic approximation (red and black, respectively). Solid curves give theoretical prediction, while stars are simulation output.](image)

![Figure 5: The climate model hierarchy as a six-dimensional Cartesian product.](image)
**Progress Report Title:** Aerosol Instantaneous Radiative Forcing Component of the RFMIP (Radiative Forcing Model Intercomparison Project)

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

**CICS/GFDL Collaborator:** David Paynter (GFDL), V. Ramaswamy (GFDL)

**Other Participating Researchers:** William Collins (LBNL), Daniel Feldman (LBNL)

**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:** GFDL’s contribution to RFMIP is in quantifying the spread in the instantaneous radiative forcing by aerosols due to radiative transfer parameterization error. 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:**

GFDL’s responsibilities to RFMIP are to quantify the component of intermodel spread in aerosol instantaneous radiative forcing due to radiative parameterization error. To accomplish this each participant model’s solar fluxes will be reproduced with a line-by-line radiation code. My primary work at GFDL has been in developing that global line-by-line benchmark code framework for use in RFMIP as well as other applications in radiative transfer relevant to the lab’s interests. I have continued development work on this tool, including coupling it to the radiative transfer solver DISORT. It is now ready to be used for RFMIP, awaiting data from modeling centers. I am a lead author on a paper that uses this tool to expose significant errors in climate model radiative parameterizations in calculating aerosol radiative effect. I have begun introducing the benefits of this global radiative tool to a wider audience by creating a set of guidelines and FAQ for models participating in this part of RFMIP.

**Outreach Activities:** Co-supervision of Princeton AOS Graduate Student Shiv Priyam Raghuraman

**Publications:**


**Presentations:**


Progress Report Title: CI-MIP5 Model-based Assessment of Anthropogenic Influence on Highly Anomalous Arctic Warmth during November-December

Principal Investigator: Jonghun Kam (Princeton Postdoctoral Research Associate)

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

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: This project is aimed at improved understanding of the causes of an extreme climate event (high average temperatures) over the Arctic during November-December 2016. We used multiple climate models and observations to assess the possible role of anthropogenic forcing in the extreme event and to test whether climate model simulations and projections are consistent with observations.

Methods and Results/Accomplishments:

For this project, we analyzed highly anomalous warmth which occurred over the Arctic during November-December 2016. We included an observational uncertainty assessment using five observational temperature datasets. This work was a contribution to an annually published special issue of the Bulletin of the American Meteorological Society which seeks to explain extreme weather and climate events during the past year in the context of long-term climate change. While much of the methodology follows previous contributions by Knutson and collaborators, the new study which I led focused on the sensitivity of Arctic regional averaged temperature anomalies during November-December 2016 to observational data and used an improved method to construct confidence intervals. A model/observational comparison, using CMIP5 models to simulate internal decadal climate variability and the response to historical and projected anthropogenic and natural forcings, was applied to unusual seasonal-mean Arctic warmth in 2016. A time-evolving long-term trend analysis and a focused event attribution analysis for the 2017 anomalies was presented including an assessment of the fraction of attributable risk (FAR) to anthropogenic forcing. Uncertainties in the analysis include in: the climate model response to external forcings, the specification of the external forcing agents, and the simulation of internal climate variability. Limited model data (control run length, numbers of ensemble members) also increases uncertainties. To reduce uncertainties from limited ensemble members, we chose climate models that have more than two ensemble members for both the historical and natural-only forcing runs. In an enhancement relative to our previous studies we included an assessment of modeled vs. observed internal decadal variability using observed estimates from multiple data sources.

We found that according to CMIP5 simulations and multiple observational datasets the highly anomalous Arctic warmth during November-December 2016 most likely would not have been possible without anthropogenic forcing. Due to the relatively short observational record, and uncertainties in the forced response mean, the estimate of real-world decadal internal variability remains uncertain (e.g., Knutson et al. 2016), and will require further evaluation in the future, for example with paleoclimate data (e.g., Delworth and Mann 2000).
**Outreach Activities:** Invited Talk at Earth System Research Laboratory/NOAA, Feb. 9th, Boulder, CO

**References:**


**Publications:**


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![Fig. 1](image-url)

**Fig. 1.** (a) Estimated FAR of exceeding the first- and second-ranked observed Arctic Nov–Dec temperature anomaly thresholds (large orange and yellow circles, respectively), based on the CMIP5 multimodel ensemble. Small dots indicate the observational dataset used. Columns M1–M8 show estimates from individual CMIP5 models (second-ranked observed anomaly threshold) for each observational dataset. (M1–M8 correspond to the different CMIP5 models used in the study.) Risk ratios (the relative risk of the event in the current climate relative to a pre-industrial climate) are indicated by the y-axis labels along right edge. (b) Simulated internal decadal standard deviation of the M1–M8 control runs (green bars), along with observational-based estimates from low-pass-filtered Nov–Dec Arctic temperatures (°C) from five observational datasets (horizontal colored lines), with a model-estimated All-Forcing (natural + anthropogenic) response removed from the observed variability for the comparison to modeled internal variability.
**Progress Report Title:** Impacts of Variability in Iron Supply on Marine Biogeochemistry

**Principal Investigator:** Charlotte Laufkötter (Princeton Postdoctoral Research Associate)

**CICS/GFDL Collaborator:** John P. Dunne (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:** Iron is an essential nutrient and limits phytoplankton growth in several regions in the ocean, most notably the Southern Ocean. Because of large uncertainties in the sources and sinks of the iron cycle, the current generation of Earth System Models uses constant iron forcings derived from observation-based dust climatologies, independent from the land model and typically assuming a constant fraction of soluble iron in dust. In addition, no iron inputs from icebergs are considered. Charlotte Laufkötter improved the representation of the iron cycle by a) creating and analyzing simulations with inter-annually variable dust-iron input and a variable soluble iron fraction and b) including iron inputs from icebergs.

**Methods and Results/Accomplishments:**

In her last 5 months in Princeton, Charlotte Laufkötter has focused on finishing her work on impacts of varying iron supply to the Southern Ocean and communicating her research to the scientific community. She has analyzed the impacts of iron carried by icebergs and the implications of temporally varying dust on marine biogeochemistry and the carbon cycle in the Southern Ocean. Overall, her work has substantially improved the performance and theoretical foundation of the marine biogeochemical component of GFDL’s Earth System Model.

To obtain a projection with inter-annually varying iron inputs, Charlotte Laufkötter replaced the offline iron forcing with the dust emissions from the LM3 land model. In addition to the default dust emissions she used the dust emission parameterization developed by Evans et al. 2016, which features changes in dust emission depending on changes in land surface. She also uses a parameterization of a varying fraction of soluble iron that she previously developed. Charlotte Laufkötter has then compared the response of marine biogeochemistry in a simulation with inter-annually varying dust with a simulation that uses a constant climatology, focusing on changes in the Southern Ocean. First results show a strong response of marine export production to variations in dust input, with export production being four times more variable in the simulation with inter-annually varying dust compared to the simulation forced with a constant climatology. In addition, the export production reflects long-term changes in dust input, resulting in a small but significant decrease in export production during the last decades caused by decreases in dust input.

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 for iron concentration in icebergs by Raiswell et al. 2008 and Death et al. 2014. She has performed several simulations with different iron concentrations in icebergs and glacial
meltwater to determine which of the estimates results in most realistic surface iron concentrations. The
model has been evaluated using the most recent observations of iron concentrations and satellite-based
observations of chlorophyll. In the model simulation with most realistic iron and chlorophyll values, about
30% of the flux of particulate organic matter through 100m depth is driven by glacial iron sources. This
export production is associated with an uptake of 0.14 Pg carbon per year. Her results indicate that
icebergs might play a significant role in Southern Ocean carbon cycling and oceanic carbon uptake,
however, more research is needed to narrow down the uncertainties associated with the parameterization of
iron in the ocean, icebergs and glacial meltwater.

Publications:
Laufköttet, C., J. G. John, C. A. Stock, and J. P. Dunne (2017), Temperature and oxygen
dependence of the remineralization of organic matter, Global Biogeochem. Cycles, 31, 1038–1050,
Laufköttet, C., J. P. Dunne, J. G. John, A. A. Stern and C. A. Stock, Icebergs amplify the
Southern Ocean carbon cycle via iron fertilization (in preparation).

Presentations:
Laufköttet, C., J.G. John, C. A. Stock, J.P. Dunne, Temperature-dependent remineralization of
organic matter – small impacts on the carbon, EGU 2017, Vienna, Austria (poster).
Laufköttet, C., J.G. John, A. A. Stern, C. A. Stock, J.P. Dunne, Impact of iron from icebergs on
impact on the marine carbon cycle, ICDC 2017, Interlaken, Switzerland (poster).
A. Stern and C. A. Stock, Biogeochemical impacts of varying iron supply to the Southern Ocean, Ocean
Sciences 2018, Portland, Oregon (oral).
**Progress Report Title:** Responses of the Global Land Nitrogen Cycle to Anthropogenic Land Use and Climate Changes

**Principal Investigator:** Minjin Lee (Princeton Postdoctoral Research Associate)

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

**Other Participating Researchers:** Chris Milly (USGS)

**Award Number:** NA14OAR4320106

**Task II:** Cooperative Research Projects and Education

**NOAA Sponsor:** V. Ramaswamy (GFDL)

**Theme:** Earth System Modeling and Analysis

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

**Objectives:** We use the GFDL land model LM3-TAN to investigate responses of the global land nitrogen (N) cycle to anthropogenic land-use and land-cover changes (LULCC) and climate change.

**Methods and Results/Accomplishments:**

We have used the GFDL land model LM3-TAN (Lee et al., 2014) for three different studies to answer various pressing scientific questions.

First, we successfully simulated historical river flows and nitrate-N exports throughout the entire drainage network of South Korea (100,210 km²) (Lee et al., 2018, in review). Based on projections by using multiple scenarios of N-input reductions, we found three fundamental implications for effective basin management strategies: 1) short-term climate variability can produce river N export extremes and significantly mask N-input reduction effects on coastal water quality, 2) long-term mean climate can exert a stronger control on geographic variation in water N pollution than anthropogenic N inputs, and 3) the greatest effects of N-input reductions on coastal water quality are obtained in basins, which are influenced by dry climate, receiving high N inputs, and/or close to the coast.

Second, we developed a global implementation of LM3-TAN and analyzed the effect of the past two centuries of anthropogenic Nr inputs, LULCC, increasing atmospheric CO2, and climate on global and regional N fluxes to the ocean and atmosphere (Lee et al., 2018a, in prep). Our analysis suggests that tropical land has produced more than 50% of contemporary land N outputs despite covering only 34% of global land area and receiving far lower synthetic fertilizers than the extratropics. This study thus suggests that tropical LULCC and Nr inputs are thoroughly considered in policies to manage future global N pollution.

Third, we used measurement-based estimates and results of the global implementation of LM3-TAN to explore the significant role of terrestrial N storage, interacting with climate variability, in river N export extremes. We investigate an emerging new view that accumulated soil N during dry years, which is, in turn, washed out into rivers via subsequent rainfalls, can significantly amplify N exports, and thus eutrophication risks (Lee et al., 2016). We demonstrate that this phenomenon is normal, widespread, or recurring across the globe (Lee et al., 2018b, in prep). This work was presented at the 2017 AGU Chapman Conference.
References:
Lee et al. (2014), Capturing interactions between nitrogen and hydrological cycles under historical climate and land use: Susquehanna Watershed analysis with the GFDL Land Model LM3-TAN, Biogeoosci., 11, 5809–5826.
Lee et al. (2016), Climate variability and extremes, interacting with nitrogen storage, amplify eutrophication risk. GRL, 43, doi:10.1002/2016GL069254.

Publications:
Lee et al. (2018), Control of nitrogen exports from river basins to the coastal ocean: Evaluation of basin management strategies for reducing coastal hypoxia. JGR Biogeoosciences, in review.
Lee et al. (2018a), Prominence of the tropics in the recent rise of global nitrogen pollution. In prep.
Lee et al. (2018b), Terrestrial nitrogen storage under recent climate variability amplify global eutrophication risk. In prep.

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

**Principal Investigator:** Sonya Legg (Princeton Senior Research Oceanographer)

**CICS/GFDL Collaborator:** Robert Hallberg (GFDL), Stephen Griffies (GFDL), Alistair Adcroft (Princeton), Robert Nazarian (Princeton), Elizabeth Yankovsky (Princeton), Sarah Nickford (Stony Brook University)

**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), Young R. Yi (Princeton)

**Award Number:** NA14OAR4320106

**Task II:** Cooperative Research Projects and Education

**NOAA Sponsor:** V. Ramaswamy (GFDL)

**Theme:** Earth System Modeling and Analysis

**NOAA Goals:**

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

**Objectives:** To understand 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. This climate process team has now completed its term, culminating in the publication of a synthesis team paper, MacKinnon et al 2017, to which Legg contributed substantially.

Other internal-tide related work includes the study of the scattering of low-mode internal tides at continental slope canyons, carried out by CICS-funded graduate student Robert Nazarian, under Legg’s supervision. Robert Nazarian completed his PhD in December, and published two papers from his thesis work, co-authored by Legg (Nazarian and Legg, 2017a,b). A third paper is in progress. The significant results from this work include the identification of different mechanisms for internal wave breaking in continental slope canyons, including lee-waves, wave focusing, and boundary-layer overturning, and the dependence of these mechanisms on canyon aspect ratio and shape.

Legg supervised PEI-funded undergraduate intern Young R. Yi, who carried out a study of tidally-generated internal waves, leading to his Princeton Geosciences senior thesis. Results from this project show that internal tides generated at small-scale topography can lead to mixing when nonlinear wave interactions transfer energy to small vertical scales, where instability can occur. The effectiveness of this
wave-wave interaction depends on latitude and topographic steepness. In particular, for certain values of
topographic steepness, destructive interference between waves from neighboring topographic peaks
reduces the energy available in the wave field, reducing the nonlinear wave interactions, and decreasing
the turbulent kinetic energy dissipation. These results were published with Legg as co-author in Yi et al,
2017.

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 took place in March-May 2017, 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 Sarah Nickford who examined this overflow region in high-resolution
simulations initialized with observed fields.

Also related to oceanic overflows, Legg is supervising 3rd year graduate student Elizabeth
Yankovsky, who is carrying out numerical studies of dense overflows generated by buoyancy loss on
Arctic shelves. A manuscript describing the relative importance of baroclinic instability and symmetric
instability in these overflows is currently in preparation.

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 led a hands-on demonstration at the
Mercer County Boys and Girls Club STEM workshop, and participated in a panel on women in STEM at a
New Jersey state high school robotics championship. 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 MPOWER,
PWGs, and ESWN. Legg also participated in an NSF-funded workshop on Geosciences Opportunities for
Leadership in Diversity, and will be returning to the workshop this summer as a peer mentor. Major new
initiatives which Legg has spearheaded are the CICS research internships, targeted at increasing diversity
in earth and climate sciences, now in its third year, and the CICS Visiting Faculty Exchange Fellowship,
targeted at strengthening links between Princeton AOS/GFDL and minority serving institutions, beginning
its first year.

**Publications:**

MacKinnon, Jennifer; Matthew Alford; Joseph K Ansong; Brian K Arbic; Andrew Barna; Bruce
P. Briegleb; Frank O. Bryan; Maarten C. Buijsman; Eric P. Chassignet; Gokhan Danabasoglu; Steve
Diggs; Peter Gent; Stephen M. Griffies; Robert W. Hallberg; Steven R. Jayne; Markus Jochum; Jody M.
Klymak; Eric Kunze; William G. Large; Sonya Legg; Benjamin Mater; Angélique 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

Nazarian, Robert and Sonya Legg, 2017a: Internal wave scattering in continental slope canyons,
part 1: Theory and development of a ray tracing algorithm. Ocean Modelling, 118, 1-15,


Presentations:

Melet, Angelique, Robert Hallberg, Sonya Legg, Adrien Lefauve, Caroline j Muller, Maxim Nikurashin, Alistair Adcroft and Kurt L Polzin: Climatic Impacts of Parameterized Internal-wave Driven Mixing, Ocean Sciences meeting 2018.

Yankovsky, Elizabeth A. and Sonya Legg: Symmetric Instabilities in Dense Shelf Overflows, Ocean Sciences meeting 2018.


Progress Report Title: Understanding the Decline of Arctic Sea Ice and Its Influence on Mid-Latitude Weather

Principal Investigator: Dawei Li (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Rong Zhang (GFDL), 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; to assess the influence of Arctic sea ice decline in mid-latitude circulations and weather.

Methods and Results/Accomplishments:
The mechanisms for low-frequency variability of summer Arctic sea ice are analyzed using long control simulations from three coupled 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 and 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 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 to the three key predictors is stronger in models that have thicker climatological Arctic sea ice.

We develop new metrics reflecting storm and blocking activities using surface air temperature and pressure records, and examine their variations and long-term trends. This approach gives an inkling of the changes in storm and blocking activities since the Industrial Revolution in regions with abundant long-term observational records, e.g. Europe and North America. The relationship between Atlantic Multidecadal Oscillation and variations in storm and blocking activities across the Atlantic is also scrutinized. The connection between observed centennial trends and anthropogenic forcings is investigated using a hierarchy of numerical tools, from highly idealized to fully coupled atmosphere-ocean models. Pre-industrial control simulations and a set of large ensemble simulations forced by increased CO2 are analyzed to evaluate the range of natural variabilities, which paves the way to singling out significant anthropogenic changes from observational records, as well as predicting future changes in mid-latitude storm and blocking activities in the case of continued anthropogenic CO2 forcing.
Publications:


Presentations:

Li, D., Anthropogenic Changes in Mid-latitude Storm and Blocking Activities from Observations and Climate Models, AGU Fall Meeting. New Orleans, LA, December 2017.
Progress Report Title: Simulating Stratospheric Circulation in a Changing Climate

Principal Investigator: Pu Lin (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: David Paynter (GFDL), Yi Ming (GFDL), Isaac Held (GFDL), 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: To gain a better understanding of the physical processes in the stratosphere, and to resolve the stratospheric processes efficiently in the climate models

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 published on Geophys. Res. Lett.

Stratospheric ozone is prescribed as a monthly zonal mean values in most climate models. But recent studies suggested that the interaction between ozone and circulation and other radiative species may be important (Nowack et al. 2014). We explored this effect in our model by comparing simulations with prescribed ozone and with full prognostic ozone. The latter is archived either by activating the full atmospheric chemistry scheme, or by using a simplified linear scheme which assumes constant chemical production rates and life time. While changes in ozone leads to less stratospheric moistening and more high cloud increase with surface warming, we did not find any significant difference in the tropospheric circulation or climate sensitivity. These results are reported at the AGU fall meeting last year.

