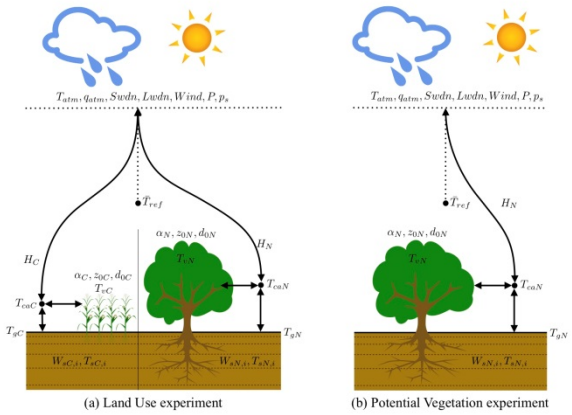
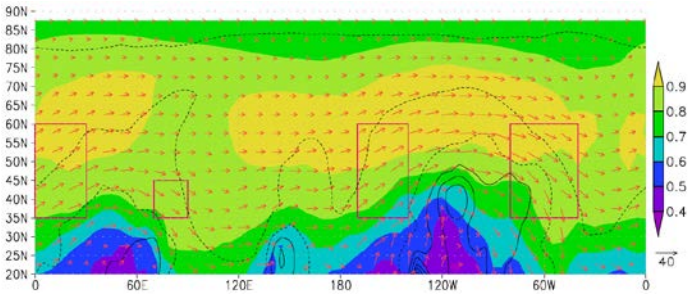
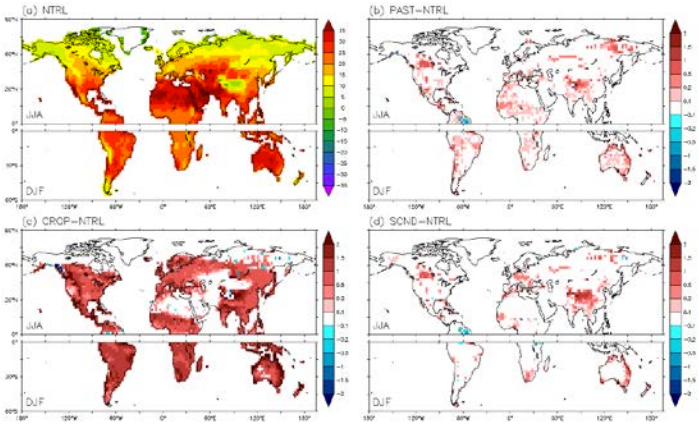


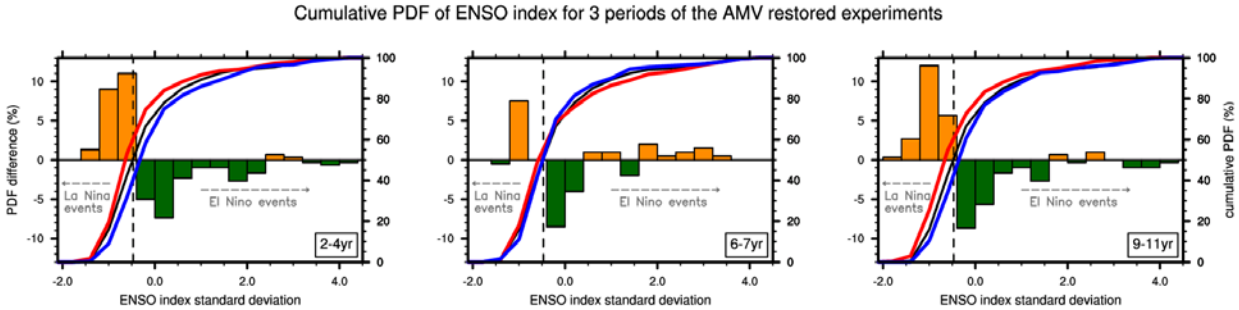
Annual Progress Report
April 1, 2014 – March 31, 2015

Cooperative Institute for Climate Science
at Princeton University
NOAA Cooperative Agreements
NA08OAR4320752 & NA14OAR4320106





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



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Cooperative Institute for Climate Science
Princeton University

Annual Progress Report under cooperative agreements NA08OAR4320752 & NA14OAR4320106

For the period April 1, 2014 – March 31, 2015

Introduction

The Cooperative Institute for Climate Science (CICS) was established in 2003 to foster research collaboration between Princeton University and the Geophysical Fluid Dynamics Laboratory (GFDL) of the National Oceanographic and Atmospheric Administration (NOAA).

The mission of CICS is to focus the core scientific competencies of Princeton University into answering key questions related to the sciences of climate change and Earth System Modeling, and so provide an effective bridge between the two institutions.

The overall vision of CICS is to:

> *be a world leader in understanding and predicting climate and the environment, integrating physical, chemical, biological, technological, economic and social dimensions, and in educating the next generations to deal with the increasing complexity and importance of these issues*.

CICS is thus built upon the strengths of two outstanding institutions and the ties between them: **Princeton University** in biogeochemistry, physical oceanography, paleoclimate, computer science, hydrology, climate change mitigation technology, economics and policy, and **GFDL** in numerical modeling of the atmosphere, oceans, weather and climate. CICS proposes research that, when combined with the ongoing activities at GFDL, is intended to produce the best and most comprehensive models of the Earth System, and therefore enable NOAA to deliver a new generation of products to decision makers.

To summarize, the main goals of this cooperative institute are as follows:

1. To aid in the development of GFDL's Earth system model by providing expertise in its constituent components, particularly in ocean modeling and parameterizations, in ocean biogeochemical cycling and ecology, in land modeling and hydrology, in understanding the interactions within and among the various components of the Earth system, and in the computational infrastructure that binds all the components together in a model.

2. To use the Earth system model and its component parts, to address problems in climate change and variability on decadal and longer timescales. This includes using the model and observational data to assess the state of the Earth system, and to provide projections of the future state of the system.

3. To educate and train future generations of scientists for NOAA and the nation as a whole, by providing access to a graduate degree program and a postdoctoral and visiting scientist program that provide academic training and a hands-on opportunity to work with NOAA scientists at a NOAA facility.

Research Themes Overview

CICS has three research themes all focused around the development and application of earth systems models for understanding and predicting climate.

Earth System Modeling and Analysis

Climate modeling at Princeton University and GFDL is continually producing new models, including atmospheric, oceanic and land models, coupled models, chemistry-radiative forcing models, cloud resolving models with new microphysics, and a non-hydrostatic limited area model. These models may, in principle, be appropriately combined to give what might be called an *Earth System Model*, or *ESM*. Such models, by definition, seek to simulate all aspects — physical, chemical and biological-of the Earth system in and above the land surface and in the ocean. Thus, an Earth System Model consists of, at least:

1. An atmospheric general circulation model, including a dynamical core for the fundamental fluid dynamics and water vapor, a radiation scheme, a scheme for predicting cloud amounts, a scheme for aerosols, and various parameterization schemes for boundary layer transport, convection and so forth.

2. An oceanic general circulation model, including a dynamical core, various parameterization schemes for boundary layers, convection, tracer transport, and so on.

3. A sea-ice dynamics model, for the modeling and prediction of sea ice.

4. An atmospheric chemistry module, for predicting chemically active constituents such as ozone.

5. A land model, for land hydrology and surface type, and a land ice model.

6. Biogeochemistry modules for both land and ocean. These may be used, for example, to model the carbon cycle through the system.

7. A computational infra-structure to enable all these modules to communicate and work together efficiently.

The goal of Earth System Modeling development at CICS and GFDL is, then, to construct and appropriately integrate and combine the above physical and biogeochemical modules into a single, unified model. Such a model will then be used for decadal to centennial, and possibly longer, studies of climate change and variability (as described primarily in the ‘applications’ section). At present, such a model does not exist in final form, and improvements are needed in two general areas:

1. Improvement on the physical side of the models, in the ocean, atmospheric, sea ice and land components.

2. Further incorporation of biological and chemical processes into the model, and ecosystem modeling.

Both of these are continual undertakings, that can never be said to be complete, although at various stages the development of a component, or a complete model, may be ‘frozen’ to allow numerical experiments to take place in a stable environment.

Developing and testing such ESMs is an enormous task, which demands a significant fraction of the resources of CICS and GFDL. Further, at any given time, model development depends on existing knowledge of how systems behave, but for that development to continue, our body of knowledge and understanding must also increase correspondingly, and without that, model development would stagnate. That is to say, one might regard ESM development as both a scientific and engineering enterprise, and proper attention and respect must be paid to both aspects. The contributions and goals of CICS might be divided into the following two general areas:

1. Development of modules (or components) for the Earth System Model (for example, the land model and parts of the ocean model), in collaboration with GFDL scientists. Note that not all of the modules above involve CICS scientists; rather, CICS complements rather than duplicates GFDL efforts. For example, the dynamical core of the atmospheric model, the Sea-ice model, and many of the physical parameterizations of the atmospheric model, have been and will continue to be developed primarily at GFDL itself. This document focuses on those components to which CICS is directly contributing.

2. Seeking improved understanding of the behavior of components of the Earth system, and the interaction of different components, thereby aiding in the long-term development of ESMs. These aspects involve comparisons with observations, use in idealized and realistic situations, and development of new parameterizations and modules. The development of ESMs is a research exercise, and is crucially dependent on continually obtaining a better understanding of the ocean-atmosphere-ice-land system.

Data Assimilation

Data assimilation, also known as state estimation, may be defined as the process of combining a model with observational data to provide an estimate of the state of the system which is better than could be obtained using just the data or the model alone. Such products are necessarily not wholly accurate representations of the system; however, especially in data-sparse regions of the globe and for poorly measured fields, the resulting combined product is likely to be a more accurate representation of the system than could be achieved using only the raw data alone. (Of course, this in turn means the products contain biases introduced by whatever model is used.)