Quasi-Biennial Oscillation (QBO) has broken its regularity during the 2015/2016 winter, and most models have failed to simulate this event. We have applied wave spectra analysis to identify the waves that are responsible for this abnormality. During the onset of this event, strong wave dissipation is found to be away from its critical latitude, leading to a deceleration at the jet core. These waves include Rossby waves.
propagate horizontally from northern midlatitudes as well as tropically trapped mixed Rossby-gravity waves. These results are reported at the 19th AMS middle atmosphere meeting.

**Outreach Activities:** I gave a guest lecture on tropical troposphere warming for the atmospheric radiative transfer course at Princeton University.

**References:**


**Publications:**


**Presentations:**
Lin, P., and Y. Ming, 2017: Simulating climate change with interactive stratospheric ozone. Talk. AGU Fall meeting, American Geophysical Union, New Orleans, LA.

Progress Report Title: Modeling the Responses and Feedback of Coastal Marine Ecosystems to Global Change

Principal Investigator: Xiao Liu (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: John Dunne (GFDL), Charles Stock (GFDL), Alistair Adcroft (Princeton), Matthew Harrison (GFDL), Minjin Lee (Princeton)

Other Participating Researchers: Laure Resplandy (Princeton)

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 (30%)
Resilient Coastal Communities and Economies Goal: Coastal and Great Lakes Communities are Environmentally and Economically Sustainable (20%)

Objectives: My research seeks to understand within the context of high-resolution simulations of global ocean models 1) the vulnerability of coastal marine ecosystems to changes in the environment, 2) the role that coastal oceans play in connecting (e.g. exchanging carbon and nitrogen between) land and open seas, and 3) how this role may change in the prospect of climate and other aspects of global change.

Methods and Results/Accomplishments:
Coastal oceans are productive and critical for sustaining biodiversity and fisheries. These systems also happen to be particularly vulnerable to changes in the environment and are strongly shaped by human activities. However, the complex coastal processes and the associate rates and time scales are poorly represented in the current generation of global climate models due to coarsened resolution. In this work, a hierarchy of global ocean-ice models (at 1°, 1/2°, 1/4°, and 1/8°) are assessed to investigate the sensitivity of coastal retention time-scales to model resolution. At 1/8° the model predicts a wide range of retention time-scales from two weeks to several years (Figure 1). Results show that for most coastal systems these time-scales are substantially longer and more comparable to observation-based estimates when simulated at higher resolutions. This analysis identifies a systemic bias in the representation of coastal processes in the coarsened models. Results of this work have been presented at the 2018 Ocean Sciences Meeting, and a manuscript is being prepared for publication.

It is hypothesized that water retention time-scales are critical for determining both the properties of coastal ecosystems and the role the coastal oceans play in global biogeochemical cycles. To examine this hypothesis, a biogeochemical model is coupled to the mentioned physical models and run in a forced mode for the global ocean. Preliminary results suggest that longer coastal retention time-scales in the higher-resolution models correspond to an improved representation of coastal biogeochemical and ecological processes (e.g. magnitude of phytoplankton blooms, subsurface and benthic deoxygenation). Further investigation is underway for a better mechanistic understanding. These analyses will eventually allow us to identify the components of both physical and biogeochemical models where special treatment is
required for a better representation of coastal processes. Experiments with the improved models will be conducted to predict the responses of coastal ecosystems to long-term and abrupt changes in the environment which are linked to both climate (e.g. warming) and human activities (e.g. increased riverine loading), and to understand how changes in coastal processes will ultimately feedback on and mediate changes in the climate.

Figure 1. A global map of mean coastal residence time ($\tau$) simulated by the 1/8° model. Results are averaged for the coastal domain (shallower than 200 m) of each of the 61 Large Marine Ecosystems in the global ocean and for a 10-year period between 1998 and 2007.

Figure 2. Comparison of model simulated coastal residence times between the a) 1°, b) 1/2°, c) 1/4° model against the 1/8° model. Results are presented as percentage differences relative to the 1/8° model. Red (blue) color indicates that residence time for the region is overestimated (underestimated) in the coarser model. The root-mean-square-errors (RMSE) are calculated from the log-transformed data.
**Outreach Activities:** Skype seminar titled “Marine biosphere and the climate 101” presented to a research working group (https://climategroup.wordpress.com/) that has 90+ active members. The group strive to foster academic interactions among members from different research fields who share common interests in climate science (February 2018); Guest lectures scheduled to be given to GEO 428 students (undergraduate and graduate) at Princeton University. The topic relates to satellite observations of marine phytoplankton and productivity (forthcoming; April 2018).

**Presentations:**


**Progress Report Title:** Data Assimilation System for Seasonal to Decadal Climate Prediction

**Principal Investigator:** Feiyu Lu (Princeton Postdoctoral Research Associate)

**CICS/GFDL Collaborator:** Tom Delworth (GFDL), Tony Rosati (GFDL), Matt Harrison (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:** Developing state-of-the-art data assimilation system for the latest ocean (MOM6) and coupled (SPEAR) models at GFDL; facilitating the evaluation of climate variability and initialization of seasonal to decadal climate prediction

**Methods and Results/Accomplishments:**
Shortly after starting my postdoc appointment at GFDL (Sep. 2017), I started developing a new data assimilation (DA) system for the latest GFDL models, in particular MOM6. The previous DA system (ECDA v3.1) was built for CM2.1, and the ocean DA (ODA) for MOM4.

As of the time of the report, we have completed and successfully tested the framework, workflow and MOM6 interface for the ODA system. The new DA system is loosely based on the previous ECDA system, but completely modernized to make use of the new framework and capabilities of MOM6. The code is currently in evaluation for addition to MOM6 and the actual assimilation simulations in MOM6 and SPEAR models will start soon in collaboration with the ocean modeling group.
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), Alistair Adcroft (Princeton)

Other Participating Researchers: Alon Stern (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 sub-ice-shelf circulation and melting as well as the impact of melt water on the formation of sea ice

Methods and Results/Accomplishments:
I have been conducting idealized simulations designed to represent the interaction between the ocean, sea ice and thermodynamic active ice shelves around Antarctica (Fig. 1a). 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 1) the melting and circulation underneath ice shelves; and 2) the growth of sea ice, behave to changes in wind forcing, horizontal grid resolution, and in the presence/absence of troughs along the continental shelf.

Examples of model experiments showing the ocean response to downwelling and upwelling winds are shown in Figs. 1c and 1d, respectively. Upwelling winds lead to intrusions of Circumpolar Deep Water mainly through a topographic trough, as shown in Fig. 1d. Such intrusions lead to high sub-ice-shelf melting rates and the subsequent outflow of meltwater forms anticyclonic eddies over the continental shelf (not shown). Our results show that increasing the magnitude of the westerlies, which enhances the coastal upwelling, leads to a significant increase in the mean melt rate (Fig. 1b). We have identified two regimes that can be used to understand how the along-slope winds impact sub-ice-shelf melting/circulation in this idealized framework:

Downwelling winds (or cold continental shelves): in this regime the wind induced circulation (counter-clockwise) opposes the circulation induced by melting (clockwise). The amount of heat transported into the ice-shelf cavity decreases as the volume transport into the cavity increases. Therefore, sub-ice-shelf melting is inversely proportional to the volume transport into the cavity (or to the magnitude of the wind).

Upwelling winds (or warm continental shelves): in this regime the wind induced circulation reinforces the circulation induced by melting (both are clockwise). The amount of heat transported into the cavity increases as the volume transport into the cavity increases. Therefore, sub-ice-shelf melting is proportional to the volume transport into the cavity (or to the magnitude of the wind).

We used the numerical results to compute the thermal forcing (TF), which relates how the heat transport (H) into the cavity varies with respect to the volume transport (T) into the cavity; and the dynamical pump (η), which relates how T varies with respect to melting (M). We then use TF, η and the background flow to...
deduce the amount of heat coming in and out of the cavity based on analytical expressions proposed by Jourdain et al. (2017). So far, only result derived from experiments with a horizontal resolution of 1 km have been tested - we obtained a very good match between theory and model. I am currently working on the corresponding analysis for the coarser resolution experiments.

Whether the outcomes of this study can be extended to other cavities likely depends on the geometry of each cavity. Although I have finished my appointment with Princeton/GFDL in June 2017, I am still actively working on this project.

References:

Figure 1: (a) Geometry of the idealized setup. (b) 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. c) Snapshot of salinity (colors) under a downwelling (easterly) wind. The red iso-surface represents the 1037.05 kg/m³ potential density with respect to 2000 db, which is a proxy for the upper limit of the Circumpolar Deep Water (CDW). d) same as c) but for an upwelling (westerly) wind. Intrusions of CDW occur mainly through the trough.

Presentations:

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

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

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

Other Participating Researchers: Gabriel A. Vecchi (Princeton), 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.
References:


Publications:


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), Rong Zhang (GFDL)

Other Participating Researchers: Madeleine Hamann (SIO), Amy Waterhouse (SIO), 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, both idealized and realistic. This parameter study has a two-pronged approach: ray-tracing theory and high-resolution GCM simulations. With regards to the idealized 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. Although this idealized component of the project was mostly complete as of last March, we continued to conduct minor analysis in response to anonymous reviews on our submitted manuscripts. This analysis included the use of both the ray-tracing algorithm that we developed (i.e. using ray-tracing theory follows the propagation of a remotely generated internal wave into the canyon topography, and the subsequent reflections off the topography to identify potential regions of instability), as well as high-resolution numerical modeling using the MITgcm.

In addition to finalizing the analysis of the idealized canyon simulations and publication of the manuscripts (see publication list below), I analyzed ray tracing and MITgcm results for more realistic canyons (Veach, Eel and La Jolla Canyons, in collaboration with M. Hamann, A. Waterhouse and M. Alford, SIO). In addition to considering the effects of realistic topography, we additionally considered the complicating effects of variable stratification and the effects of rotation. While the ray tracing was a useful tool in providing context and intuition for the dynamics of wave scattering in the idealized canyons, its utility was limited in the realistic cases due to the realistic canyons being in a different physical parameter regime (i.e. mixing primarily due to a turbulent boundary layer rather than large scale overturns) and thus the MITgcm is primarily used.

Using the MITgcm, we found that the spatial extent of and the dynamics by which wave breaking and instability occurs in the realistic canyons varies from the idealized canyons. Specifically, Richardson number and turbulent dissipation diagnostics from MITgcm simulations of realistic canyons suggest that the maximum enhanced dissipation occurs directly above the topography rather than over a large spatial
extent, as observed for the idealized canyons. We have shown that this instability and dissipation is likely the result of a turbulent boundary layer which forms above the canyon slope and attribute its formation to regions of slope near-criticality and criticality, as well as the presence of frictionally-driven shear and convective instability. In addition to the dissipation near the slope, all three realistic canyons that we considered experience enhanced dissipation near the sea surface, which is associated with shear instability.

Interestingly, the inclusion of rotation, in addition to changing the canyon-integrated energy loss, also changes the spatial pattern of dissipation as well as the mean flow within the canyon. For the case of Eel Canyon, there is less dissipation through the entirety of the canyon while, for the case of Veatch Canyon, there is an increase in dissipation for all regions of the canyon except for the canyon head. Due to a positive up-canyon pressure gradient caused by mixing, rotation induces a geostrophic flow within and around the canyon, similar to that observed in numerous continental slope canyons. General vertically-integrated dissipation patterns from Veatch, Eel and La Jolla Canyons also agree with existing observations. Other comparisons between the simulations conducted in this thesis and observations taken from these canyons, such as the locations of maximum dissipation yield agreement, however, there is some discrepancy in the flow speeds and wave mode numbers reported in this thesis compared with observations. Additional simulations have since been run since my CICS appointment which further fill in our gaps in understanding and provide context for these results. At the conclusion of this project, we will be pursuing publication in the *Journal of Physical Oceanography*.

**Outreach Activities:** 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:**


**Presentations:**
Progress Report Title: Regional Changes in Aerosol Radiative Forcings: Mechanisms and Implications

Principal Investigator: Fabien Paulot (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Vaishali Naik (GFDL), Paul Ginoux (GFDL), Larry Horowitz (GFDL), David Paynter (GFDL)

Other Participating Researchers: S. Whitburn (Université Libre de Bruxelles), M. Van Damme (Université Libre de Bruxelles), L. Clarisse (Université Libre de Bruxelles), P.-F. Coheur (Université Libre de Bruxelles)

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 relationship between anthropogenic emissions and aerosol radiative forcing is modulated by many factors including the nature of the emissions, their atmospheric processing, and their regional distribution. Anthropogenic emissions have changed dramatically over the last 15 years, a period over which global satellite observations of outgoing radiations are available. This offers an opportunity to develop observation-based constraints on the relationship between emissions and anthropogenic forcing, which can be used to test and improve the GFDL global climate model.

Methods and Results/Accomplishments:
My first project focused on the fate of ammonia in biomass burning plumes. I showed that differences in the ratio of NH₃ to CO in biomass burning plumes between in-situ and spaceborne instruments are consistent with a rapid partitioning of NH₃ to the aerosol phase. Such partitioning effectively makes ammonia invisible from space, which is important for the interpretation of observations collected by the NOAA CrIS instrument. I also showed that this partitioning is primarily driven by the formation of ammonium nitrate and contributes disproportionately to its radiative forcing.

In a follow-up study, I focused on changes in the aerosol radiative effect over large sources of anthropogenic pollutions. I first showed that observational constraints can be derived using changes in the outgoing radiation recorded by the CERES instrument provided changes in surface albedo, water vapor, and ozone are accounted for. Comparisons with the GFDL-AM3 model show that the model captures changes well from 2001 to 2015 over Europe and the US, where they are dominated by sulfate aerosols. However, the GFDL model tends to overestimate the magnitude of the changes over India and China. I showed that this bias can be partly attributed to the large contribution of nitrate and black carbon aerosols in these regions, which makes them more sensitive to biases in ammonia and black carbon emissions. In contrast to previous studies, I further show that changes in the speciation and spatial distribution of anthropogenic emissions are modifying the relationship between anthropogenic emissions and aerosol forcing. In particular, it suggests that the relationship between SO₂ emissions and anthropogenic forcing, derived from IPCC AR5 models, needs to be revisited.
**Publications:**


**Presentations:**

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), 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 few months of my postdoc (my contract expired at the end of June 2017) I worked on revising the manuscript on the influence of cloud-radiative effects (CREs) on the ITCZ position with a developmental version of the GFDL atmosphere model version 4. After successfully addressing the reviewers’ comments, the paper was published later last year.

In order to apply the different frameworks we used in our study on the influence of the CREs on the ITCZ position to the models taking part in the climate model intercomparison project phase 5, we started developing tools to quantify the zonal-mean structure of precipitation. We developed nine indicators that characterize the zonal-mean structure of tropical precipitation. An analysis of the CMIP historical and Atmospheric Model Intercomparison Project (AMIP) simulations reveals large biases in the position and, especially, in the magnitude of the zonal-mean precipitation extrema in both sets of simulations relative to observations. We show that some of the indicators are correlated, but that at least four indicators are necessary to represent the tropical precipitation well (Figure 1). In general, model biases are larger in AMIP than in the CMIP historical simulations. Previously defined indicators can explain aspects of the biases, but for characterizing the tropical precipitation a more comprehensive terminology such as introduced here will be necessary. This work was published last year.

Publications:

Presentations:
Popp, M., Silvers, L. G. Shifting the ITCZ with longwave and shortwave cloud-radiative effects. EGU General Assembly 2017, 23th-28th of April 2017, Vienna, Austria POSTER.
Popp, M., Lutsko, N. J., Quantification of the zonal-mean structure of tropical precipitation, CFMIP Meeting, 25th-28th of September 2017, Tokyo, Japan POSTER.

Figure 1: Predictive skill in zonal-mean precipitation of the linear regression of the nine indicators to the multi-model ensemble. The top row (panels a and b) shows the root mean square error of the prediction, the middle row (panels c and d) the standard deviation from the predicted mean as well as the actual standard deviation in the models, and the bottom row (panels e and f) the correlation between the predicted precipitation and the actual precipitation in the models. The different colors indicate how many of the indicators were used for the approximation and the gray lines in panels c) and d) the standard deviation of the multi-model ensemble from the mean. The figure was adapted from Popp and Lutsko (2017).
**Progress Report Title:** Detection and Attribution of Dust Sources to Understand Dust Effects on Climate and Air Quality

**Principal Investigator:** Bing Pu (Princeton Associate Research Scholar)

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

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

**Award Number:** NA14OAR4320106

**Task II:** Cooperative Research Projects and Education

**NOAA Sponsor:** V. Ramaswamy (GFDL)

**Theme:** Earth System Modeling and Analysis

**NOAA Goals:**

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

**Objectives:** To understand factors controlling dust variability in the United States and the capability of global climate models in simulating dust optical depth

**Methods and Results/Accomplishments:**

*Projection of American dustiness in the late 21st century due to climate change (Pu and Ginoux, 2017a):* Climate models projected rising drought risks over the southwestern and central U.S. in the 21st century due to increasing greenhouse gases. These projected dry regions are largely co-located with major dust sources in the U.S. However, whether dust activity will increase in these regions in the future is not clear due to large uncertainties of dust modeling. Using satellite observation and multi-model output we developed a regression model to identify key factors controlling dust variations in the present day and projected future variation of dust. We found 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.

*Understanding the trend of fine dust concentration in the U.S. during 1990-2015 (Pu and Ginoux, 2017b):* Studies found fine dust (with aerodynamic diameter less than 2.5 microns) is an important component of the total PM2.5 mass in the western and central U.S. in spring and summer and has positive trends in the recent decade. However, the possible causes of fine dust trends, especially the increase of fine dust over the central U.S., have not been thoroughly discussed by previous studies. In this work we explored local climatic factors driving the long-term variations of fine dust from 1990 to 2015 using station data. It is found that the positive trend of fine dust concentration in the Southwest in spring is associated with precipitation deficit, while the increase of fine dust over the central Great Plains in summer is largely associated with increased atmospheric stability due to surface drying and lower troposphere warming.

*Examining the capability of Coupled Model Intercomparison Project Phase 5 (CMIP5) models in simulating global dust optical depth (Pu and Ginoux, 2018):* Dust aerosol plays an important role in the climate system by affecting the radiative and energy balances. Biases in dust modeling may result in biases in simulating global energy budget and regional climate. It is thus very important to understand how well dust is simulated in the CMIP5 models. While many features and variables are systematically examined in the CMIP5 multi-model output, we found that to our best knowledge an evaluation of global dust modeling...
in CMIP5 models is still in blank. In this study we examined the performance of seven CMIP5 models with interactive dust emission schemes by comparing dust optical depth (DOD), a key variable associated with dust radiative effect, from models with that retrieved from MODIS Deep Blue aerosol products for present-day climatology and interannual variations. Seasonal cycle and spatial pattern of DOD in very dusty regions such as North Africa and the Middle East are largely captured by multi-model mean, but observed connections between DOD and local controlling factors are not so well represented. Future projections by CMIP5 models and a regression model are also analyzed.