The process of combining data and model has grown increasingly sophisticated over the years, beginning with optimal-interpolation and three-dimensional variational data assimilation (3D-Var). Currently, most centers use 4D-Var (with time as an additional variable) and ensemble Kalman filter methods. All these methods are essentially least-squares methods or variations of least-squares methods, with the final estimate being chosen to minimize the appropriately chosen ‘distance’ between the final estimate, the data and a model prior. The difference between the various methods lies in the choice of the metric used to measure distance and the corresponding weight given to the observations and the prior estimate, and in the choice of which fields or parameters are allowed to be adjusted in order to produce the final estimate. Modern methods generally allow the error fields to evolve in some fashion, so allowing a dynamic estimation of the error covariances and a better estimate of the appropriate weights. The literature is extensive; see Kalnay (2003) and Wunsch (2006) for reviews.

There is a long history of data assimilation in meteorology, largely associated with weather forecasts: data from satellites, radio-sondes and other sources are combined with a model estimate from a previous forecast, to provide the initial state for a subsequent forecast. Re-analysis products are now available that combine model and data over the last fifty or so years into a single, consistent product. The application of data assimilation methodology in oceanography is more recent, reflecting in part the relative sparsity of data in the ocean and so the likely large errors inherent in any such analysis. However, with the advent of

near-routine observations from satellites (e.g., altimeters) and profiler drifters (e.g., the Argo float system), a much higher density of observations is possible and ocean data assimilation has become a practical proposition. This is important because it is the initial state of the ocean, and not the atmosphere, that will largely determine the evolution of the ocean and the climate on the decadal and longer timescales, and so determining the natural variability of the climate. Still more recently, inverse modeling, an optimization technique closely related to data assimilation, has been applied to oceanic and terrestrial biogeochemical fields – for example, CO2, CH4, and CO – in an attempt to constrain the carbon budget. Here, the field is still in its infancy.

Analogous to the development of ESMs, data assimilation in ESMs has many components, and research in CICS focuses on a subset of these, as follows.

• Ocean data assimilation in climate models. By estimating the ocean state using all available data (including ARGO, altimetry, and hydrographic sections), the detection and prediction of climate change and variability on decadal timescales is enabled.

• High resolution ocean data assimilation, both to gain experience in this activity for the next generation of ocean climate models and for present-day regional models.

• Ocean tracer inversions for determining water mass properties, pathways, and sources and sinks of biogeochemical tracers, and to evaluate the ocean component of the Earth system model.

• Analyzing satellite observations of ocean color to elucidate ocean ecosystem processes.

• Atmospheric inversions for estimating high-quality, time-dependent flux maps of CO2, CH4, and CO to the atmosphere from tracer observations in the atmosphere and oceans, to evaluate the sources of these tracers and elucidate source dynamics.

• Use of terrestrial ecosystem carbon dynamics to evaluate carbon fluxes and help evaluate ESM parameter variability.

The overall goal of this activity is to collaborate with GFDL to create a capability whereby data can be combined with an Earth system model to provide a better assessment of the state of the current Earth system, and that can be used to provide forecasts of the future state of the system.

Earth System Modeling Applications

The development and the use, or the *applications*, of an Earth System model must proceed hand-in-hand, and in this section we focus on how the ESM will be used to address problems of enormous societal import. The problems we focus on involve decadal and centennial timescales, the interaction of natural and anthropogenically-forced variability, and the changes and impacts on the environment that affect society. *The overall goal of this activity is to use the Earth system model, in whole or in part, to investigate problems associated with climate change and its impacts on timescales of a decade or longer*.

The applications may be conveniently divided into three general areas:

1. Applications involving one or two individual components of, the ESM — for example, integrations of the ocean general circulation model to better understand the large-scale circulation, and how it might respond to global climate change, or integrations involving the ocean circulation and the biogeochemical tracers within it.

2. Applications involving the physical components of climate system; coupled ocean-atmosphere-land-ice models. These are the traditional 'climate models', and will remain of singular importance over the lifetime of this proposal.

3. Applications involving the ESM as a whole. Typically, these involve the biological and biogeochemical components of the model, for these depend also on the physical aspects of the model and therefore require many model components.

In all of the above areas both idealized and realistic model integrations are being performed: the former to better understand the behavior of the models and the interactions between their components, and the latter to give the best quantitative estimates of the present and future behavior of the Earth system. As with the other themes, CICS seeks to complement GFDL activities by providing expertise in distinct areas, typically those that are concerned with the dynamics of subsystem (e.g., the ocean circulation and its biogeochemistry and the land) where CICS has particular expertise, or that are concerned with understanding the interactions between those systems. Applications involving integrations of the comprehensive, state-of-the are ESM that are aimed at providing quantitative measures of the present and future state of the Earth system, for example for future IPCC assessments, are carried out as part of a close collaboration with GFDL.

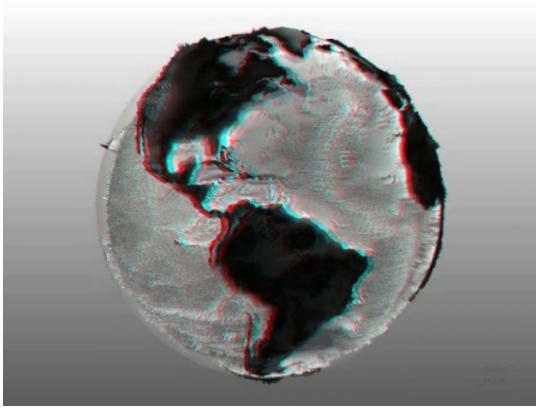
Education/Outreach

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.

Art of Science

AOS co-sponsored the Art of Science 2014, a competition that explores the interplay between science and art. The 2014 competition drew more than 250 submissions from 25 departments across the University. The exhibit includes work by undergraduates, graduate students, postdocs, faculty, staff, and alumni and consists of 44 still images and 12 videos of artistic merit created during the course of scientific research. This is the first Art of Science competition to include a video category. Martin Jucker, an AOS Associate Research Scholar who won first prize in the 2013 competition for his still image *East-West, West-East*, was a finalist in this year's video category for his video entry *Fly Me*. Entries were chosen for their aesthetic excellence as well as scientific or technical interest.

First Prize Image: Watermarks
Sara Sadri, Civil and Environmental Engineering



Finalist in Video Category: Fly Me
Martin Jucker, Atmospheric and Oceanic Sciences

The physical gallery of the 2014 exhibit was on view in the Friend Center on the Princeton University campus through the end of April 2015. The Art of Science online galleries can be found at: http://artofsci.princeton.edu/.

CICS Summer Internship

During the summer of 2014, CICS supported summer intern Nathan Serota, a recent Princeton graduate. Nathan worked with CICS scientist Elena Shevliakova and GFDL scientist Larry Horowitz on the analysis of the aerosol-land carbon cycling interactions over the historical period, and in the near future, as simulated in the GFDL atmospheric general circulation model AM3. The model has advanced treatment of aerosol physics as well as land carbon cycle processes. Nathan had done preliminary analysis of existing historical experiments in his senior thesis; however, these earlier experiments were not forced consistently and did not save all of the necessary outputs to perform the analysis of changes in the terrestrial carbon cycle in detail. The new set of experiments with expanded diagnostics and consistent forcing settings was performed. Nathan and his collaborators are preparing a manuscript to document their findings. CICS funding covered his summer stipend.

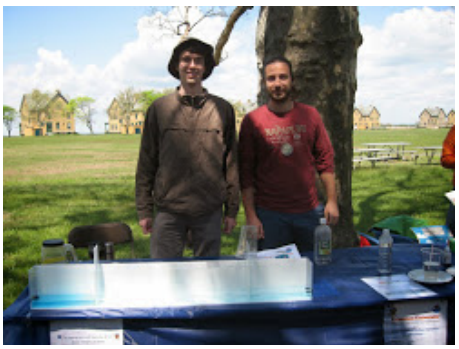
Mentoring Physical Oceanography Women to Improve Retention (MPOWIR) NOAA Graduate Internship

MPOWIR, a community mentoring program designed to improve retention of female physical oceanographers, has for several years sponsored a graduate internship at NOAA laboratories, including GFDL. Every year one-two female physical oceanography students, enrolled in a graduate program in the USA, are selected to spend 8-10 weeks working in a NOAA lab. The program aims to expose the students to the range of work carried out at NOAA facilities, and ultimately improve the diversity of the NOAA workforce. In the summer of 2014 one student, Alejandra Sanchez-Franks from Stony Brook University, was selected as an MPOWIR intern working at GFDL with Rong Zhang. Alejandra had a successful summer of research at GFDL, culminating in a research seminar, and leading to continuing collaboration. The NOAA funding, administered through CICS, covered a summer stipend, housing, and travel-related expenses.

Ocean Fun Days 2014

Scientific inquiry and fun went hand-in-hand at the eleventh annual celebration of Ocean Fun Days at Island Beach State Park and Sandy Hook located on the coast of New Jersey. CICS scientists spent the weekend of May 17th and 18th, 2014 alongside of children and families as part of the yearly event that features eco-friendly hands-on programs and interactive activities designed to promote the wise use of New Jersey's marine and coastal resources.

L to R: Sonya Legg (CICS), Anna FitzMaurice (CICS), Hannah Zanowski (CICS), and Ivy Frenger (AOS, Princeton)



L to R: Todd Mooring (CICS) and Philip Pika (ETH Zurich)

The event included dozens of exhibitors, displays, and demonstrations by marine scientists, researchers, and environmentalists that promote natural resources and energy conservation. Among the educational displays and exhibits was an exhibit manned by CICS Director Sonya Legg and CICS Scientists Anna FitzMaurice, Todd Mooring, and Hannah Zanowski demonstrating how temperature and salinity drive ocean currents, and another demonstrating oceanic acidification. Ocean Fun Days is presented by New Jersey Natural Gas through its Conserve to Preserve Foundation, in partnership with the New Jersey Sea Grant Consortium (NJSGC), the Asbury Park Press, the New Jersey Department of Environmental Protection, the New Jersey Division of Parks and Forestry and the National Oceanic and Atmospheric Administration (NOAA).

2015 Young Women's Conference in Science, Mathematics, Technology, and Engineering

On March 19, 2015, CICS Associate Director Sonya Legg and CICS Scientist Hannah Zanowski, an AOS graduate student, took part in the 14th annual Young Women's Conference along with colleagues from the AOS Program. Hosted by the Princeton Plasma Physics Laboratory, the event attracted nearly 500 students from 60 middle and high schools throughout New Jersey, Pennsylvania, and Maryland as a means of cultivating girls' interest in STEM subjects and career paths.