**Outreach Activities:** March 18th, 2017: Volunteer for the 11th annual science fair at Monmouth Junction Elementary School (grades K through 5), NJ; May 20th, 2017: Volunteer for New Jersey Ocean Fun day at Island Beach State Park, NJ

**Publications:**

**Presentations:**
Pu, B., and P. Ginoux, 2017: Climatic factors contributing to long-term variations of fine dust concentration in the United States, American Geophysical Union (AGU) fall meeting, New Orleans, LA.
**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:**

We continued to expand our diagnostics that were developed in year 1 and 2 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.

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 aimed to address these topics and submit a couple of papers, before Dr. Ray’s dedicated NOAA/CPO funding was exhausted on 31 August 2017.

References:

Presentations:
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)

Other Participating Researchers: Baylor Fox-Kemper (Brown), Qing Li (Brown)

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 and GFDL climate models. Understand the importance and variability of the wave-driven component of vertical mixing (Langmuir turbulence) in climate simulations.

Methods and Results/Accomplishments:
Earth Systems Models have historically suffered from biases in under-predicting upper-ocean mixing. One region where this bias is particularly notable is in the Southern Ocean, where simulated mean mixed layer depth using GFDL’s MOM6 (Fig 1b) average approximately 50 m, which is roughly 30 m shallower than the observations of Hosoda et al. (2010) (Fig 1a).

This discrepancy motivated a high-resolution process model investigation to understand and parameterize the role of surface waves in ocean mixing via a wave-turbulence interaction mechanism called Langmuir turbulence (LT). The result was a modified parameterization for upper ocean mixing that significantly improves the simulated mixed layer depth in the Southern Ocean relative to observations (Fig 1c). The implications of this new parameterization are significant for improving climate models through simulating atmosphere-ocean exchange and ocean uptake of properties such as heat and carbon.

Another finding of this study is the failure of the wave-driven parameterization to improve mixed layer depth biases in the Equatorial region (Fig1a-c). The model bias in this region is therefore likely unrelated to missing wave processes, motivating future work to improve parameterized turbulent mixing driven by other sources (e.g., due to vertical current shear).

Outreach Activities: NOAA Science Days, 2018.

References:

Publications:
Reichl, B.G. and Hallberg, R. An Energetically Constrained Planetary Boundary Layer (ePBL) Approach for Ocean Climate Simulation. In Revision.


Presentations:


Figure 6: Summer mixed layer depths from [a] observed climatology by Hosoda et al. 2010 and [b] GFDL CM4/MOM6 prototype model with no wave-driven mixing (original) and [c] the same model with the new wave-driven mixing parameterization (Langmuir Turbulence, LT). The mixed layer depth is determined by a threshold vertical density change of 0.03 kg/m³.
**Progress Report Title:** Exploring the Relationship between Surface PM$_{2.5}$ and Meteorology in Northern India

**Principal Investigator:** Jordan Schnell (Princeton Postdoctoral Research Associate)

**CICS/GFDL Collaborator:** Vaishali Naik (GFDL), Larry Horowitz (GFDL), Fabien Paulot (Princeton), Paul Ginoux (GFDL), Ming Zhao (GFDL)

**Other Participating Researchers:** Jingqiu Mao (U. Alaska-Fairbanks), Kirpa Ram (Banaras Hindu 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:**
1) Evaluate the ability of the new-generation Atmospheric Model (AM4) to simulate wintertime fine particulate matter (PM$_{2.5}$) and its relationship to meteorology over Northern India.
2) Evaluate the impact on air quality from the electrification of the U.S. transportation sector.
3) Implement the MEGAN biogenic emission module into AM4.

**Methods and Results/Accomplishments:**

**Under review:** We compared two simulations of GFDL-AM4 nudged to observed meteorology for the period 1980–2016 driven by pollutant emissions from two global inventories developed in support of the Coupled Model Intercomparison Project Phases 5 (CMIP5) and 6 (CMIP6), and compared results with ground-based observations from India’s Central Pollution Control Board (CPCB) for the period 1 October 2015–31 March 2016. Overall, our results indicate that the simulation with CMIP6 emissions produces improved concentrations of pollutants over the region relative to the CMIP5-driven simulation. While the particulate concentrations simulated by AM4 are biased low overall, the model generally simulates the magnitude and daily variability of observed total PM$_{2.5}$ (Figure 1). Observed PM$_{2.5}$ abundances are by far the highest within the densely populated Indo-Gangetic Plain, where they are closely related to boundary layer meteorology, specifically relative humidity, wind speed, boundary layer height, and inversion strength. The GFDL AM4 model reproduces the overall observed pollution gradient over Northern India as well as the strength of the meteorology–PM$_{2.5}$ relationships in most locations.

**Ongoing:** We use a simple method to remap the marginal electric load necessary to power a hypothetical electric vehicle shift, one that does not require the use an energy dispatch model and can easily be implemented by other modeling groups to test the effect of electrical generation centralization. We then use a high resolution (~0.5°) version of the GFDL AM4 to investigate five electrification scenarios designed to test the effect of the magnitude of electric vehicle market penetration and the effect of marginal electricity generation type. Most simulations have been completed and the analysis is ongoing. The base simulation is also being used to evaluate the chemistry in this resolution of the model.

**Ongoing:** Currently the AM4 only has the ability to simulate interactive biogenic emissions of isoprene. I have recently implemented a similar scheme to simulate interactive emissions of all biogenic compounds that are emitted in the AM4. Sensitivity studies are currently being evaluated and the results will be fully described in a documentation paper.
Publications:

Presentations:
Schnell, J. L., Global air pollution episodes and the meteorology that drives them, presented at the Chemistry-Climate Model Initiative (CCMI) Science Workshop, June 15, 2017, Toulouse, France (invited)
Schnell, J. L., Exploring the relationship between surface PM$_{2.5}$ and meteorology in Northern India, presented at the Third Workshop on Atmospheric Composition and the Asian Monsoon, June 6, 2017, Guangzhou, China.

Figure 1. Time series of daily average PM$_{2.5}$ (1 October 2015 – 31 March 2016) for the grid cells over (a) New Delhi and (b) Kanpur/Lucknow, Uttar Pradesh. The min-to-max range of the multiple observations sites are shown in grey with their median in black. The number of sites is given in the panel titles. Modeled abundances are shown in (blue) CMIP5-dry, (red) CMIP6-dry, (green) CMIP6-wet, and (magenta) CMIP6-wet calculated with the GEOS-CHEM hygroscopic growth factors. The dashed vertical lines represent the 5-day festival of Diwali.
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), Michael Wolovick (Princeton)

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

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: 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 contributions to sea level are determined by ice discharge through the grounding line – a transition between the grounded and floating parts of an ice sheet. This transition is controlled by a number of glaciological, oceanographic and atmospheric processes (e.g. ice basal sliding, sub-ice-shelf and surface melting, etc.). Accurate representation of this transition in continental-scale ice-sheet models remains challenging. In collaboration with Dr. Haseloff, a new analytical method for computations of the rate of ice discharge through the grounding line has been developed. This method allows for accounting accurately for the grounding line migration and evaluating stability of the grounding line.

About 50% of the ice-shelf mass loss happens through calving. Large tabular icebergs whose horizontal extent is on the order of tens to hundreds kilometers typically calve twice per century. As they drift away from ice shelves they calved from, these icebergs disrupt ocean circulation in their vicinity, modify water masses by injecting freshwater as they melt, and alter ocean hydrography. Despite the fact that large icebergs contain vast volumes of fresh water in its frozen form, they are not represented in global ocean models. In collaboration with Drs. Stern, Adcroft, Hallberg and Marques, a new framework has been developed that allows for explicitly simulating the presence of the large tabular icebergs and their interactions with surrounding oceans. The state-of-the-art framework is based on a set of Lagrangian particles that held together and interact with each other via bonds (Fig. 1). Breaking of these bonds allows for representing calving events and iceberg break-up events (Stern et al., 2017).

In order to assess impacts of ocean waves on the ice-shelf stress regime, a new theory of propagation of the flexural gravity waves through the ice-shelf/sub-ice-shelf cavity with variable geometry has been developed (Sergienko, 2017). The results of this theory suggest that higher frequency waves have stronger effects on thinner ice shelves, and these kinds of waves could cause flexural stresses near the ice-shelf fronts sufficient to cause propagation of existing rifts or development of new ones.
Figure 1. Schematic showing how tabular icebergs are constructed using Lagrangian elements. (a) Hierarchy of ice elements’ physical structure: (i) Previous iceberg models represent icebergs using non-interacting point-particle elements; (ii) In the new framework ice elements are given finite extent so that they are able to interact with the ocean across multiple grid cells, and can interact with other elements; (iii) These finite extent elements can be joined together by numerical bonds (magenta lines) to form larger structures such as tabular icebergs. (b) Aerial photograph of a tabular iceberg with elements superimposed over it to illustrate how the Lagrangian elements can be used to model tabular icebergs. In this schematic, the ice elements (purple dots) are initialized in a staggered lattice covering the surface area of the iceberg. (Stern et al., 2017).

References:


Publications:


Presentations:


**Progress Report Title:** Improvements to the Modular Ocean Model’s Neutral Mixing Physics, Diagnostic Output, and Offline Capabilities

**Principal Investigator:** Andrew Shao (Princeton Postdoctoral Research Associate)

**CICS/GFDL Collaborator:** Robert Hallberg (GFDL), Alistair Adcroft (Princeton), Stephen Griffies (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:**
- Improve the representation of parameterized physics in the Modular Ocean Model version 6
- Encourage the use of MOM6 and use by validating model diagnostics and improving the offline tracer capabilities

**Methods and Results/Accomplishments:**

The second year as a postdoctoral fellow with CICS branched from the experiences and skill training acquired during the first year. Three primary activities were undertaken: 1) overcome the deficiencies of the offline tracer transport capabilities detailed in the previous report 2) development of a new neutral mixing parameterization for Module Ocean Model version 6 (MOM6) 3) implement and validate diagnostics for the Coupled Model Intercomparison Project 6 (CMIP6).

The offline tracer component of MOM6 has been developed to the point where it may soon be feasible for use in scientific studies. Last year’s report concluded that that tracer transport could not be done in the arbitrary Lagrangian-Eulerian vertical coordinate framework, but could be done by remapping the mass transports onto a fixed Eulerian grid. However, large biases were seen in both the biogeochemistry and ideal age tracers compared to the prognostic model. While a number of avenues were systematically explored and eliminated, the primary cause was narrowed down to the flux limiter of the advection scheme which was overly greedy and vastly skewed the tracer trajectories in regions with large horizontal velocities. By imposing a linear limiter, the offline model’s skill was significantly improved with little to no additional computational overhead. Work is ongoing to document the technical challenges and to demonstrate the use for biogeochemical modeling.

The neutral mixing parameterization in MOM6 represents a significant advancement over the Griffies [1998] and Redi [1989] implementations used in most global climate models. I have taken over the development of the existing implementation of the algorithm and am currently improving a variety of its numerical aspects. Some of the noteworthy advancements included moving to a higher-order discontinuous representation of density, inclusion of an iterative technique to find positions of neutral buoyancy, and the development of new flux limiters to ensure that fluxes within the sublayers are density-preserving. Additionally, a number of new test cases have been developed to demonstrate various aspects of the algorithm.

Lastly, I have been involved in GFDL’s contribution to CMIP6 by implementing and validating a subset of the requested diagnostics, in particular heat and salt tendencies and vertical mass transport. For the former, the frazil heat flux diagnostics was redesigned to close the heat budget in the native, hybrid
vertical coordinate. Additionally, a number of changes to the code were done to ensure that heat and salt budgets closed on diagnostics remapped from the native vertical grid to isopycnal and depth coordinate grids requested by CMIP6. A framework for regression testing diagnostics was also developed and will be implemented in the future.

**Outreach Activities:** Introduction to Python course for summer interns, provided guidance and advice to Sarah Nickford

**Publications:**

**Presentations:**
Shao, Andrew. Ocean Sciences Meeting 2018, OM44C-2136: Improvements to an Extrema-diminishing, Density-preserving Lateral Diffusion Algorithm, Portland, OR, USA.
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 Hemmler (GFDL), Nadir Jeevanjee (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 and Responsibilities:
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. To this end I am the lead scientist at AOS/GFDL for the Cloud Feedback Model Intercomparison Project (CFMIP) which is an international effort to compare and improve cutting edge climate model simulations of cloud feedback processes.

Methods and Results/Projects:
Overview: Over the past year I have shown that tropical low-level clouds are the primary drivers of the decadal variability in the effective climate sensitivity. This is true especially outside of the regions typically dominated by stratocumulus clouds (Silvers et al. 2018). In addition, along with collaborators at GFDL, we analyzed the role of SST patterns in determining the equilibrium climate sensitivity in ESM2M and CM3 over multi-millennial length simulations (Paynter et al. 2018).

Clouds impact the Earth system through their interaction with radiation. My research looks at the connection between the Earth’s surface, the physical processes which impact cloud evolution, and the radiative fluxes at the top of the atmosphere.

Mock-Walker Circulations with a Nonhydrostatic AM4.0: This research leverages GFDL uniquely flexible modeling system to run AM4.0 in a doubly periodic domain. This allows us to compare simulations with AM4.0-like physics to simulations with explicitly-resolved convection. Promising proof of concept results were presented at the 2018 GFDL Poster Exposition. This modeling framework holds great potential to both address basic scientific questions as well as functioning as a testbed for the development of new GFDL parameterizations.

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). I used this framework to analyzing simulations with AM2.1, AM3, and AM4.0 to compare and contrast the relationship between the lower atmospheric stability, cloud feedback, and the global mean feedback-parameter (Silvers et al. 2018). I am also using these experiments as part of two separate inter-comparison studies with Timothy Andrews, and Kyle Armour.
SST patterns, Clouds and the Climate Sensitivity: Experiments with AM4.0 have been conducted which use the SST patterns from the millennial-length simulations described in Paynter et al. 2018 to drive the atmosphere of AM4.0. This provides a unique way to study atmospheric response to particular SST patterns. Both Silvers et al. 2018 and Paynter et al. 2018 illustrated the fundamental role that clouds play as conduits between SST patterns and measures of the climates sensitivity to perturbations. These papers are now providing the foundation for experiments I have conducted which are being used to better understand how clouds respond to particular SST patterns.


Publications:


Silvers, L.G., and N. Jeevanjee: Bridging the gap between GCMs and CRMs with AM4.0. In preparation.

Silvers, L.G., and G. Cesana: How important is cloud phase and vertical structure in the new GFDL atmospheric climate model? In preparation.


Presentations:
Silvers, L.G. 2017, Seminar, McGill University, Montreal, Canada, October. Invited Talk.
Silvers, L.G. 2017, Seminar, Stony Brook University School of Marine and Atmospheric Science, Stony Brook, NY, March. Invited Talk.


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.
Progress Report Title: Exchange Mechanisms in the Urban Boundary Layer

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

CICS/GFDL Collaborator: Elena Shevliakova (GFDL), Sergey Malyshev (Princeton/GFDL), Jiachuan Yang (Princeton), Tyler Van Buren (Princeton)

Other Participating Researchers: Hamidreza Omidvar (Princeton), Antonin Rocher (ENS Cachan)

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

Objectives: We use a combination of laboratory experiments and numerical simulations to elucidate the turbulent transport mechanisms in and just above urban canopies, with the aim of advancing existing parameterizations of these exchanges in GFDL models.

Methods and Results/Accomplishments:
Experimentally, we have completed preliminary laboratory measurements on the turbulent exchange mechanisms that occur in the response of a model ABL to the presence of a model urban streetscape. We generated an artificial ABL in our large wind tunnel (Hohman et al. 2015) as our well-characterized initial condition, and then introduced up to 8 idealized building elements. By heating one element, we can track the heat and momentum fluxes over and within the turbulent boundary layer using a combination of Particle Image Velocimetry and our nano-scale temperature sensors, in a technique developed by Williams et al. (2015). So far, we have used a single building geometry, represented by a two-dimensional heated bar (see figures 1 and 2), chosen so that direct comparisons can be made with the accompanying LES computations by Bou-Zeid. Schlieren visualizations have been completed to track the temperature interface, and an IR camera has been used to document the surface temperature distribution on the building element. Detailed measurements using temperature probes have been completed following the renovations of the laboratory, at several positions downstream of the heated element and different combinations of passive building elements in front of and behind the heated element (Rocher, 2017).

On the simulations side, we have worked on 2 sub-projects: (1) setting up large eddy simulations of various urban configurations that mimic the experiments at first, and then that go beyond the experiments (e.g. with building facets heated realistically: roof + one of the walls (morning of afternoon) OR the ground (around noon). The results undermine the conceptual frameworks used in parameterizing surface-flow exchanges and confirmed that dispersive exchanges, due to the spatial variability of the time-averaged flow, are very significant, behave quite differently from turbulent exchanges, but have been completely ignored so far (Li et al. 2015). We are developing improved parameterizations based on these simulations that we will implement in the GFDL land model in Y3. (2) We are setting up simulations to understand how the change in the ratio of mean wind to surface buoyancy flux causes a transition in the city-scale flow from a plume to a bubble (see Fig. 3).
**Outreach Activities:** Princeton Plasma Physics Laboratory, The Ronald E. Hachter “Science on Saturdays” Lecture for high school students and teachers, [https://tinyurl.com/yar3dbmy](https://tinyurl.com/yar3dbmy); IEEE Integrated Stem Education Conference, Keynote Talk, [https://tinyurl.com/ybaepy9h](https://tinyurl.com/ybaepy9h)

**References:**


**Publications:**


Hohman, Tristen. Interaction of wind turbines with the atmospheric boundary layer. (PhD, 2017).
Figure 7. Experimental setup with one heated cube.

Figure 2. Left: details of heated element. Right: building element arrangements (heated element is shown in black).

Figure 3. Streamwise velocity in a streamwise-vertical slice for an intermediate case showing the beginning of the transition from bubble to plume.
**Progress Report Title:** Characterizing South American Monsoon Variability with the Moist Static Energy Budget

**Principal Investigator:** Jane Smyth (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:** I aim to better understand the seasonal variability of rainfall over the South American monsoon sector (southern Amazonia) and its response to warming sea surface temperatures.