L to R: CICS Scientist Hannah Zanowski, AOS Colleagues Ivy Frenger, Anna Trugman, Rebecca Asch, and Alison Gray

The CICS interactive displays included an experiment exploring ocean acidification, a salinity taste test (students tasted water of different salinities and ordered them from least salty to saltiest -- the salinities of the water were designed to be comparable to ocean salinities from various parts of the world), and an "ice-berg" experiment. In this last experiment, CICS/AOS scientists place dyed ice cubes into beakers containing either fresh water or salt water. Based on the behavior of the meltwater from the ice cube in each, which floated on top of the salty water, but convectively mixed into the fresh water, the students tried to guess which beaker had the salt water. The experiment demonstrated how both temperature and salinity determine the density of sea water, and showed how the supply of heat from the ocean influences the rate of melt of ice-bergs and ice-shelves. The Conference was mutually beneficial in that it afforded CICS/AOS scientists the opportunity to hone their communication skills, in addition to introducing middle and high school aged girls to women scientists and the wide breadth of careers available to them in STEM fields.

Structure of the Joint Institute

Princeton University and NOAA's Geophysical Fluid Dynamics Laboratory have a successful 47-year history of collaboration that has been carried out within the context of the Atmospheric and Oceanic Sciences Program (AOS). The Cooperative Institute for Climate Science (CICS) builds and expands on this existing structure. The CICS research and education activities are organized around the four themes discussed previously in the Research Themes Overview. The following tasks and organizational structure have been established to achieve the objectives:

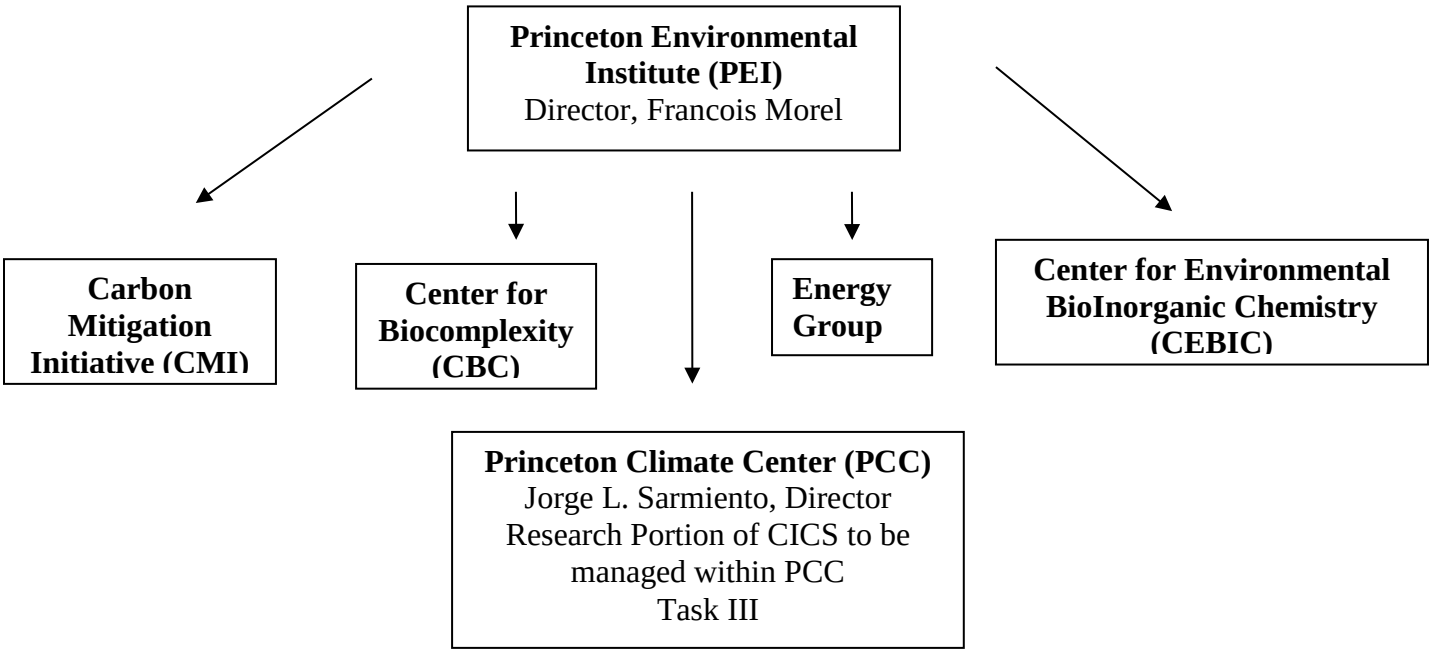
I. Administrative Activities including outreach efforts are carried out jointly by the AOS Program and Princeton Environmental Institute (PEI).

II. Cooperative Research Projects and Education are carried out jointly between Princeton University and GFDL. These will continue to be accomplished through the AOS Program of Princeton University. They include a post-doctoral and visiting scientist program and related activities supporting external staff working at GFDL and graduate students working with GFDL staff. Selections of 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.