**Methods and Results/Accomplishments:**

We are using the GFDL AM4 atmospheric circulation model to study the seasonal cycle of rainfall over South America. We utilize the moist static energy (MSE) budget as a theoretical framework to understand the climatological precipitation variability in this region. We next use the MSE framework to diagnose mechanisms of precipitation change in an experimental simulation in which the prescribed sea surface temperature fields in each month are warmed uniformly by 2 K. This experiment is motivated by the need to understand the hydroclimate impacts of global warming. We find that in spring, the monsoon onset season, the South American monsoon sector dries significantly in the experimental simulation. Using the MSE budget, we attribute this response to an enhancement of the horizontal moist static energy gradients and the resulting weakening of ascent over the region. A strengthening of the South American low level jet, a northerly synoptic wind feature which transports moisture from the Amazon to La Plata river basins, also contributes to the negative precipitation anomalies over the monsoon sector.

**Outreach Activities:** I participated in Ocean Fun Days 2017.

**References:**


**Presentations:**

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

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

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

Other Participating Researchers: Edward Brzostek (West Virginia University), Richard Phillips (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:

My research focused on two main areas. First, I worked on evaluating and improving our ability to model terrestrial carbon and nitrogen cycling through the incorporation of current knowledge about soil organic matter formation, decomposition, and stabilization and how it interacts with plant growth. I implemented and tested a coupled vegetation-soil nitrogen cycle model including plant acquisition of nitrogen by symbiotic interactions with mycorrhizal fungi, including the impacts of these relationships on soil carbon cycling and published an ecosystem-scale evaluation of a preliminary version of that model (Sulman et al., 2017). In addition, I worked with an expert in microbial physiology to implement and test new microbial dormancy and activation processes in the soil model (Salazar et al., 2018). I also coordinated a model synthesis and meta-analysis involving soil carbon models from five different research groups (including GFDL, NCAR, Oak Ridge National Laboratory, and Lawrence Berkeley National Laboratory). The goal of this model comparison was to evaluate current models and identify key uncertainties and data needs to improve confidence in these models moving forward. In a related collaboration, I worked with Dr. Will Wieder to incorporate multiple soil models into a global testbed to facilitate constraining parameters and evaluating uncertainty in global simulations (Wieder et al., 2018). This project provided valuable tools for improving parameterization of soil organic matter cycling in GFDL ESM simulations. I also contributed to a review of proxy data sources in soil organic matter science and their role in climate-related research (Bailey et al., 2018).

In addition to soil model development, I used ecosystem-atmosphere flux measurements to improve understanding of controls on ecosystem carbon cycling and its response to drought and warming. This work included analysis of fluxes from a peatland ecosystem subject to decadal-scale changes in hydrology, resulting in an undergraduate-led publication (Pugh et al., 2018) and ongoing collaborations to quantify drought impacts on agriculture and forest carbon and water fluxes.
Outreach Activities: Led ecosystem modeling discussion group for graduate students and postdocs, UC Merced; served as American Geophysical Union Biogeosciences Section Executive Committee Early Career Representative; spoke about climate and earth system research to visiting high school groups at UC Merced.

Publications:


Presentations:


N acquisition strategies determine ecosystem responses to elevated CO2 in the GFDL global land model. 5th iLEAPS Science Conference, Oxford, United Kingdom, Sept 2017.

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/GFDL), John Dunne (GFDL), Paul Ginoux (GFDL)

Other Participating Researchers: Sam Rabin (KIT/Princeton)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: To 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 line of research this year involved running model experiments with the newly developed version 2 of the Fire on Natural and Agricultural Lands model (FINAL) and further development of the injection of fire emissions into the atmospheric component of the GFDL ESM. Experiments included a set of historical simulations with the terrestrial component of the ESM in which the drivers of trends in model global fire activity were identified. We also used these simulation results to investigate changes in the interannual variability of fire emissions with changes in and cover and land use since the year 1700. This is the first time this question has been addressed with a model. The results of these experiments were published in Global Biogeochemical Cycles.

To be able to simulate fire emission feedbacks in the atmosphere and back onto the terrestrial biosphere I coupled the prognostic fire emissions to the atmospheric chemistry and aerosol modules within AM4 in the GFDL ESM using a plume rise scheme. Fires are driven by prognostic temperature, precipitation, humidity and lightning flash frequency fields from the atmospheric model component and human population information from an inventory. Fire emissions of carbon are split into trace gas and aerosol species in AM4 and these constituents are released into the model atmosphere using a version of the Sofiev et al. (2012) injection height scheme. I tested the sensitivity of aerosol optical depth and carbonaceous aerosol concentrations to this model development in a series of present-day coupled model simulations in which the connections between fires and the atmosphere are systematically switched on and off. The overall aim of this work is to create a fully coupled modeling system in which the interplay between fires and atmospheric processes can be simulated.
Reference:

Publications:


Progress Report Title: Understanding Decadal/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 decadal/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 2017-2018 year at CICS/NOAA GFDL, in collaboration with Rong Zhang and Tom Knutson at GFDL, I carried out extensive numerical analyses on both observations and a large amount of model output from CMIP5 archive to understand: i) the pronounced decadal/multi-decadal variability in the observed Atlantic major hurricane frequency; ii) the underestimated Atlantic Meridional Overturning Circulation (AMOC) low frequency variability and its associated impacts on various climate phenomena and the North Atlantic decadal predictability.

Atlantic major hurricane activity has caused substantial damage to coastal settlements and infrastructure. Two hypotheses have been proposed previously as key causes of multi-decadal variability of Atlantic hurricane frequency: i) ocean variability associated with AMOC and ii) changes in anthropogenic sulfate aerosol forcing. By analyzing observations and GFDL-ESM2G coupled model simulations, my analyses show that the decline trend within 2005-2015 in Atlantic major hurricane frequency is consistent with a weakening of the AMOC inferred from ocean observations, but is inconsistent with the response to a recent reduction in anthropogenic aerosols. Coherent multi-decadal variations involving the inferred AMOC and Atlantic major hurricane frequency/Atlantic Multi-decadal Variability (AMV)/wind shear, in observations since the late 1950’s and in the 500-year GFDL-ESM2G coupled model pre-industrial control simulations, provide new evidence for the hypothesis of multi-decadal AMOC variability as the prime driver of multi-decadal variability of Atlantic hurricane frequency. The observed reduction of anthropogenic sulfate aerosol AOD contributes to slight SST warming trends and decreasing trends in the Hurricane Shear Index that would lead to more Atlantic major hurricane frequency, in contrast with the observed trend. We expect that whether the Atlantic major hurricane frequency returns to the 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.

AMOC has profound impacts on various climate phenomena. By analyzing both observations and a large set of simulations from the Coupled Model Intercomparison Project Phase 3 and 5 (CMIP3 and
CMIP5), my analyses show that most models underestimate the amplitude of low-frequency AMOC variability. Besides, my analyses show that stronger low-frequency AMOC variability leads to stronger linkages between AMOC and key variables associated with AMV, and between the subpolar AMV signal and northern hemisphere surface air temperature (NHSAT). The low-frequency extra-tropical NHSAT variability might increase with the amplitude of low-frequency AMOC variability. The Atlantic decadal predictability is much higher/lower in models with stronger/weaker low-frequency AMOC variability. These results provide a new perspective for understanding the important role of the AMOC on Atlantic multi-decadal variability and associated impacts and predictability. These results also indicate that the linkages between AMOC and AMV, as well as the associated climate impacts and Atlantic decadal predictability, could be substantially hampered in CMIP models due to their underestimation of the amplitude of low-frequency AMOC variability.

Publications:

Presentations:
Yan, Xiaoqin, Poster presentation ‘The Role of AMOC in the Recent Decline of Atlantic Major Hurricane Frequency’ at GFDL 2018 Poster Expo, January 2018.
**Progress Report Title:** Symmetric and Baroclinic Instability in Dense Shelf Overflows

**Principal Investigator:** Elizabeth Yankovsky (Princeton Graduate Student)

**CICS/GFDL Collaborator:** Sonya Legg (Princeton), Robert Hallberg (GFDL), 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 objective is to study the dynamics of dense water overflows in the continental shelf regions of the Arctic Ocean through high-resolution numerical simulations. The focus is on the roles of baroclinic and symmetric instability in mixing and water mass modification – insights will be applied to improving parameterizations in larger-scale ocean models such as the GFDL-MOM6.

**Methods and Results/Accomplishments:**

The creation and export of dense water from continental shelves governs thermohaline circulation in many regions of the world ocean, particularly the Arctic. The non-hydrostatic MITgcm is applied to model dense shelf overflows in three increasingly complex scenarios: 2D without rotation, 2D with rotation, and 3D with rotation. All setups feature a shelf region that undergoes constant negative buoyancy forcing at the surface representative of the Arctic shelves during the fall and winter seasons. Initial temperature and salinity stratification are based on data from the Kara and Barents Seas. Unlike prior studies, we resolve a wide spectrum of submesoscale variability and employ a nonlinear equation of state to accurately capture mixing processes.

We find that the 2D nonrotating case behaves according to known theory – the overflow descends along slope as a gravity current until reaching a relatively shallow neutral buoyancy level. However, in the rotating cases we have identified novel dynamics: in both 2D and 3D the submesoscale range is dominated by symmetric instability (SI). In the 2D case, SI is found to be the dominant mixing mechanism. In 3D, baroclinic eddies dominate although SI is observed along density fronts. Remarkably, through two different dynamics the 2D SI-dominated case and 3D eddy-dominated case lead to roughly the same final water mass distribution, highlighting the role of SI in certain overflow regimes.

In addition to conducting this research project, I used CICS funds to attend the Les Houches Summer School held from July 31 to August 25, 2017, in the Les Houches Physics School. This year’s topic was “Fundamental aspects of turbulent flows in climate dynamics.” I attended lectures on clouds and moist convection, atmosphere and ocean turbulence, dynamical systems, and statistical physics, and interacted with scientists working on the forefronts of climate science.

**Outreach Activities:** I presented a program to teach children about the ocean and climate at the local Plainsboro Public Library. I continue to volunteer for 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 Estuarian 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 oceanic dynamics, ocean acidification, and climate change with ten groups of students from various local schools.

Publications:

Presentations:
Progress Report Title: Eddy Momentum Flux Parametrization in Ocean Models

Principal Investigator: Laure Zanna (Princeton Visiting Faculty)

CICS/GFDL Collaborator: Alistair Adcroft (Princeton), Steve Griffies (GFDL)

Other Participating Researchers: Scott Bachman (NCAR), James Anstey (CCCma)

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

Methods and Results/Accomplishments:

The role of turbulent mesoscale eddies is crucial for the ocean circulation and its energy budget. The sub-grid scale eddy variability needs to be parametrized in ocean models, even at so-called eddy permitting resolutions. I have focused on implementing a novel parametrization of turbulence in ocean simulations. The parametrization represents turbulent eddy momentum fluxes using a non-Newtonian stress (Porta Mana & Zanna 2014, Anstey & Zanna 2017, Zanna et al 2017).

I set up a series of idealised numerical simulations with MOM6 at eddy permitting resolutions. I have focused on a double gyre set up to implement and test the parametrization. The non-Newtonian stress depends on the partially resolved scales and their variability and is shown to be a good parametrization of ocean turbulence by sharpening gradient and enhancing the kinetic energy inverse cascade. I have developed a set of diagnostics in Python to examine the contributions to kinetic energy and their transfer between scales.

The parametrization possesses attractive features for implementation in global models: little computational cost, flow- and scale-awareness, and a dependence on the life cycle of mesoscale turbulence. The parametrization is shown to enhance turbulence in idealised simulations with MOM6. We are still in the initial phase of testing and are planning to incorporate an energy equation to mostly stabilise the numerical simulations.

References:

Publications:
Progress Report Title: Implement Time-Varying Reservoir in GFDL Land Model

Principal Investigator: Yujin Zeng (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Chris Milly (GFDL), Elena Shevliakova (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: Implement a module for representing time-varying reservoirs in the GFDL land model

Methods and Results/Accomplishments:
There are more than 57,000 artificial large water reservoirs (max depth > 15) around world, and these reservoirs play important functions in irrigation, flood control, generating hydropower, supplying water to cities and river navigation. The reservoir building would cause some hydrological effects by its control on the irrigation rate and stream discharge. Along with these hydrological effects, there are also some environmental effects. The river nutrient and chemical transport is also affected by the reservoir construction.

Currently the reservoirs are represented as lake tiles with fixed area in the GFDL land model. However, from the Figure 1, we can see that in reality the reservoirs were built in different years. That means, the area of the reservoir in the model gridcell should be time-varying rather than being fixed. So, to represent the time-varying reservoirs in the GFDL land model, we came up with a two-steps scheme (as shown in the Figure 2). The first step is to set some soil tiles under the reservoir (or lake) tile in the model, and the second step is to conduct the reservoir (lake) area changing while conserving the water, energy and carbon.

Presentations:
Zeng, Yujin, Effects of lateral groundwater flow and water resources exploitation on land surface and climate, North American Land Data Assimilation System Telecon, USA, February 2018.
Figure 1: Years of construction for the large water reservoirs around the world

Figure 2: Two-steps scheme for representing time-varying reservoirs in the GFDL land model
Progress Report Title: Understanding the Controlling Factors of Tropical Precipitation Distribution

Principal Investigator: Yi Zhang (Princeton Graduate Student)

CICS/GFDL Collaborator: Stephan Fueglistaler (Princeton)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: Understanding the tropical precipitation from the probability distribution perspective; quantifying the performance of several commonly used controlling factors for tropical precipitation; describing tropical rainfall and its change with interannual variability and global warming

Methods and Results/Accomplishments:

It is known to all that tropical precipitation organizes on various spatial scales and responds to annual cycle and interannual variability. To characterize the variability of precipitation, people have used various methods. Tropical convection shows strong relation to sea surface temperature (Zhang, 1993) and subcloud layer buoyancy (Williams and Pierrehumbert, 2017). The spatial distribution of precipitation is often considered to be determined by the lower level convergence that is closely related to SST gradients (Lindzen and Nigam, 1987) or the atmospheric energy budget (Neelin and Held, 1987). We show that all the thermodynamic metrics used can explain rainfall to some degree, but fails to capture the near invariance of precipitation PDF with seasons and land-ocean contrast. The total response of global hydrological cycle to global warming is controlled by the radiative divergence change of the atmosphere, which is 2-3%/K (Held and Soden, 2006). Studies show that response of extreme precipitation exceeds that is implied by Clausius-Clapyron scaling (Allan and Soden 2008, O’Gorman 2012). We show that hydrological sensitivity can be different when using tropical mean SST and local SST where it actually rains. Our results imply that studying the PDF of thermodynamic variables may offer a better view to the tropical precipitation mystery.

References:


Progress Report Title: Cloud-Resolving Model Development and Application

Principal Investigator: Linjiong Zhou (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Shian-Jiann Lin (GFDL), Lucas Harris (GFDL), Xi Chen (Princeton)

Other Participating Researchers: Jan-Huey Chen (UCAR)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: Enabling and improving cloud-resolving simulation by developing an advanced cloud microphysics

Methods and Results/Accomplishments:

Improving the current GFDL MP: We continually worked on the current GFDL cloud microphysics (MP) in the past year. The whole scheme had been reorganized and is now easier to read and study. Meanwhile, we found and fixed several issues regarding mass and energy conservation. Among all upgrades to GFDL MP, the most important one is on the cloud radii diagnosis used for radiation processes. It used to be an over-simpliﬁed, rough scheme that built for Zhao-Carr cloud microphysics scheme. We developed our own cloud water radius diagnosis based on Martin et al. (1994), and Kiehl et al. (1994), cloud ice radius diagnosis based on Heymsfield and McFarquhar (1996), Donner et al. (1997), Fu (2007), Kristjansson et al. (2000), and Wyser (1998). The radii of rain, snow, and graupel were directly derived from Lin et al. (1983). The large-biased outgoing longwave radiation and TOA net shortwave radiation have been signiﬁcantly reduced using this new diagnosis. More importantly, this improvement is accompanying with the maintenance of global forecast skill.

Developing the inline GFDL MP: The current GFDL MP was separated into two parts, one is fast saturation adjustment built in the dynamical core, the other one is the traditional cloud microphysics processes put in the physics package. For cloud-resolving modeling, cloud microphysics is as important as the dynamical core. Therefore, an intense coupling of dynamical core and cloud microphysics is necessary. We moved the whole GFDL MP into the dynamical core, in-between the vertical remapping, which we call inline GFDL MP. We also revised the energy conservation completely. Inline GFDL MP enables the model to simulate cloud processes in much higher frequently than other physics. Together with the new cloud radii diagnosis, it has been used in the DYAMOND (DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains) project for cloud-resolving simulation comparison with other GCRMs (Global Cloud Resolving Models) around the world. It is also used for convective-scale prediction in this year’s Spring Experiment.

Enabling sub-grid orographic effect in GFDL MP: When resolution goes high, terrain can be resolved better and better. However, no matter how high the model resolution is, terrain cannot be fully resolved. Sub-grid variability inside the grid box of the model plays an important role in the dynamical and thermodynamically processes. It has been argued that terrain precipitation is poorly simulated in the global model. Better depicting of the terrain, its variation in the grid box, and its interaction with cloud microphysics is important in improving terrain precipitation, especially in global models of low to
moderate resolutions. We have initially built this idea into GFDL MP. The preliminary result showed some improvement in the terrain precipitation. A lot of coding and analysis are still on going.

**Publications:**

**Documents:**

**Presentations:**
Progress Reports:

Earth System Model Applications
Progress Report Title: Orographic Controls on the Hydroclimate of Asia, and Temporal Compounding of Heat Wave Events

Principal Investigator: Jane Wilson Baldwin (Princeton Graduate Student)

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

Other Participating Researchers: Gabriel Vecchi (Princeton), Michael Oppenheimer (Princeton), Chris Milly (USGS), Simona Bordoni (Caltech), Lei Zhao (Princeton), Dan Li (Boston University)

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: 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 are close to publication in peer-reviewed journals.

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. I have written a paper on this work, which is currently being readied for journal submission.

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, 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. This work has been written up and revised for publication, and is currently in review at the Proceedings of the National Academy of Science (PNAS). I won an Outstanding Student Presentation Award for this work at the American Geophysical Union fall meeting this year, which is given to the top 2-3% of student presenters.

I have also been involved in two collaborations exploring interactions between the urban heat island effect (UHI) and heat waves. One study, first authored by Lei Zhao, has used GCM land model simulations to understand determinants of UHI change during heat waves over the USA. This work was published in Environmental Research Letters in early 2018. Another study, in collaboration with Dan Li’s group at Boston University, has explored similar questions using a large station-based dataset over China. Understanding these factors that can exacerbate heat waves in cities is critically important for addressing urban heat wave mortality.