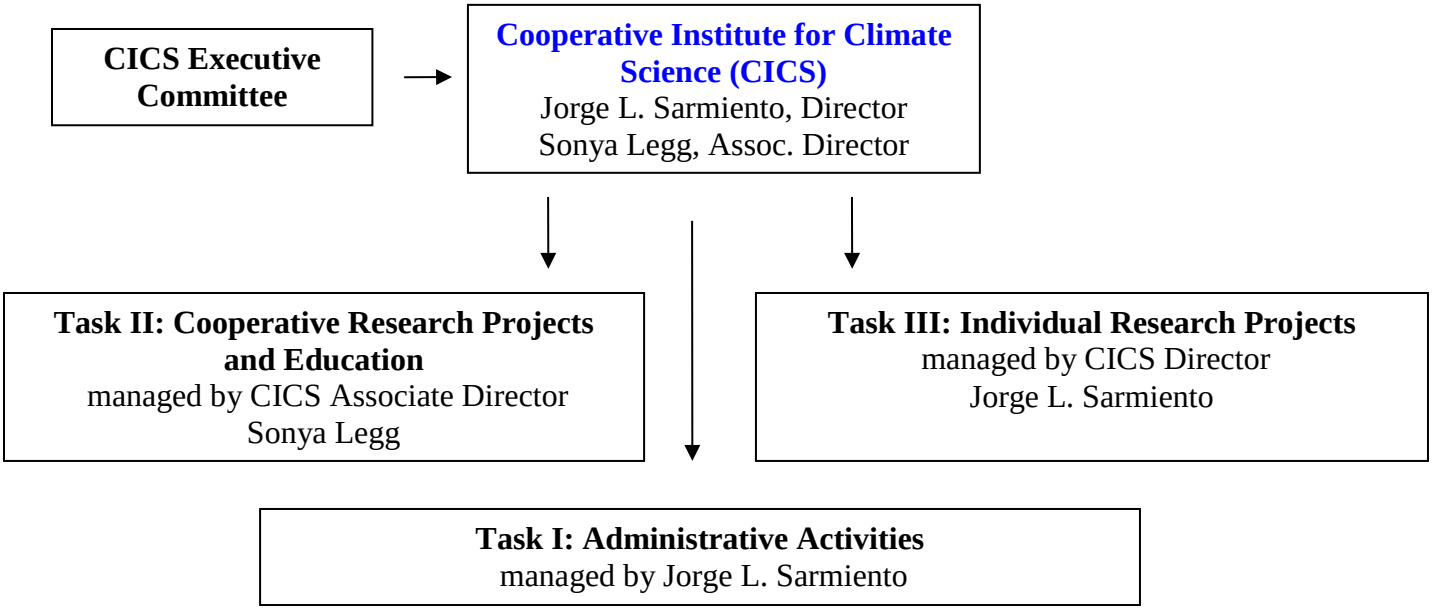
III. Principal Investigator led research projects supported by grants from NOAA that comply with the themes of CICS. These all occur within AOS and the Princeton Environmental Institute (PEI), and may also include subcontracts to research groups at other institutions on an as needed basis.

The Director is the principal investigator for the CICS proposal. The Director is advised by an Executive Committee consisting of the Directors of the AOS Program and Princeton University associated faculty.

Princeton Environmental Institute Structure



Cooperative Institute for Climate Science Structure



CICS Committees and Members

PEI's Princeton Climate Center (PCC) Advisory Committee
Jorge L. Sarmiento – Director of CICS and Professor of Geosciences
Stephen W. Pacala – Professor of Ecology and Evolutionary Biology
Michael Oppenheimer – Professor Geosciences and Public and International Affairs, WWS
Denise Mauzerall – Professor of Civil and Environmental Engineering and Public and International Affairs, WWS

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

Executive Summary of Important Research Activities

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

EARTH SYSTEM MODELING: DEVELOPMENT and ANALYSIS

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

Model Representation of Atlantic Meridional Overturning Circulation

The Atlantic Meridional Overturning Circulation plays an important role in the climate system, by carrying warm surface waters northward through much of the Atlantic, with compensating return flow of dense water at depth. The ability of coupled climate models to simulate this ocean heat transport and its variability is an important gage of their reliability for climate projection and prediction. Postdoctoral researcher **Yohan Ruprich-Robert**, working with Rym Msadek (UCAR) and Tom Delworth (GFDL), has shown that GFDL climate models show a variety of different timescales for AMOC decadal variability. Multi-millennial pre-industrial forcing simulations with the coupled models CM2.1, CM3 and FLOR, which include different atmospheric components but similar ocean components, demonstrate that although the same processes are responsible for the variability in each of these models, the timescale for AMOC variability varies from 17 years (CM3) to 27 years (FLOR). Graduate student **He Wang**, with **Sonya Legg** (CICS) and Robert Hallberg (GFDL), has examined AMOC in GFDL models CM2M and CM2G, which use different ocean models with contrasting representations of the Nordic sea overflows. Model AMOC strength and variability is sensitive to the strength of ocean vertical mixing, while the pathway of the surface branch of the AMOC, the North Atlantic current, is sensitive to the location of the deep channels between the Nordic seas and the North Atlantic basin. Together, these studies demonstrate the sensitivity of the AMOC and its variability to both the oceanic and atmospheric model components, and the importance of continued model refinement for decadal climate prediction.