**Outreach Activities:** Last spring I participated in Climate Science Day on Capitol Hill representing the American Geophysical Union. I met with various New Jersey congressional offices and the House Committee on Science, Space, and Technology to discuss the importance of climate science, and followed up to build relationships with those offices. While most meetings were with staffers, I had the pleasure of meeting in person with Congressman Rodney Frelinghuysen, and in response to his inquiry explained how global climate models, such as those developed at GFDL, work. I presented a guest lecture on the science of climate change for reporter Michael Lemnick’s Princeton undergraduate seminar “ENV 316: Climate Science and Communications”. I also presented my heat waves research in Princeton’s interdisciplinary Conversations on the Environment, Responsible Energy and Life (CEREAL) discussion series. Finally, I have continued to work as a resident graduate student at Princeton, performing scientific outreach in numerous capacities from helping organize 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:**


**Presentations:**


**Progress Report Title:** Investigating the Intertropical Convergence Zone and Monsoons in an Idealized Moist Model with Full Radiative Transfer

**Principal Investigator:** Spencer Clark (Princeton Graduate Student)

**CICS/GFDL Collaborator:** Yi Ming (GFDL), Isaac Held (GFDL), Peter Phillipps (GFDL)

**Award Number:** NA14OAR4320106

**Task II:** Cooperative Research Projects and Education

**NOAA Sponsor:** V. Ramaswamy (GFDL)

**Theme:** Analysis or Earth System Model Applications

**NOAA Goals:**

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

**Objectives:** Our objective is to use simple models to understand aspects of what controls the location of rain in the tropics and how it might respond to climate change.

**Methods and Results/Accomplishments:**

This year we finished a paper investigating the role of feedbacks involving water vapor in setting the sensitivity of the latitude of the intertropical convergence zone (ITCZ) to hemispherically asymmetric forcings. In this paper, we discussed experiments where we prescribed hemispherically-asymmetric heating perturbations in an aquaplanet idealized moist model [based on Frierson et al. (2006) and Frierson (2007)] coupled to a full radiative transfer code, with interactive water vapor and radiation (i.e. with the water vapor feedback) and prescribed water vapor (i.e. without the water vapor feedback). We found that for a given forcing magnitude and location, the ITCZ shifted about twice as far in the model configuration with the water vapor feedback versus without. Through energy flux equator theory [Kang et al. (2008); Frierson and Hwang (2011); Bischoff and Schneider (2014)], the physical mechanism we diagnosed as being most responsible for this amplification effect was the absorption of longwave radiation by the water vapor associated with the ITCZ moving into the already warmer hemisphere. More details can be found in our manuscript in the Journal of Climate (Clark et al., 2018).

In addition to studying what controls the location of the zonally-symmetric component of the precipitation rate, we also began working on monsoons. To simulate monsoon-like behavior in the idealized moist model, we broke the zonal-symmetry of the aquaplanet configuration by adding a crude representation of land. The only things distinguishing the land surface from the ocean surface in our crude representation are evaporation controlled by a bucket hydrology model [as in Byrne and O’Gorman (2012) or Vallis et al. (2018)] and a heat capacity 1/10th that of the ocean. To get a sense for how close these basic assumptions get us to present-day climate, we ran a simulation with Earth’s orbital parameters and continental geometry.

In analyzing our simulation, we focused mainly on the Indian monsoon region. When compared with observations and reanalysis (for the lower tropospheric winds and precipitation in June, July, August, and September) we find that the simulation of the monsoon in our model is fairly crude when compared with that of comprehensive general circulation models. In particular, the precipitation does not extend as far northward in our simulation as it does in observations, and it is less intense. One aspect of the Indian monsoon that our simulation does appear to capture is the intraseasonal variability. Following Adames and Ming (2018) we assessed this for our simulation by computing the power spectrum of the JJAS precipitation rate averaged between 10N and 25N and lag-regressing the precipitation rate, 850 hPa
winds, and 850 hPa geopotential height against a filtered precipitation index over the east coast of India. The power spectrum of precipitation in the simulation shows a similar pattern to that which exists in TRMM observations (Huffman et al., 2007) (i.e. westward propagating disturbances lasting 3-5 days between zonal wavenumber 3 and 25). In addition, we can clearly make out a westward propagating low-pressure system in the lag-regression sequence (see Figure 1), that was also seen in a more comprehensive model (Adames and Ming, 2018). This simulation serves as a proof of concept that this configuration of the idealized moist model with full radiative transfer could serve a simple testing ground for theories regarding the time and spatial scales of intraseasonal precipitation variability in monsoon regions. We plan on pursuing this configuration further in future work.

Figure 1: Lag-regression of JJAS simulated precipitation rate (filled contour plot), 850 hPa winds (arrows), and 850 hPa geopotential height (contour lines) against a precipitation index as defined in Adames and Ming (2018).

Outreach Activities: Assistant mentor to Bridgette Befort, a NOAA Hollings Scholar intern under Yi Ming at GFDL between May and August of 2017. Mentor to Kemal Aziz, a high school student at the Staten Island Technical High School for a project for the New York City Science and Engineering Fair.

References:

**Publications:**

**Presentations:**
**Progress Report Title:** Understanding Controlling Factors of Humidity Extratropical Clouds with an Idealized Model

**Principal Investigator:** Michelle Frazer (Princeton Graduate Student)

**CICS/GFDL Collaborator:** Yi Ming (GFDL), Isaac Held (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:** My main project over this period involves examining the physical controls of extratropical humidity and clouds by considering a range of factors from microphysics to large-scale circulation in an idealized setting (the Held-Suarez dynamical core) in order to ultimately improve the understanding of cloud effects in general circulation models (GCMs). With a manuscript in preparation, I am transitioning to exploring mixed-phase cloudiness with the same modeling framework. An additional project aims to explore the policy implications of stratospheric aerosol albedo modification.

**Methods and Results/Accomplishments:**

My research examines the physical controls of extratropical humidity clouds by considering a range of factors from microphysics to large-scale circulation in an idealized model. The Held-Suarez dynamical core (Held and Suarez 1994) is utilized with the addition of passive water vapor (after Galewsky, et al. 2005) and cloud tracers (after the cloud scheme in Zhao, et al. 2009). This model captures the large-scale free tropospheric features of humidity and cloud fraction. As passive tracers, clouds do not feed back on circulation or temperature, allowing various cloud processes to be explored in isolation. Comparison with simple saturation adjustment highlights the roles of cloud processes in redistributing atmospheric moisture in two central ways. Within the model's explicit treatment of cloud microphysics, re-evaporation of hydrometeors plays a key role in moistening and increasing clouds in the lower troposphere. The sub-grid-scale relative humidity distribution assumed within the cloud macrophysics scheme influences the location and magnitude of the extratropical cloud maxima, with implications for the isentropic transport of moisture from the tropics and drying of the polar upper troposphere. Furthermore, simple alterations to the model's general circulation to mimic anthropogenic climate change demonstrate the first-order role of circulation in controlling extratropical clouds. The cloud response in terms of cloud fraction is induced by change in the meridional temperature gradient, while absolute temperature changes affect cloud condensate. Detailed changes in circulation features are essential for understanding the simulated cloud response to climate change. The results substantiate the utility of such idealized models for elucidating cloud processes in a systematic manner. I am currently expanding my research to explore mixed-phase cloudiness within this modeling framework.

Additionally, as part of a PEI-STEP fellowship, advised by Michael Oppenheimer and Rob Socolow and in collaboration with Harvard researchers, 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: Through the Princeton Energy and Climate Scholars (PECS) I had the opportunity to present on Climate Policy to the Princeton Day School’s (PDS) Energy and Climate Scholars (ECS) program and am currently mentoring a group of ECS high school students to present on climate policy at their upcoming PDS climate conference.

References:

Presentations:
Progress Report Title: Long Term Variability of Marine Ecosystems in Earth System Models

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

CICS/GFDL Collaborator: Charles Stock (GFDL), Keith Dixon (GFDL), Andrew Ross (GFDL)

Other Participating Researchers: Gabriel Vecchi (Princeton), Andrew Barton (Scripps), Carlos Cáceres (U Strathclyde), Carlos Gaitán (Arable Inc.), Ricardo González (U Strathclyde), Barbara Muhling (UCSC), Desire Tommasi (UCSC), Vincent Saba (NMFS)

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 potential of Earth Systems Models (ESM) simulations to improve our understanding of 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:
Our work has focused on four 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, (ii) the development of a hybrid approach to take advantage of GFDL forecast products in the prediction of surface water conditions in estuaries, (iii) an analysis of the reliability of different wind reanalysis products for ocean model forcing, with an emphasis on coastal upwelling, and (iv) the contribution to a series of assessments lead by other colleagues related to the importance of long term climate variability on marine populations.

The assessment of marine ecosystem variability in ESMs analyzed the predictability of short term changes in marine Net Primary Production (NPP), from monthly to seasonal scales. The assessment was conducted using both satellite observations and the output of ESM2M COBALT simulations (Stock et al. 2014). The analysis highlighted that internal feedbacks and horizontal advection can lead to an extended predictability of ocean biogeochemical variables like NPP when compared with physical variables like sea surface temperature (SST), especially in frontal regions (transitions) separating major ocean biomes. We also developed a hybrid empirical-dynamical approach to forecast surface water conditions in estuaries, using Chesapeake Bay as a target of a pilot study. The small extent of estuaries and the mélange of oceanic and terrestrial influences represent a major challenge for traditional forecasting strategies. Our approach builds upon seasonal forecasts of atmospheric temperature based on ensemble simulations of the GFDL Global Climate Model forecast system FLOR, which are translated to anomalies at the estuary scale using Empirical Statistical Downscaling (ESD). These anomalies serve as input to a local spatial statistical model of the evolution of temperature conditions in the bay, the output of which leads to an improvement of short term forecast skill above persistence. The results of both projects support the potential for extending seasonal to inter-annual physical climate predictions to predict ocean productivity.

The assessment of wind reanalysis products focused on identifying the differences and limitations of datasets currently in use in ocean model forcing experiments, with emphasis on the assessment of
recently released Japanese 55-year Reanalysis for driving ocean-ice models (JRA55-do). We focused on coastal regions and in quantities of particular interest for ocean dynamics derived from wind stress components and their spatial derivatives. The results revealed systematic differences between different products, with an increase in quality in recent, higher resolution products. Biases remained in some regions of particular interest, like the Peruvian and in the Namibian regions, which suggest the need of nonlinear adjustments.

We also developed several projects targeting the assessment of the impact of long term climate variability on marine populations. Research led by A. Barton (UCSD) analyzed the dynamics of 150 plankton species in the English Channel. The study tested Di Lorenzo and Ohman (2013) double integration hypothesis, a framework that explains the emergence of regime shifts in marine ecosystems. The study found only partial support to this idea and proposes instead a model featuring the tight coupling within the planktonic food web that can overwhelm double integration effects and lead to similar dynamics among trophic groups. A project led by C. Petrik (AOS) focused on the application of life history theory to improve our understanding of recruitment variability in commercially fished species. This work features the emergence of Rockfishes as a distinct group in terms of their life history strategy, which makes them particularly sensitive to fishing. Other undergoing and collaborative work involved: (i) an analysis of plankton phenology in the Bay of Biscay using in situ and remote sensing data (lead by R. González-Gil, U. Strathclyde); and (ii) a metaanalysis of plankton grazing experiments focusing on the characterization of functional allometric relationships (lead by C. Cáceres, U. Strathclyde).

References:

Publications:
Figure 1. Map of the overall correlation between *in situ*, sea surface temperature anomalies observed in Chesapeake Bay (each dot correspond to a CTD station), and temperature forecasts at Thomas Point based on one month ahead FLOR forecasts of surface air temperature anomalies (1985-2015).

Figure 2. Graphical abstract of the manuscript by González-Gil et al. (in press) that illustrates the preconditioning of deep convective mixing during winter on the development of the phytoplankton bloom the next spring. The manuscript analyzed a long-term time series of *in situ* and satellite observations that revealed a strong relationship between the intensity (maximum depth) of winter mixing and the timing and intensity of the following spring bloom.
Progress Report Title: The Temporal Evolution of Ocean Heat Uptake

Principal Investigator: Jie He (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Mike Winton (GFDL), Stephan Fueglistaler (Princeton)

Other Participating Researchers: Gabriel Vecchi (Princeton)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

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: To understand the time evolution of ocean heat uptake patterns

Methods and Results/Accomplishments:

The rate of global mean surface warming is largely regulated by the ocean heat uptake. Previous studies suggested that the pattern of ocean heat uptake does not linearly scale with the strength of the radiative forcing. We hypothesize that the nonlinearity largely results from the nonlinearity of ocean circulation changes, which affects the spatial distribution of ocean heat content.

In this study, we analyze the temporal evolution of ocean heat uptake in a large ensemble of global warming simulations with constant radiative forcing (1% per year CO2 increase). We use redistributed heat and added heat tracers to decompose the ocean heat uptake into a part driven by circulation changes and a part due to passive uptake of heat anomalies.

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

Principal Investigator: Nathaniel Johnson (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Andrew Wittenberg (GFDL), Lakshmi Krishnamurthy (Princeton), Sarah Kapnick (GFDL), Jie He (Princeton), Salvatore Pascale (Princeton), Baoqiang Xiang (UCAR), Ángel Muñoz (Princeton)

Other Participating Researchers: Gabriel Vecchi (Princeton), Jiaxin Black (Scripps/GFDL), Steven Feldstein (Penn State), Michelle L’Heureux (NOAA CPC), Dan Harnos (NOAA CPC), Steve Baxter (NOAA CPC), Shang-Ping Xie (Scripps), Yu Kosaka (U. Tokyo), Xichen Li (Institute of Atmospheric Physics), Changhyun Yoo (Ewha Womans University), Chueh-Hsin Chang (National Taiwan University), Tyler Janoski (Columbia), Tony Broccoli (Rutgers), Neven Fučkar (Oxford)

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 work 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 contributed to projects that have improved our understanding of North American climate variability and predictability from timescales of a few weeks to decades. In June 2017, I finished supervising a postdoctoral research scientist, Dr. Jiaxin Black, for a project that developed new weeks 3-4 forecast products for the NOAA Climate Prediction Center. The results of this effort include a published article on subseasonal forecasts of atmospheric teleconnection patterns and the transition of new statistical forecast tools into official operations, an accomplishment that was deemed “a great success” by NOAA (http://cpo.noaa.gov/News/News-Article/ArtMID/6226/ArticleID/1597/New-NOAA-forecast-product-guides-3-to-4-week-temperature-and-precipitation-outlooks). Following the end of Dr. Black’s postdoctoral appointment, I have examined subseasonal forecast skill in the GFDL FLOR model. In collaboration with Ángel Muñoz, Baoqiang Xiang, and Gabriel Vecchi, I am working to improve understanding of subseasonal predictability while simultaneously developing a hybrid dynamical/statistical forecast method with the GFDL FLOR model for weeks 3-4 forecasts.

I also have continued to investigate 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. Through a series of several experiments with FLOR, 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 on seasonal-to-centennial climate variability and change. Most notably, I completed a manuscript on the increase of Northern Hemisphere continental temperature extremes during the recent global warming hiatus. I performed numerous diagnostic analyses of observational and climate model simulations, including a long control simulation of the GFDL FLOR model, to determine the dominant sources of variability of continental extreme temperature occurrence. We find that the dominant sources of wintertime cold and summertime warm extreme temperature occurrence variability are closely linked to naturally occurring large-scale climate patterns that are distinct from the dominant sources of global mean temperature variability. This manuscript is currently under review.

In addition, I contributed to a recently published paper that examined the sources of seasonal prediction skill in the forecast models of the North American Multi-Model Ensemble. I also contributed to a manuscript on the changes in eastern U.S. blizzards under climate change, as determined through simulations with the GFDL FLOR climate model, which is currently under revision. This manuscript is led by Mr. Tyler Janoski, a former Hollings Scholar I co-mentored with Dr. Sarah Kapnick during his summer internship at GFDL. I also worked closely with Dr. Jie He on a study about the relationship between tropical precipitation and sea surface temperatures, which has resulted in a manuscript that is currently under review.

**Outreach Activities:**

Since March 2017, I have served as one of the primary writers for the climate.gov ENSO Blog (https://www.climate.gov/news-features/department/enso-blog). The ENSO Blog, which has received more than 1.7 million unique page views over the four years of its existence, provides an opportunity to communicate scientific principles related to the El Niño–Southern Oscillation (ENSO) to a general audience. I have written or served as lead editor for three blog posts over the course of the year. I also edit each of the twice-per-month blog posts, and for one week out of every five, I serve as the lead moderator of the blog comments. As moderator, I approve comments and respond to questions from the general public about ENSO and climate prediction in general.

In a separate though related activity, I have volunteered to contribute to the Climate Prediction Center/International Research Institute for Climate and Society’s monthly ENSO forecasts. Since August 2017, I have served as one of about 12 forecasters who provide probabilistic seasonal ENSO forecasts for lead times of one month to one year, which contribute to the CPC/IRI consensus ENSO forecast each month.

**Publications:**


Johnson, N. C., S.-P. Xie, Y. Kosaka, and X. Li, 2018: Increasing occurrence of cold and warm extremes during the recent global warming slowdown. Nature Communications, accepted in principle.


Fučkar N. S., V. Guemas, N. C. Johnson, and F. J. Dobas-Reyes, 2018: Dynamical prediction of Arctic sea ice modes of variability. Climate Dynamics, under revision.

Presentations:

Johnson, N. C. (August 2017). Bridging the gap in NOAA’s extended and long range prediction systems through the development of new forecast products for weeks 3 and 4. NOAA NGGPS/MAPP PIs Meeting in College Park, Maryland. Invited.
**Progress Report Title:** Vortices and Jets in Planetary Atmospheres

**Principal Investigator:** Yohai Kaspi (Princeton Visiting Faculty)

**CICS/GFDL Collaborator:** Isaac Held (GFDL)

**Other Participating Researchers:** Timothy Merlis (McGill)

**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 Juno spacecraft has been orbiting Jupiter since July 2016, providing an unprecedentedly accurate gravity spectrum of the planet, which enabled determining the depth of the dynamical atmosphere of Jupiter (Kaspi et al., 2018). Due to its unique polar orbit, Juno provided also the first ever polar views of the planet, revealing an unexpected number of vortices congregated at the high latitudes while low latitudes are dominated by jets. This combination of new data coming from gravity, microwave and imaging, and modern modeling capabilities enables developing new theoretical understanding of the dynamics driving Jupiter's atmosphere. Our goal has been to answer fundamental questions about the dynamics such as: What sets the latitude of separation between the cyclone and jet dominated regimes? What sets the typical size and distance between the cyclones? What stops the vorticity from congregating at the pole (as on Saturn)? and How does deep convective heating affect the properties of the cyclones? Answering these questions is essential not only to our understanding of giant planet dynamics, but to our understating of GFD and climate in general.