Rainfall Extremes due to Landfalling Tropical Cyclones

Tropical cyclones have much greater societal impacts when they make landfall, and **James Smith**, and graduate student **Maofeng Liu**, together with their GFDL collaborators Tom Knutsen and Gabe Vecchi, are examining the properties of landfalling tropical cyclones using GFDL climate model simulations, high resolution simulations and case studies. Particular emphasis on extreme rainfall events shows that the greater moisture-carrying capacity of a warmer atmosphere, combined with a frequency of landfall in the eastern US which does not decline over the 20th century, leads to an enhancement in rainfall within 500km of the storm center in a warming climate. Some of these studies are made possible by the enhanced prediction capabilities of the GFDL FLOR model, in which **Liwei Jia** and **V. Balaji** have played a key role, along with numerous GFDL and UCAR collaborators.

EARTH SYSTEM MODELING: APPLICATIONS

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

Regional Climate Impacts of Aerosols

Aerosols play an important role in the radiative balance of the atmosphere, through both absorption and scattering of incoming solar radiation. Aerosol levels vary due to both anthropogenic and natural influences, and increasingly, earth system models will be used to simulate these variations. Several studies have examined the impact of different regionally-important aerosols on local climate. Graduate student **Geeta Persad** has examined the effect of increases in anthropogenic aerosols in East Asia on reductions in surface solar radiation, using GFDL's AM2.1 and AM3 models, in collaboration with Ramaswamy and Yi Ming at GFDL. While as much as half of the surface dimming can be attributed to increased absorption in the atmosphere, the response of the regional climate is dominated by the surface cooling, leading to reduced monsoonal onshore flow. Saharan dust is a natural aerosol which shows large multi-decadal fluctuations; graduate student **Jeffrey Strong**, with GFDL collaborator Gabe Vecchi, has examined the impact of these variations on the regional climate of West Africa and the North Atlantic, including the effects on tropical cyclones, using the GFDL FLOR model.

Climate Modulation of Surface Ozone

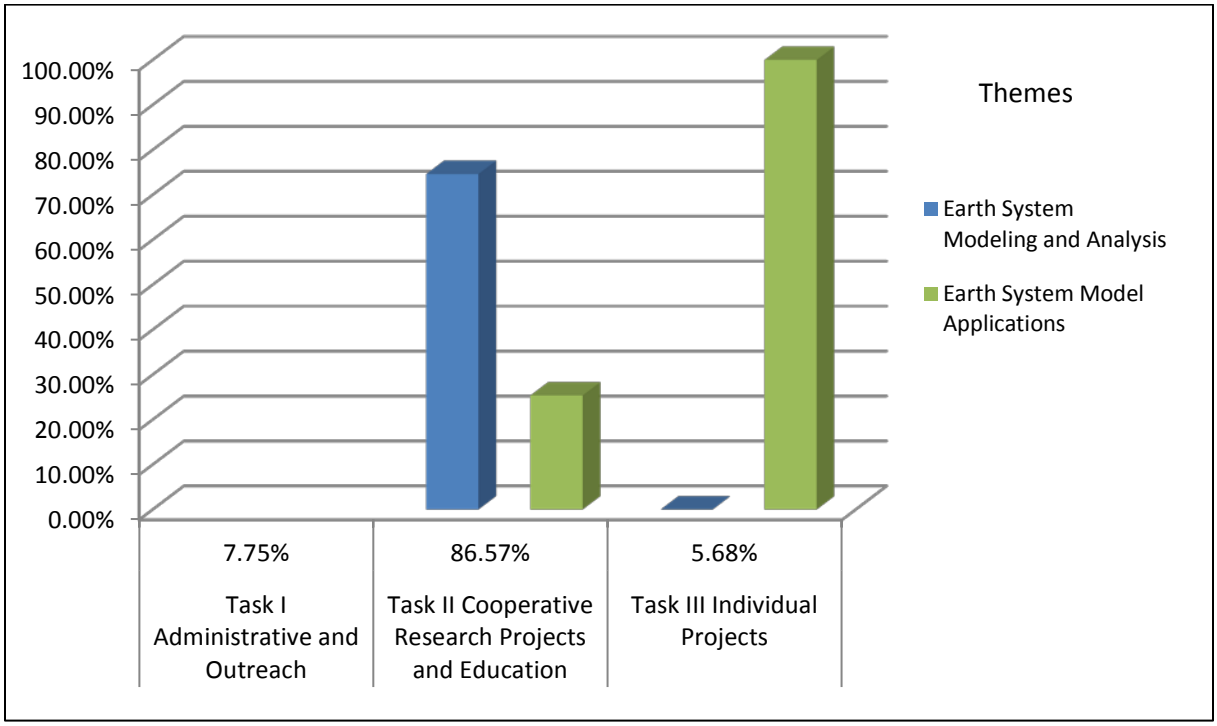
High surface ozone levels are dangerous for human health, and in addition to being driven by local pollution, can also be elevated by intrusions of ozone-bearing stratospheric air. Using observations and GFDL model AM3, **Meiyun Lin** has examined the connection between climate variability and these stratospheric intrusions, which tend to occur in the late spring following strong La Niña winters. This connection between climate variability and increased surface ozone allows for improved predictability of elevated surface ozone levels, with a lead time of a few months.