**Methods and Results/Accomplishments:**

In recent years the Geophysical Fluid Dynamic Laboratory (GFDL) High-Resolution Atmospheric Model (HiRAM) has provided a new framework to study cyclones on a global scale. This provides a leap forward in the ability to treat convection and small coherent atmospheric features, similar to the transition two decades ago where idealized General Circulation Models (GCMs) enabled simulating the general circulation at a reasonable accuracy. HiRAM is based on GFDL's lower resolution AM2 model, using cubed-grid topology, with modified convection and cloud schemes, better applicable for high-resolution capturing some of the physics that were parameterized in the lower resolution models. A hierarchy of models based on HiRAM has been recently developed including f-plane, slab ocean and global SST configurations. This provides a perfect framework for addressing the questions mentioned above regarding the cyclone dynamics on Jupiter.

In this project, we have utilized HiRAM to a general configuration where we have found that by varying the rotation rate of the planet and the radiative time scale we can control the number, size and life time of vortices in the polar regions. Due to the beta effect vortices always drift towards the poles, similar to the new observations of Jupiter.
The figure below shows a few examples taken from snapshots of simulations with different rotation rates and radiative time scales. Soon we expect to have more results in order to elucidate on the difference between Jupiter’s north and south poles.

**Outreach Activities:** I gave a lecture about NASA’s Juno mission to Jupiter at Community Park Elementary School at Princeton.

**Publications:**

Progress Report Title: Climate Variability and Predictability

Principal Investigator: Lakshmi Krishnamurthy (Princeton Climate Prediction Specialist)

CICS/GFDL Collaborator: Xiaosong Yang (UCAR), V. Balaji (Princeton), Sarah Kapnick (GFDL), Andrew Wittenberg (GFDL), Bill Stern (GFDL), Fanrong Zeng (GFDL), Seth Underwood (GFDL), Ángel G. Muñoz (Princeton)

Other Participating Researchers: Gabriel A. Vecchi (Princeton), Liwei Jia (CPC/NOAA), Karin van der Wiel (Royal Netherlands Meteorological Institute), Rym Msadek (CNRS/CERFACS), Karen Paffendorf, Monika Barcikowska (EDF)

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: 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; evaluation of seasonal forecast skill of the Indian monsoon in GFDL forecast system

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. Evaluation of seasonal forecast skill of the Indian monsoon in GFDL forecast system and the source of predictability are being investigated. GFDL models tend to forecast droughts accurately but fail to forecast floods in general. However, when accompanied by an ENSO, models forecast floods and drought accurately. During non-ENSO years, they fail to predict floods and forecast weak droughts. The inability of the GFDL models to forecast floods during non-ENSO years may be related to their inability to capture eastern pole of IOD (Indian Ocean dipole) and EQUINOO (atmospheric component of IOD). Another plausible cause may be that the model erroneously forecasts El Niño in the tropical Pacific which may be leading to droughts over India rather than floods. Failure to capture droughts during non-ENSO years may be related to the inability of models to forecast strong warm SSTs along the west coast of North America. The SSTs along the west coast of America related to PDO are crucial for affecting rainfall over India via seasonal footprinting mechanism.
High-resolution coupled and uncoupled models from the Geophysical Fluid Dynamics Laboratory (GFDL) were used to investigate the simulation of the CLLJ and its teleconnections and further compare with low-resolution models. The high-resolution coupled model FLOR shows improvements in the simulation of the CLLJ and its teleconnections with rainfall and SST over the IAS compared to the low-resolution coupled model CM2.1. The CLLJ is better represented in uncoupled models (AM2.1 and AM2.5) forced with observed sea-surface temperatures (SSTs), emphasizing the role of SSTs in the simulation of the CLLJ.

Further, the forecast skill for observed rainfall using both high- and low-resolution predictions of rainfall and SSTs for the July-August-September season was analyzed. The role of statistical correction of model biases, coupling and horizontal resolution on the forecast skill was determined. Statistical correction dramatically improves area-averaged forecast skill. But, the analysis of spatial distribution in skill indicates that the improvement in skill after statistical correction is region dependent. Forecast skill is sensitive to coupling in parts of the Caribbean, Central and South America, and it is mostly insensitive over North America. Comparison of forecast skill between high and low-resolution coupled models does not show any dramatic difference. However, uncoupled models show improvement in the area-averaged skill in the high-resolution atmospheric model compared to lower resolution model. Understanding and improving the forecast skill over the IAS has important implications for highly vulnerable nations in the region. In present times, where most of the resources are invested in coupled models and improving resolution, this study also provides insights on sensitivity of forecast skill to coupling and resolution, which may help plan future efforts in model development.

The causes and probability of occurrence of unprecedented high-intensity flooding induced by extreme precipitation over Chennai in India during November-December of 2015 was determined. This extreme event led to extensive damage to human life and property. It is of utmost importance to determine the odds of occurrence of such extreme floods in future and the related climate phenomena, for planning and mitigation purposes. A suite of simulations from GFDL high-resolution coupled climate models was used to investigate the odds of occurrence of extreme floods induced by extreme precipitation over Chennai and the role of radiative forcing and/or large-scale SST forcing in enhancing the probability of such events in future. Climate of 20th century experiments with large ensembles suggest that the radiative forcing may not enhance the probability of extreme floods over Chennai. Doubling of CO2 experiments also fail to show evidence for increased occurrence of such events in a global warming scenario. Further, this study explores the role of SST forcing from the Indian and Pacific Oceans on the odds of occurrence of Chennai-like floods. Neither El Niño nor La Niña enhances the probability of extreme floods over Chennai. However, warm Bay of Bengal tends to increase the odds of occurrence of extreme Chennai-like floods. The atmospheric condition such as a tropical depression over Bay of Bengal favoring the transport of moisture from warm Bay of Bengal is conducive for intense precipitation. The results of this study, which quantifies the risk of Chennai precipitation extremes in the present and future climate, can help guide planning of for example, infrastructure and housing projects for future events. Thus, the results from this study that the years with warm Bay of Bengal SSTs may increase the odds of occurrence of Chennai-like flood event is crucial information for decision makers for adaptation and mitigation purposes. This information will help them plan for any future risks that may be posed by extreme flooding over Chennai and in disaster preparedness and management. While this study provides insights on an individual event and its likelihood for change in the future, the methodologies and framework used in this investigation can be applied elsewhere.

**Publications:**


Krishnamurthy, L et al. Seasonal forecast skill of the Indian monsoon in the GFDL high-resolution forecast system (in preparation).

**Presentations:**

Krishnamurthy, L., Poster presented at GFDL poster EXPO on February 2018 titled, Seasonal forecast skill of the Indian monsoon in GFDL high-resolution forecast system.

Krishnamurthy, L., Poster presented at NMME/SubX Science Meeting on September 2017 titled, Seasonal forecast skill of the Indian monsoon in GFDL high-resolution forecast system in College Park, Maryland.

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

Progress Report Title: Air Quality, Ecosystem-Atmosphere Interactions, and Climate

Principal Investigator: Meiyun Lin (Princeton Research Scholar)

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

Other Participating Researchers: Li (Alex) Zhang (Princeton)

Award Number: NA14OAR4320106

Task III: Individual Projects

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Model Applications

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

Objectives: Systemically investigate how air quality means and extremes respond to changes in global-to-regional emissions, stratosphere-to-troposphere transport, drought, and ecosystem-atmosphere interactions in present and future climate

Methods and Results/Accomplishments:
Removal by dry deposition to the Earth’s surface represents an important control on near-surface O₃ concentrations. Understanding the factors controlling O₃ dry deposition velocity (V_d,O₃) has implications for interpreting observed surface O₃ trends, especially over areas where land-atmosphere interactions are known to play a role in regional climate. In southern Europe, for example, the lack of precipitation and the associated depletion of soil moisture result in reduced evaporative cooling and thereby amplify the summer hot extremes [Hirschi et al., 2011]. Under drought stress, plants close their stomata to conserve water, consequently limiting O₃ uptake by vegetation [Gerosa et al., 2009b; Emberson et al., 2013]. Recent measurements have demonstrated considerable interannual variability in V_d,O₃ and the role of stomatal versus non-stomatal deposition pathways [Mikkelsen et al., 2004; Gerosa et al., 2009a; Rannik et al., 2012; Clifton et al., 2017]. However, simulating such land-biosphere-atmosphere interactions in air quality models proves challenging [Fowler et al., 2009; Rydsaa et al., 2016; Lin et al., 2017]. Current global models typically parameterize V_d,O₃ using the resistance-in-series approach developed by Wesely (1989) with some modifications [e.g., Hardacre et al., 2015]. While the Wesely scheme has success in some applications [Park et al., 2014; Val Martin et al., 2014], the lack of sensitivity to soil moisture and vapor pressure deficit is problematic [e.g., Kavassalis and Murphy, 2017].

The influence of changes in O₃ dry deposition, expected to evolve with climate and land use, is often overlooked in air quality projections. Leveraging a new parametrization scheme for calculating tracer dry deposition velocities in the NOAA GFDL dynamic vegetation land models (LM3/LM4) coupled to the NOAA GFDL atmospheric chemistry-climate models (AM3/AM4), this project investigates how surface O₃ air quality means and extremes respond to changes in ecosystem-atmosphere interactions in present and future climate. Preliminary results in Figures 1 and 2 demonstrate the improved simulations of ozone deposition to forests and surface ozone concentrations in GFDL AM4/LM4.

Over the last two years Meiyun Lin has authored 20 peer-reviewed publications and obtained approximately $250,000 external funding. Her first-authored paper (Lin et al., 2017) was featured in Princeton News, NOAA Research, National Public Radio, and many other public media outlets. The
paper has been cited by 30 times within just one year and was among the three GFDL papers nominated for the 2018 NOAA OAR Outstanding Paper Award. Lin was invited to give seminars at Harvard University, MIT, University of Toronto, and many other national and international conferences. She also contributed to presentations during many NOAA leadership visits to GFDL and Princeton/AOS.

Figure 1: Improved simulations of ozone deposition sink to forests in GFDL LM4.0 compared to LM3.0. Credit: Meiyun Lin et al. (2018, in prep)
Figure 2: Improved simulations of surface ozone with interactive dry deposition in GFDL AM4/LM4.0. Springtime mean daily max 8-hour ozone mixing ratios in the northern Hemisphere from observations and GFDL AM4 with ozone deposition velocities from LM4.0 and GEOS-Chem. Credit: Meiyun Lin et al. (2018, in prep).

Publications:


**Presentations:**

Lin, M.Y., Feb 22, 2018, NOAA Climate Program Office Director Visit to GFDL: Heat waves, drought, and air quality.

Lin, M.Y., Feb 12, 2018, NOAA OAR's Director of Weather and Air Quality John Cortina's Visit to GFDL: Atmospheric chemistry and connection to Earth system modeling.


Lin, M.Y., Aug 18, 2017, Congressional Staff Visit to GFDL: Air Quality and Climate.


**Progress Report Title:** Impact of Mountains on Tropical Circulation in Two Earth System Models

**Principal Investigator:** Sergey Malyshev (Princeton Professional Specialist)

**CICS/GFDL Collaborator:** Ronald J. Stouffer (GFDL) John P. Krasting (GFDL), Andrew T. Wittenberg (GFDL)

**Other Participating Researchers:** Zachary Naiman (U. of Arizona) Paul J. Goodman (U. of Arizona), Joellen P. Russel (U. of Arizona)

**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:** Explore the role of mountains in shaping Earth’s climate system

**Methods and Results/Accomplishments:**

Land surface topography is a fundamental boundary condition of Earth’s climate system. Previous studies have used a paleo approach in which orographic height and location correspond to best estimates of continental configurations and orography from specific periods in Earth’s history; a regional approach, in which the height of specific orography is varied; and a global approach, in which the height of all of Earth’s land surface topography is varied systematically.

In this study, we present the results of an idealized experiment in which we adopted the global approach to varying Earth’s land surface topography in order to better understand the influence of mountains, at the largest scale, on the climate system. Two state-of-the-art Earth system models (ESM2Mb and ESM2G) were used in an idealized experiment to explore the role of mountains in shaping Earth’s climate system. We removed all land surface topography from two state-of-the-art ESMs and ran our “PANCAKE” simulations for over 500 model years.

Similar to previous studies, removing mountains from both ESMs results in the winds becoming more zonal and weaker Indian and Asian monsoon circulations. However, there are also broad changes to the Walker circulation and El Niño–Southern Oscillation (ENSO). Without orography, convection moves across the entire equatorial Indo-Pacific basin on interannual time scales. ENSO has a stronger amplitude, lower frequency, and increased regularity. A wider equatorial wind zone and changes to equatorial wind stress curl result in a colder cold tongue and a steeper equatorial thermocline across the Pacific basin during La Niña years. Anomalies associated with ENSO warm events are larger without mountains and have greater impact on the mean tropical climate than when mountains are present. Without mountains, the centennial-mean Pacific Walker circulation weakens in both models by approximately 45%, but the strength of the mean Hadley circulation changes by less than 2%. Changes in the Walker circulation in these experiments can be explained by the large spatial excursions of atmospheric deep convection on interannual time scales. These results suggest that mountains are an important control on the large-scale tropical circulation, impacting ENSO dynamics and the Walker circulation, but have little impact on the strength of the Hadley circulation.
Differences (PANCAKE minus CONTROL) of 100-yr means (years 401–500) for (a) precipitation, (b) pressure velocity $\omega$, and (c) sea surface temperature. All values are from ESM2Mb. Values for $\omega$ are at 500 hPa; negative (blue) values are in the upward direction. Results for $\omega$ do not change significantly when different pressure levels, or an average of pressure levels, are used to represent the mid-troposphere. Areas where the difference between PANCAKE and CONTROL mean values are more than two standard deviations of annual mean CONTROL values over the 100-yr period are hatched.

Publications:
Progress Report Title: The Impact of Climate Change on the Transmission and Incidence of Directly-Transmitted Childhood Diseases

Principal Investigator: C. Jessica E. Metcalf (Princeton Assistant Professor)

CICS/GFDL Collaborator: Saki Takahashi (Princeton)

Award Number: NA14OAR4320106

Task III: Individual Projects

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Model Applications

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

Objectives: Our goal was to develop methods and approaches to characterize the impact of climate drivers on infectious disease transmission, with a focus on directly transmitted childhood infections.

Methods and Results/Accomplishments:
The potential impacts of climate change on human health are increasingly recognized. Characterizing this impact for infectious diseases is complicated by the fact that the core process, e.g., transmission between individuals (directly, or via vectors, or environmental routes) is frequently unobserved. We first reviewed existing methods and approaches across a broad scope of pathogen life-histories, then collated data from an array of settings (from Mexico to Thailand), and finally developed methods to disentangle transmission for chicken pox, using a combination of mechanistic modeling and panel regression approaches. From this basis, we project future burden and shifts for this infection under climate change for Mexico. We then adapted the methods to address interactions between pairs of pathogens, and evaluate seasonal drivers, a necessary foundation to further evaluating the impact of climate drivers on important pathogens such as Respiratory Syncytial Virus (RSV). To date, we have submitted two articles, and anticipate several more over the coming year, both on climatic drivers of RSV, leveraging US wide data; and cyclone impacts on health system functioning, using data from Madagascar and elsewhere.

Outreach Activities: I am advising two undergraduate thesis topics on the topic of climate and infectious disease, including one on dengue in India (Claire Felten, WWS), and one on cyclones and health systems functioning (Maria Malik, EEB).

References:

Publications:  
See submissions listed above; publications should be forthcoming.

Presentations: Metcalf, Jessica, Oct 2017. Climate drivers of infectious disease: disentangling direct and indirect effects Invited Talk. Earth Systems Science Center, Stanford University, USA.
Progress Report Title: GFDL Curator System and Data Portal Infrastructure and CMIP6

Principal Investigator: Serguei Nikonov (Princeton Earth System Modeler)

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

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Model Applications

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

Objectives: Redesign Curator subsystems and adaptation data publication workflow to CMIP6 project and begin publishing CMIP6 datasets on GFDL ESGF Node

Methods and Results/Accomplishments:
CMIP6 has a 6-year report cycle and 2017 was a year of final preparations – GFDL workflow to massive climate simulations and publication of resulted datasets. As Curator includes infrastructure for publishing experiments, this period the system has undergone final review and verification of its capabilities (volume limitation, performance, reliability, modelers’ end users’ expectation and satisfaction). Thorough tests were done with all components – curator DB, experiments mapper, fremetar (FRE metadata rewriter), and storage (Hitachi 1.5 PB).

Special attention was given to ESGF Suite – global federation for metadata/data sharing, discovering, searching, navigation and downloading. Active participation in CDNOT (CMIP Data Node Operations Team) moves ESGF to a new level of resilience, resistance and reliability and distinct vision of a capability of the system. The Data Challenges (DC1, 2, 3) which are being conducted by CDNOT instill confidence in exploitation of ESGF in CMIP6 course. A successful start of CMIP6 data publishing became a main result of this work throughout all components.

Another substantial constituent was migration to new technologies: Docker Containers and Clouds. Participation in the DREAM project (Distributed Resources for the Earth System Grid Advanced Management) allows GFDL to get technology for the fast deployment of ESGF Suite from Docker containers in any environment. It’s implied to use it for installing on Google clouds and running there – GFDL Data Portal, CMIP data firstly. Using the cloud will bring mutual benefits – as to data holders and/or end users. Maintenance will be minimalized due to using containers with embedded environment specific; data volume limitation will be mitigated by Google expanded resources and the speed up of data access for end users is very promising.

Publications:
Presentations:


**Progress Report Title:** Global Marine Biogeochemistry Prediction

**Principal Investigator:** Jongyeon Park (Princeton Postdoctoral Research Associate)

**CICS/GFDL Collaborator:** Charles Stock (GFDL), John Dunne (GFDL), Xiaosong Yang (GFDL), Anthony Rosati (GFDL), Jasmin John (GFDL)

**Other Participating Researchers:** Shaoqing Zhang (Ocean University of China and Qingdao National Laboratory for Marine Science and Technology)

**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 develop an optimal strategy for biogeochemical initializations on the GFDL’s seasonal to decadal global climate prediction system; to assess the seasonal to multi-annual prediction skill for global marine biogeochemistry

**Methods and Results/Accomplishments:**

During the last year, we have continued working on global marine biogeochemistry prediction. First, an optimal strategy to initialize ocean biogeochemical model was developed. GFDL’s marine biogeochemistry model was integrated with an ensemble coupled-climate data assimilation system used for seasonal to decadal global climate prediction. Our initial implementation using the full ocean and atmospheric assimilative physics exhibited marked degradation of simulated equatorial marine biogeochemistry due to momentum imbalances that arise during physical data assimilation relative to simulations with atmospheric assimilation alone. This degradation addressed by weighting model over data constraints in a narrow band around the equator. Despite the weak data constraint at the equator, off-equatorial data constraints still improved physical and biogeochemical simulations relative to non-assimilative ocean control simulation. This work was accepted for publication in *Journal of Advances in Modeling Earth Systems*.

We then performed retrospective prediction runs using the optimal initialization strategy and accessed the prediction skill of marine biogeochemistry. A set of two year-long, multi-member ensemble runs have been performed every month from 1991 to 2014. The 24-year-long retrospective forecasts showed considerable potential for seasonal to multi-annual prediction of marine biogeochemistry. Although forecast skill varied by region and initialization month, our earth system prediction system can provide skillful global marine biogeochemistry predictions about one year in advance in many ocean basins (Figure 1). We further investigated potential utility of our earth system prediction system for marine resource management. We found that reported temporal variability of annual fish catch in the California Current Large Marine Ecosystem obtained from Sea Around Us Project database is well explained by predicted fish catch estimated from predicted chlorophyll concentrations with correlation
coefficients between the reported and predicted fish catch 0.77 and 0.63 at 0-1 year and 1-2 year lead times, respectively. We also found that combining chlorophyll-based prediction with SST information further improved the prediction skill of fish catch to 0.85 at 0-1 year lead time and 0.82 at 1-2 year lead time.

Our plan is to start writing a paper with the initial result of marine biogeochemical predictions. In addition, we will start to discuss about the means of providing future prediction of marine biogeochemistry and continue our efforts to improve the prediction skill through the assimilation of satellite ocean color data and/or high-resolution modeling (e.g. ESM4) coupled with GFDL’s coupled-climate data assimilation system.

Outreach Activities: Attended 2018 Ocean sciences meeting, session on “Linking Observations and Modeling to Better Understand Marine Biogeochemical Cycling”

References:
Sea Around Us Project database (http://www.seaaroundus.org/data/#/lme)

Figure 1. (Upper panel) The spatial map of anomaly correlation coefficients (ACCs) between the predicted and satellite chlorophyll concentrations at 1-3 month and 4-6 month lead times. Black boxes represent the areas selected for detailed analysis: Indian Ocean, Tropical Pacific, Southern Pacific, North Atlantic, and Tropical Atlantic. (Lower panel) Anomaly correlation coefficients as a function of initialization month (x-axis) and lead time month (y-axis) in the selected five ocean basins. Both closed and open dots indicate that ACCs are significant at 95% confidence level; open dots indicate the persistence forecast ACCs above the dynamical forecast ACCs.
Publications:


Presentations:

Park, J.-Y., Global integration of ocean biogeochemistry with data assimilative ocean physics, 2018 Ocean sciences meeting, Portland, OR, USA.
Progress Report Title: Present and Future Hydroclimate of the North American Monsoon and Other Semi-arid Regions

Principal Investigator: Salvatore Pascale (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Sarah B. Kapnick (GFDL), Thomas Delworth (GFDL), P. Ginoux (GFDL), E. Shevliakova (GFDL)

Other Participating Researchers: Hiroyuki Murakami (Princeton), Simona Bordoni (Caltech), G. Vecchi (Princeton), B. Pohl (CNRS, France), W. Boos (Berkeley), D. Kirshbaum (NASA)

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

Objective: The primary objectives of this project are to understand the effects of natural variability and anthropogenic warming on the summertime North American monsoon, and the physical drivers of droughts in other semi-arid regions like southern Africa or Mediterranean-like regions.

Methods and Results/Accomplishments:
Key tools for my research are the high-resolution global coupled models developed at the GFDL: CM2.5 (Delworth et al., 2012) and FLOR (Vecchi et al., 2014). These models have a relatively high horizontal atmospheric resolution (50 km) which makes them suitable to investigate regions with complex topography like the North American Southwest. The model outputs are compared with various observational data sets and reanalysis for validation and future model improvement work.

Over the last year, I led a study to identify and explain the key role of sea surface temperature remote biases in the response of the North American monsoon to increased greenhouse gases. This has been documented in a letter published in Nature Climate Change (Pascale et al., 2017). This research provides a fundamental understanding of the North American monsoon and explains why climate models have difficulty reproducing precipitation in this region. Furthermore, I have also led a study to evaluate the impact of CO₂ forcing on the Gulf of California moisture surges and extreme precipitation associated with such surges. This has been documented in a manuscript (Pascale et al., 2018a), which is presently under review for Journal of Climate. Finally, I am leading a study of climate variability in Southern Africa related to elucidate under which conditions El Niño years do not lead to expected summertime droughts (Pascale et al., 2018b). This research is performed in collaboration with an international expert on Southern African climate (B. Pohl). I am also contributing with my precipitation and monsoonal expertise to a project on High Mountain Asia aerosols, hydrologic cycle, and landslides (Ginoux et al., 2018, Kapnick et al., 2018, Kirshbaum et al. 2018).

Outreach Activities: Co-mentor of Mrs. Haylie Mikulak during her undergraduate internship with the Hollings Scholar Program at GFDL in the summer of 2017. Mentor of Mrs. Laura Queen during her undergraduate internship with the Hollings Scholar Program at GFDL in the summer of 2018.
References:
Delworth, T. et al., 2012: Simulated climate and climate change in the GFDL CM2.5 high-resolution coupled climate model, J. Climate, 25, 2755-2781

Publications:

Presentations:
**Progress Report Title:** Understanding the Super Greenhouse Effect through ENSO Events

**Principal Investigator:** Shiv Priyam Raghuraman (Princeton Graduate Student)

**CICS/GFDL Collaborator:** V. Ramaswamy (GFDL), David Paynter (GFDL), Yi Ming (GFDL), Leo Donner (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:** We aim to understand how the greenhouse effect changes during anomalous events such as ENSO events and how changes in water vapor impact the heat budget of the atmosphere.

**Methods and Results/Accomplishments:**

At times in the deep tropics there is a remarkable anti-correlation between the clear sky outgoing longwave radiation (OLR) and the sea surface temperature (SST), an anomaly, considering the rest of the Earth displays a positive correlation between these two quantities. This phenomenon, the “Super Greenhouse Effect”, and its causes are not clearly understood, and there is a degree of ambiguity from earlier studies of the phenomenon. We investigate the causes and quantify the relative roles of factors important for generating the super greenhouse effect using ERA Reanalysis climatological data as input for a radiative transfer code, and CERES clear sky OLR data.

We focus on the Central and Eastern tropical Pacific since it exhibits this phenomenon during El Niño and La Niña events during the 2000-2016 period. We show that enhanced moistening of the middle troposphere results in the largest contribution to OLR relative to other layers and is a dominant factor in producing the super greenhouse effect. Increases in water vapor, by increasing the temperature profile of the column while holding the relative humidity fixed, does not produce the super greenhouse effect and therefore large shifts in relative humidity are required to produce the phenomenon. In addition to the dominance of the middle troposphere, the lower troposphere via absorption in the window region plays a non-negligible role in determining the magnitude of the super greenhouse effect.

**Outreach Activities:** NJ Ocean Fun Days with Dr. Legg in May 2017

**References:**


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

Principal Investigator: Keith Rodgers (Princeton Research Oceanographer)

CICS/GFDL Collaborator: John Dunne (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 and the ocean carbon cycle

Methods and Results/Accomplishments:

Work over the last year has focused on application of the Large Initial Condition Ensemble suite of runs conducted with GFDL’s Earth system model ESM2M. The first stage of this work (Rodgers et al., 2015) and the second stage (Frölicher et al., 2016) presented a methodological framework for estimating uncertainties in projections in projections of ecosystems stressors, with the second of these having been accomplished through collaboration with Charles Stock at GFDL.

Newer work conducted over the last year has focused on several new topics, in collaboration with Sarah Schlunegger (PhD student of Jorge Sarmiento at Princeton) and John Dunne at GFDL. The initial phase of this collaborative work has focused on quantifying uncertainties in projections of ocean carbon pumps (solubility, soft tissue, and calcium carbonate) under future climate change through application of GFDL’s Earth system model ESM2M. A publication for this stage (with Sarah Schlunegger as first author) will be submitted in April 2018 to Nature Climate Change. The second stage involves a Large Ensemble Model Inter-comparison Project (LE-MIP) where the projections of emergence timescales for carbon pumps are compared amongst four ESMs from international modeling groups. The results of this work has advanced and been presented at an international conference, and it is expected that a manuscript will be submitted before the end of 2018.

Outreach Activities: A summer undergraduate intern was hosted last summer, Nicole Rinaldi (Princeton U., funded by the Princeton Environmental Institute).

Publications:

Progress Report Title: Seasonal Prediction of Estuarine Water Quality

Principal Investigator: Andrew Ross (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Charles Stock (GFDL), Keith Dixon (GFDL), Fernando Gonzalez-Taboada (Princeton)

Other Participating Researchers: Vincent Saba (NMFS)

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: Develop the capability to predict seasonal variations in water quality in Chesapeake Bay and other estuaries

Methods and Results/Accomplishments:

I began work in January 2018 to develop methods for making seasonal predictions of estuarine water quality and related properties. The initial focus of this project is on water quality in Chesapeake Bay, a large, productive, and economically important estuary located along the U.S. East Coast. Much of this work will leverage seasonal predictions of water temperature (SST) and salinity derived from GFDL’s FLOR (Forecast Oriented Low Resolution Ocean) model produced using statistical downscaling developed by collaborator Keith Dixon and additional statistical modeling developed by collaborator Fernando Gonzalez-Taboada.

I am currently conducting research with several goals: 1) Understanding causes of successful and unsuccessful seasonal climate forecasts. Seasonal forecasts of climate produced by FLOR are the foundation of the planned seasonal water quality forecasts. To understand where these forecasts may be skillful or unreliable, it is important to understand what aspects of the global climate system impact the local climate and whether these aspects can be predicted by FLOR. To do so, I am evaluating correlations between local and global climate in reanalysis data and comparing the results with similar correlations in FLOR forecasts. 2) Developing seasonal predictions of the occurrence of Vibrio species occurrence or infections. Muhling et al. (2017) created a system for projecting long-term changes in the occurrence of three Vibrio species. Since the three Vibrio species are sensitive to SST and salinity, occurrence or infections should be predictable at the seasonal scale given reliable predictions of SST and salinity. 3) Developing seasonal predictions of dissolved oxygen and hypoxia. Several previous studies have attempted predictions of summer dissolved oxygen in Chesapeake Bay. These studies have primarily relied on observed nitrogen loading during winter and spring to predict average summer hypoxia (e.g., Scavia et al., 2006). I am researching whether forecasts of summer climate conditions from GFDL’s FLOR model can be used to improve these seasonal forecasts. Future work may compare the results with dynamical ocean model simulations, such as those successfully used to predict hypoxic conditions one to two days in advance (Friedrichs et al., 2018).
References:

Presentations:
Progress Report Title: Constraining Aerosol Forcing from Land Surface Air Temperature Records

Principal Investigator: Zhaoyi Shen (Princeton Graduate Student)

CICS/GFDL Collaborator: Yi Ming (GFDL), Isaac Held (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: Integrate model simulations and observations to reduce the uncertainty in aerosol forcing

Methods and Results/Accomplishments:
Understanding the anthropogenic influence on regional climate change is important for policy making and adaption planning. Atmosphere/land global climate models (AGCMs) with prescribed oceanic boundary conditions allow a decomposition of historical climate change into a fast component that occurs on an atmospheric adjustment time scale of months or less, and a slow component due to changing ocean and sea ice. These two components are simultaneously present in comprehensive coupled climate models. The slow component contains much of the uncertainty in climate sensitivity and is where the forced signals are mixed most strongly with natural variability [e.g., Knutson et al., 2013]. Here we use AGCMs to investigate the fast component of the anthropogenic influence on regional temperature change. We analyze land surface air temperature changes since mid-20th century from observations and in historical simulations with different forcing agents using the Geophysical Fluid Dynamics Laboratory atmospheric model AM2 and AM3. Although the fast component of the anthropogenic warming is often thought of as small, we find that it is detectable in the observed warming of Northern Hemisphere land during summer and autumn in recent decades. We suggest that the fast response to aerosol forcing in isolation is significant on subcontinental scales.

Despite an improved understanding of aerosol processes and more observations of aerosol properties in recent years, uncertainties in the radiative effects of aerosols remain the dominant contributor to the overall uncertainty in anthropogenic forcing, and thus the response of the climate system [Boucher et al., 2013]. In this study we make a first attempt to constrain historical aerosol forcing from sustained observations of land surface air temperature using AGCMs. The lower internal variability in AGCMs allows one to analyze observed climate change on smaller spatial scales and shorter time scales. The fast response of the land surface air temperature to aerosol forcing in recent decades is significant in Europe and less robustly in Asia. Preliminary results show that the more negative aerosol forcing may be more realistic. The implications on aerosol forcing would be more reliable if this kind of AGCM simulation, with and without aerosol forcing, were made available for multiple climate models.

Outreach Activities: Participated in the 12th annual Monmouth Junction Elementary School Science Fair

References:

Publications:

Presentations:
Progress Report Title: Potential Sources for Extended Weather Predictability

Principal Investigator: Yongqiang Sun (Princeton Postdoctoral Research Associate)

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

Other Participating Researchers: Kun Gao (Princeton), Fuqing Zhang (PSU)

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: Identify periods and regions of increased weather predictability (“forecasts of opportunity”)

Methods and Results/Accomplishments:

The sub-seasonal to seasonal prediction (S2S) project database (Vitart et al 2017) is explored in order to separate periods of extended predictability for different regions (with a focus on the CONUS) from periods of relative low predictability. Composites of these periods are then compared to understand the physical mechanisms behind different weather predictability behaviors. We focus on the teleconnections (interactions) between midlatitudes and tropics, especially the linkage between mid-latitude weather predictability and the MJO (both its phase and amplitude). The tropical diabatic heating spectrum is shown to have a strong impact on the mid-latitude weather pattern at sub-seasonal time scales. The robustness of this linkage and the interaction pathways will also be investigated using datasets from different operational centers.

The performance of Geophysical Fluid Dynamics Laboratory (GFDL) High-resolution Atmospheric Model (HiRAM) and the Next Generation Global Prediction System with FV3 dynamic core in capturing these pathways will be evaluated and examined in detail to maximize their potential for sub-seasonal prediction.

References:

**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:** Nicolas Van Oostende (Princeton), Charles Stock (GFDL), John Dunne (GFDL)

**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:** Represent observed (phyto)plankton community size structure in both oligotrophic and eutrophic (spring bloom-type) marine environments. Despite their general success, state of the art biogeochemical models have significant biases for some important biological events. Here we investigate whether revised parameterization of physiological characteristics and a slightly more complex model foodweb structure can improve the skill of models to simulate observations of the timing and magnitude of the subarctic North Atlantic spring bloom and the depth of the chlorophyll maximum in oligotrophic oceans.

**Methods and Results/Accomplishments:**

The approach is based on results from our previous CICS-supported work in collaboration with C. Stock (GFDL) and R. Dussin (Rutgers University) which, for the first time, successfully simulated the chlorophyll concentration gradient of >3 orders of magnitude from oligotrophic to highly productive coastal upwelling along the west coast of North America (Van Oostende et al. in review). The simulation of peak chlorophyll levels (~3-10 mg m⁻³) during coastal upwelling was accomplished by adding a third phytoplankton size group, representing large or chain-forming diatoms, and by changing the mesozooplankton grazing interactions in the baseline COBALT model accordingly. This approach was supported and guided by field observations, theoretical concepts and results from coastal upwelling mesocosm simulation experiments (Chisholm 1992, Thingstad 1998, Raimbault et al. 1988, Irigoien et al. 2004, Van Oostende et al. 2015). We hypothesize that the increased resolution of the phytoplankton communities offered by a third phytoplankton size class, which has different light harvesting characteristics and higher grazing resistance, can also address biases in spring bloom dynamics while preserving deep chlorophyll maxima, to simultaneously match both of these large-scale features in the model.

The COBALT version we created for the current project with three phytoplankton size classes, rather than two for the regional application, has been encoded to run in a global simulation. Our baseline experiment will be a coarse resolution (1 degree) using the new MOM6 COBALT-CORE experiment based on Stock et al. (2014). This will allow us to test the sensitivity of results to new MOM6 configurations with improved mixed-layer dynamics. The skill of the new model configuration will be tested by performing observation-bias and sensitivity analyses using e.g., *in situ* chlorophyll profiles from
the Bermuda Atlantic Time-Series for the subtropics and using remote sensing time series such as SeaWiFs for the subarctic spring bloom. Should the comparisons with these data sets indicate the need for further refinement of the phytoplankton physiological traits, we will assess the model performance in terms of trade-offs, e.g., the metabolic costs such as C respiration, associated with maintaining high chlorophyll-to-C ratios or light affinity depending on the dynamics of the light (Shuter 1979; Geider et al. 2009; Talmy et al. 2013). That is, we will consider whether both an additional functional type and additional physiological complexity are needed to eliminate model biases, or if an additional group with similar physiological complexity is sufficient. Success in reducing bloom and deep chlorophyll biases to a degree similar to that accomplished in our work in the California Current Ecosystem (Van Oostende et al., in review) could make this an integral part of the future CMIP model evaluations.

**Outreach Activities:** A graduate student performed work in the lab on projects related to the CICS project. She grew subtropical *Synechococcus* strains in order to assess the impact of temperature and light limitation for future use in ecosystem models. The graduate student met regularly with Ward and Van Oostende and was 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 Introductory Oceanography course for science majors. Student evaluations listed this module as their favorite, because of the hands-on experience and the opportunity to generate real data.

**References:**


**Publications:**


Presentations:


Progress Report Title: Geoengineering Outlet Glaciers and Ice Streams

Principal Investigator: Michael Wolovick (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Olga Sergienko (Princeton)

Other Participating Researchers: John Moore (Beijing Normal University and University of Lapland, Finland)

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 the possibility of using geoengineering to prevent or slow sea-level rise from the marine ice sheet instability

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.

Over the past year, I have written, revised, and submitted for publication a manuscript describing the potential for targeted geoengineering to counteract the marine ice sheet instability. I have begun collaboration with Dr. John Moore of Beijing Normal University and the University of Lapland on this project, and I visited Dr. Moore's research group in Beijing from Nov. 10-20 to further this collaboration. We submitted the manuscript for publication in Science shortly thereafter; unfortunately, it was rejected from that publication. Based on the feedback from those reviews, we revised the manuscript extensively and resubmitted for publication at PNAS. Unfortunately, it was rejected there as well. We are currently revising the manuscript for resubmission yet again. Over the course of these revisions we have run additional model tests and have explored the efficacy of a variety of different interventions. I have also revised all parts of the manuscript extensively, including an in-depth discussion of the societal issues and costs associated with targeted geoengineering. I have also collaborated on a Nature Comment lead-authored by Dr. Moore which calls for more research into glacial geoengineering in general. This comment was published in March of 2018.

Interview with reporter for News Deeply, resulting in publication of the following article:
Publications:


Presentations:


Progress Report Title: Understanding 2014-2016 Record Warm Global Mean Surface Temperatures

Principal Investigator: Jianjun Yin (Princeton Visiting Faculty)

CICS/GFDL Collaborator: Stephen Griffies (GFDL), Ronald Stouffer (GFDL, retired)

Other Participating Researchers: Jonathan Overpeck (UMichigan), Cheryl Peyser (UAzizona)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GF DL)

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 large record-breaking event of global mean surface temperature (GMST) during 2014-2016 (Figure 1) and the underlying mechanism, and to provide the 21st century projections of such events under different greenhouse-gas emission scenarios

Methods and Results/Accomplishments: In this study, we analyze various observational datasets including six GMST datasets (Figure 1), three ocean temperature and heat content datasets, sea level data from satellite altimetry and tide gauges, as well as other important long-term climate variability indices. All the data show in concert that the large 2014-2016 jump of record warm GMST was mainly induced by a rapid release through the recent strong El Niño of unusually large amounts of ocean heat from the subsurface layer of the northwestern tropical Pacific. This heat had built up since the 1990s mainly due to greenhouse-gas forcing and possible remote oceanic effects.

With 40 CMIP5 models, we also systematically analyze large record-breaking events of GMST in the 20th century simulations and 21st century projections. For the first time, we quantify and compare these important statistics of global warming in the model simulations and projections. Our results indicate that the fundamental cause, and robust predictor of large record-breaking events of GMST during the 21st century, is the greenhouse-gas forcing rather than internal climate variability alone. Such events will increase in frequency, magnitude, and duration, as well as impact, in the future unless greenhouse-gas forcing is reduced.

Outreach Activities: Media coverage
https://uanews.arizona.edu/story/record-jump-20142016-temps-largest-1900

Presentations:

Figure 1. Time series of six GMST datasets and the mean of the six datasets. The red dots denote record-breaking years of GMST after 1980. See Yin et al. (2018) for details.
Progress Report Title: Variability and Predictability of North American Climate Arising from the Tropics

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 quantify how much climate (e.g., precipitation) variability over North America (or mid-latitudes in general) originate (through atmospheric teleconnection) from tropical climate variability on interannual and longer time scales, and assess the associated implications for the predictability of North American (or mid-latitude) climate variability.

Methods and Results/Accomplishments:

Many previous studies have shown an important role of tropical variability (e.g., ENSO, PDO) in the precipitation variability and predictability over North America (see Seager and Ting, 2017 for a review). However, recent analysis and observations have shown North American monthly precipitation variability is dominated by local atmospheric internal dynamics and atmosphere-land interactions, which is contradictory with previous results. To address this disagreement, I have designed a set of AMIP-type experiments to quantify the relative role of tropical ocean variability versus global atmospheric variability in precipitation over North America (and extratropics in general). The method is to compare a control experiment forced by global climatological boundary conditions with experiments forced by sinusoidal sea surface temperature (SST) anomalies imposed to the tropics. The advantage of this experimental design lies in the simplicity of prescribed sinusoidal forcing (with a specific period and uniform pattern) that can be readily detected compared to ENSO signal (without a definite period).

I have conducted, with the GFDL AM2.5, a 1000-year control simulation and six 100-year forced simulations. The forced simulations have the same sinusoidal period of 3 years (to mimic ENSO) but differ in their amplitude and region where the forcing is imposed. In the first three simulations, the sinusoidal SST forcing is imposed in the whole tropics (5°N~5°S with a 5° linear buffer zone), but has different amplitudes: 0.5K, 1K and 2K; in the other three simulations, the SST forcing has the same 1K amplitude, but is imposed in different oceans: tropical Pacific, Indian and Atlantic.

Preliminary analysis shows that the imposed tropical forcing has limited impacts on the variance of monthly precipitation in the extratropics (See Figure). For example, over North America, the imposed SST forcing in the whole tropics with a 2K amplitude slightly enhances the monthly precipitation variance at the prescribed 3-year frequency, with the largest increase of less than 20% over southwestern North America. Further analysis will be conducted to assess the changes in the probability distribution of monthly precipitation caused by the imposed tropical forcing.

During the past year in addition to the above ongoing research, I have published two papers on the robustness of anthropogenically forced decadal hydroclimate changes (see below).
**Figure.** The percentage of the variance of monthly precipitation at the 3-year frequency explained by the imposed 3-year sinusoidal SST forcing over the whole tropics (10N-10S).

**References:**

**Publications:**

**Presentations:**
Zhang, H., 2017 AGU Fall meeting, oral presentation: Detectability of Decadal Anthropogenic Hydroclimate Changes over North America.
Zhang, H., 2018 AMS annual meeting, oral presentation: Detectability of Decadal Anthropogenic Hydroclimate Changes over North America.
Progress Report Title: Decadal Variability and Predictability

Principal Investigator: Liping Zhang (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Tom Delworth (GFDL), Richard G. Gudgel (GFDL), Fanrong Zeng (GFDL)

Other Participating Researchers: Xiaosong Yang (UCAR)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: V. Ramaswamy (GFDL)

Theme: Earth System Model Applications

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

Objectives: To understand the role of natural internal Southern Ocean (SO) variability in the observed SO trends in recent years; to access the decadal prediction skill of Southern Ocean SST and its associated climate impacts

Methods and Results/Accomplishments:

We investigated the potential physical drivers responsible for the observed Southern Ocean (SO) SST and sea ice trends in recent decades. This is a critical goal in climate science especially with the importance of the SO for the uptake of heat and carbon from the atmosphere. Observations suggest a weakening of SO convection and deep-water formation between the 1980s and 2000s, coincident with the surface overall cooling trend and increasing sea ice. Here we find that these observed trends are consistent with a particular phase of the natural multidecadal variability of SO deep convection as derived from climate model simulations. Ensembles of climate change simulations are conducted starting from different phases of this variability. Simulations started from an active phase of SO convection, such as may have occurred in the 1970s, can reproduce the observed pattern of SST and sea ice trends, particularly during the warm season (DJFMAM). In contrast, simulations initialized from an inactive phase of SO convection do not reproduce the observed changes and are similar to the results of most climate models used in the CMIP5 ensemble. We argue that the natural multidecadal variability of SO deep convection could modulate the transient climate response to anthropogenic forcings, and that weakening of SO deep convection is a potential driver for observed SST and sea ice trends over the SO.

Publications:


Zhang, Liping, Thomas L. Delworth, William Cooke and Xiaosong Yang, 2017: Natural variability of Southern Ocean convection as a driver of observed climate trends. (Submitted to Nature climate change).
Presentations:

Figure 1: Annual SST and sea ice time series and trends. (a) Time series of Southern Ocean (SO) area mean (50°-70°S) SST (°C) anomalies over 1890-2012 and sea ice extent (SIE, 10¹² m²) anomalies over 1979-2012. These anomalies are with respect to their long term mean values. The SST data are from Hadley Centre Sea Ice and Sea Surface temperature (HadISST; magenta line) and Extended Reconstructed Sea Surface Temperature (ERSST; Red line) version 3. The sea ice data are from HadISST (green line) and National Snow and Ice Data Center (NSIDC, blue line). (b) SST trend in HadISST over 1979-2012. (c) Sea ice concentration (SIC) and SLP trends in NSIDC over 1979-2012. (d) SST and (e) SIC/SLP trends in ensemble mean results of SPEAR_AM2 historical run over 1979-2012. Units are °C/30-yr for the SST trend, 100%/30-yr for the SIC trend and hPa/30-yr for the SLP trend. Stippling on trends means the trend is significant at the 95% level based on two-sided Student’s t-test.
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*Including Presentations
2017-2018 Peer-Reviewed Publications


• MacKinnon, Jennifer; Matthew Alford; Joseph K Ansorg; Brian K Arbic; Andrew Barna; Bruce P. Briegleb; Frank O. Bryan; Maarten C. Buijsman; Eric P. Chassignet; Gokhan Danabasoglu; Steve Diggs; Peter Gent; Stephen M. Griffies; Robert W. Hallberg; Steven R. Jayne; Markus Jochum; Jody M. 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, doi:10.1175/BAMS-D-16-0030.1.


2017-2018 Non Peer-Reviewed Publications/Presentations


• Balaji, V. Workshop on the Future of Earth System Modeling, Caltech and JPL Center for Climate Sciences, 8 November 2017: Modeling Systems at the end of Dennard Scaling.


• Balaji, V. NOAA Big Data Project invited talk, 2 June 2017: Climate Science on the Cloud.


• Hazleton, A. T. and M.A. Bender, 2018: Global and Nested fvGFS Performance on Tropical Cyclones, HFIP Weekly Telecon.

• Hsieh, Tsung-Lin. A quasi-steady baroclinic eddy with hypohydrostatic convection, 21st Conference on Atmospheric and Oceanic Fluid Dynamics, June 2017, Portland, OR.

• Jeevanjee, Nadir. Vertical Velocity in the Gray Zone, poster presentation at WGNE workshop on systematic errors in weather and climate models, June 2017, Montreal, Canada.

• Jeevanjee, Nadir. Vertical Velocity in the Gray Zone, oral presentation at AMS Atmosphere and Ocean Fluid Dynamics conference, June 2017, Portland, OR.

• Johnson, N. C. (January 2018). Hybrid dynamical-statistical S2S forecasts with weather types over North America. 98th AMS Annual Meeting.


• Johnson, N. C. (August 2017). Bridging the gap in NOAA’s extended and long range prediction systems through the development of new forecast products for weeks 3 and 4. NOAA NGGPS/MAPP PIs Meeting in College Park, Maryland. Invited.


• Krishnamurthy, L., Poster presented at GFDL poster EXPO on February 2018 titled, Seasonal forecast skill of the Indian monsoon in GFDL high-resolution forecast system.

• Krishnamurthy, L., Poster presented at NMME/SubX Science Meeting on September 2017 titled, Seasonal forecast skill of the Indian monsoon in GFDL high-resolution forecast system in College Park, Maryland.


• Legg, Sonya, Einar Povl Abrahamsen, Christian E. Buckingham, Alexander Forryan, Eleanor Frajka-Williams, Stephen Matthew Griffies, Michael Paul Meredith, Alberto Naveira Garabato, Keith W Nicholls, Sarah Nickford, Kurt L Polzin, Jean-baptiste Sallee and Carl Spingys: Numerical Simulations of Mixing in Dense Water Flowing through the Orkney Passage, Ocean Sciences meeting 2018.
• Li, D., Anthropogenic Changes in Mid-latitude Storm and Blocking Activities from Observations and Climate Models, AGU Fall Meeting. New Orleans, LA, December 2017.

• Lin, M.Y., Feb 22, 2018, NOAA Climate Program Office Director Visit to GFDL: Heat waves, drought, and air quality.

• Lin, M.Y., Feb 12, 2018, NOAA OAR’s Director of Weather and Air Quality John Cortina’s Visit to GFDL: Atmospheric chemistry and connection to Earth system modeling.


• Lin, P., and Y. Ming, 2017: Simulating climate change with interactive stratospheric ozone. Talk. AGU Fall meeting, American Geophysical Union, New Orleans, LA.


• Melet, Angelique, Robert Hallberg, Sonya Legg, Adrien Lefauve, Caroline j Muller, Maxim Nikurashin, Alistair Adcroft and Kurt L Polzin: Climatic Impacts of Parameterized Internal-wave Driven Mixing, Ocean Sciences meeting 2018.

• Metcalf, Jessica, Oct 2017. Climate drivers of infectious disease: disentangling direct and indirect effects Invited Talk. Earth Systems Science Center, Stanford University, USA.


Park, J.-Y., Global integration of ocean biogeochemistry with data assimilative ocean physics, 2018 Ocean sciences meeting, Portland, OR, USA.


Popp, M., Silvers, L. G. Shifting the ITCZ with longwave and shortwave cloud-radiative effects. EGU General Assembly 2017, 23rd-28th of April 2017, Vienna, Austria POSTER.

Popp, M., Lutsko, N. J., Quantification of the zonal-mean structure of tropical precipitation, CFMIP Meeting, 25th-28th of September 2017, Tokyo, Japan POSTER.

Pu, B., and P. Ginoux, 2017: Climatic factors contributing to long-term variations of fine dust concentration in the United States, the American Geophysical Union (AGU) fall meeting, New Orleans, LA.


- Shao, Andrew. Ocean Sciences Meeting 2018, OM44C-2136: Improvements to an Extrema-diminishing, Density-preserving Lateral Diffusion Algorithm, Portland, OR, USA.


- Silvers, L.G. 2017, Seminar, McGill University, Montreal, Canada, October. Invited Talk.

- Silvers, L.G. 2017, Seminar, Stony Brook University School of Marine and Atmospheric Science, Stony Brook, NY, March. Invited Talk.


• 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.


• Sulman, B. N., N acquisition strategies determine ecosystem responses to elevated CO2 in the GFDL global land model. 5th iLEAPS Science Conference, Oxford, United Kingdom, Sept 2017.


• Yan, Xiaoqin, Poster presentation ‘The Role of AMOC in the Recent Decline of Atlantic Major Hurricane Frequency’ at GFDL 2018 Poster Expo, January 2018.


Zeng, Yujin, Effects of lateral groundwater flow and water resources exploitation on land surface and climate, North American Land Data Assimilation System Telecon, USA, February 2018.

Zhang, H., 2017 AGU Fall meeting, oral presentation: Detectability of Decadal Anthropogenic Hydroclimate Changes over North America.

Zhang, H., 2018 AMS annual meeting, oral presentation: Detectability of Decadal Anthropogenic Hydroclimate Changes over North America.


2017-2018 Ph.D. Theses


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

<table>
<thead>
<tr>
<th>Name</th>
<th>Rank</th>
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</thead>
<tbody>
<tr>
<td>Curcio, Joanne</td>
<td>Communications Coordinator</td>
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<tr>
<td>Feibush, Eliot</td>
<td>Visualization/Computational Scientist</td>
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<tr>
<td>Kirton, Lisa</td>
<td>Administrative Assistant</td>
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<tr>
<td>Legg, Sonya</td>
<td>Associate Director</td>
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<tr>
<td>Sarmiento, Jorge L.</td>
<td>Director</td>
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<tr>
<td>Valerio, Anna</td>
<td>Graduate Student Administrator</td>
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QUEST SUMMER INSTITUTE-OUTREACH SUPPORT

<table>
<thead>
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<tbody>
<tr>
<td>Carson, Steve</td>
<td>Summer QUEST Facilitator</td>
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<td>Friend, Martha</td>
<td>Summer QUEST Lead Teacher</td>
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<td>Hill, Michelle</td>
<td>Summer QUEST Lead Teacher</td>
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SUMMER STUDENT RESEARCH INTERNS

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<tr>
<td>Boaggio, Katie</td>
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<td>Lloveras, Daniel</td>
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<td>Mikulak, Haylie</td>
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<tr>
<td>Cardinale, Caroline</td>
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<tr>
<td>Yi, Young Ro</td>
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Departures - Task II

Ruprich-Robert, Yohan-5/4/17: Barcelona Supercomputer Center
Mastrorocco Marques, Gustavo-6/9/17: NCAR, Project Scientist
Popp, Max-6/30/17: Laboratory of Dynamic Meteorology (LMD), Postdoc
Jeevanjee, Nadir-7/31/17: Princeton University, Hess Fellow
Kam, Jonghun-8/15/17: University of Alabama-Tuscaloosa, Assistant Professor
Ray, Sulagna-8/31/17: University of Connecticut, Postdoctoral Research Associate
Laufkotter, Charlotte-8/31/17: University of Bern, Postdoctoral Associate
Schnell, Jordon-9/4/17: Northwestern University, Postdoc
van Huijgevoort, Marjolein-9/7/17: KWR, The Netherlands, Scientific Researcher
Marianne Haseloff-9/17/17: Oxford University, Postdoctoral Research
Ward, Daniel-9/30/17: Karen Clark & Company, Senior Meteorologist
Gonzalez Taboada, Fernando-11/16/17: Princeton University, Associate Research Scholar
Malyshev, Sergey-11/10/17: NOAA/GFDL, Physical Scientist
Shao, Andrew-12/31/17: University of Victoria, Postdoctoral Associate
Munoz, Angel Garikoitz-1/16/18: IRI, Columbia University, Associate Research Scientist
Li, Dawei-1/31/18: Rutgers University, Postdoctoral Associate
Sulman, Benjamin-2/28/18: University of California, Merced, Project Scientist
Ph.D. Defenses

Student: Robert Nazarian (December 2017)
Advisor: Sonya Legg
Dissertation: Internal Wave Scattering in Continental Slope Canyons
Present Affiliation: Lecturer in Geosciences, Princeton University

Student: Nicholas Lutsko (June 2017)
Advisor: Isaac Held
Dissertation: Aspects of Eddy Momentum Fluxes in the General Circulation of the Troposphere
Last Known Affiliation: Postdoc, MIT

Student: Anna FitzMaurice (January 2018)
Advisor: Robert Hallberg
Dissertation: Parameterizing the Melting of Icebergs in Global Climate Models
Present Affiliation: Machine Learning/Data Scientist, eQualitie, Montreal
### Task II: Cooperative Research Projects and Education Supported Personnel

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<tr>
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<tr>
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**Task II: Cooperative Research Projects and Education Supported Personnel CONTINUED**

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<tr>
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<td>Sergienko, Olga</td>
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<td>Shevliakova, E.</td>
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<td>Zhou, Linjiong</td>
<td>Postdoctoral Research Associate</td>
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**Task II: Cooperative Research Projects & Education Supported Personnel (Visiting Faculty)**

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<tr>
<td>Huang, Yi</td>
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<td>Zanna, Laure</td>
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### Task III: Individual Research Projects Supported Personnel

<table>
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<tr>
<td>Chou, Cleo</td>
<td>Postdoctoral Research Associate</td>
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<td>Dussin, Raphael</td>
<td>Rutgers Research Associate</td>
<td>Curchitser, E./Stock, C.</td>
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<tr>
<td>Fenley, Andreia</td>
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<td>Fueglistaler, Stephan</td>
<td>Professor</td>
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<td>$ 17,180²⁵</td>
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<td>Using Models to Improve our Ability to Monitor Ocean Uptake of Anthropogenic Carbon (Task III)</td>
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CICS FY’18 List of Awards for Institutional Award NA14OAR4320106

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<td>Cooperative Institute for Climate Science – Task III</td>
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<tr>
<td>PI: Jorge L. Sarmiento</td>
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