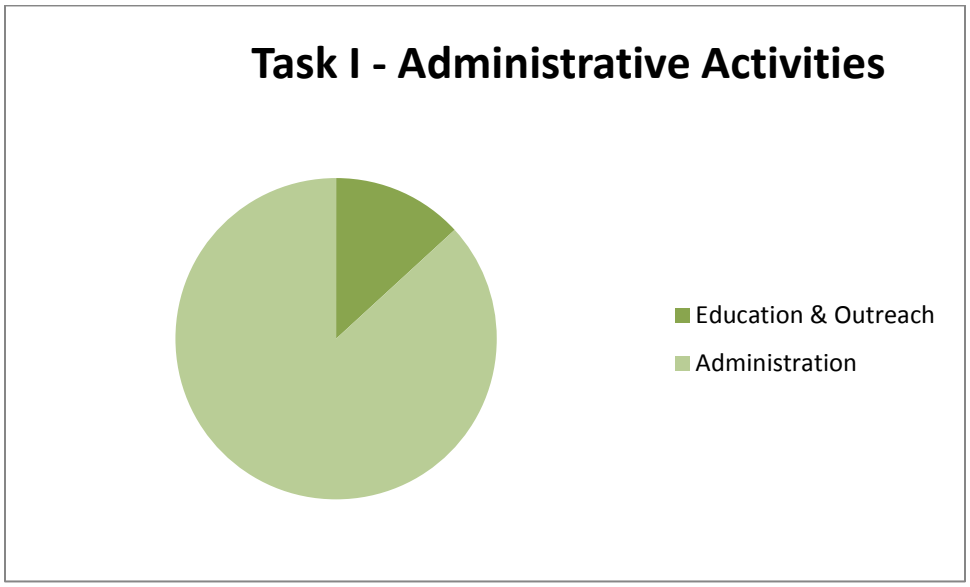
Seasonal and Decadal Climate Projections for Marine Resource Management

It is well established that environmental fluctuations affect the productivity of numerous fish stocks. Recent advances in prediction capability of dynamical global forecast systems, such as the state of the art GFDL FLOR model, allow for climate predictions of fisheries-relevant variables at a seasonal and decadal scale relevant to the fishery management decision making process. As part of the NOAA SEED project "Seasonal to decadal-scale climate predictions for marine resource management", Charles Stock (GFDL), Gabe Vecchi (GFDL), Rich Gudgel (GFDL), CICS scientist **Desiree Tommasi**, and collaborators at NOAA ESRL, NOAA NMFS, NOAA CPC, George Mason University, and the University of Washington, have shown that the GFDL FLOR model produces skillful monthly to interannual SST predictions over the continental shelf, where most of the global fish yield is generated. The availability of skillful SST projections at this "fishery relevant" scale raises the potential for better constrained estimates of future fish biomass and improved harvest decisions. **Desiree Tommasi** is examining the utility of incorporating such seasonal and decadal scale climate forecasts into the marine resource management framework thorough a variety of proof of concept applications, such as Pacific sardine harvest control rules and bluefin tuna spatial management strategies. She has shown that, for Pacific sardine, a harvest control rule that includes future environmental information can produce higher long-term yield and stock biomass, and reduce the probability of either catch or stock biomass falling below threshold values than the current management rule. An international workshop - led by Dr. Tommasi and coordinated through CICS - will be held in June 2015 in Princeton to develop additional

applications of climate predictions in marine resource management. This work has also spurred additional exciting marine resource and earth system forecasting possibilities within CICS. For example, CICS scientists **Andrew Barton**, **Charlotte Laufkötter**, and **Fernando Taboada**, are assessing the extension of short-term predictive capacity to include biogeochemical and ecosystem variables as part of NOAA's "Marine ecosystem tipping points" initiative. Such predictions allow us to better resolve the complex connections between physical climate changes and ecological responses, which often amplify subtle changes in physical variables, as was evident in the late 70s "regime shift" in the North Pacific. A better understanding of ecosystem tipping points and their drivers will allow for marine resource management decisions that are more resilient to variable ecosystem productivity.

NOAA Funding by Task and Theme





Task I – Administration and Outreach

This task covers the administrative activities of the Cooperative Institute and support of its educational outreach activities. Administrative funding included minimal support of the CICS Director, Associate Director and Administrator. Educational outreach activities included funding for a MPOWIR supported graduate student as well as a summer intern.

Project Titles

Cooperative Institute for Climate Science (CICS)
NOAA Cooperative Awards NA08OAR4320752 & NA14OAR4320106

Education/Outreach Projects

- Art of Science
- CICS Summer Internship
- Mentoring Physical Oceanography Women to Improve Retention (MPOWIR) NOAA Graduate Internship
- Ocean Fun Days 2014
- 2015 Young Women's Conference in Science, Mathematics, Technology, and Engineering

Earth System Modeling and Analysis Projects

- Hybrid Ocean Model Development (Alistair Adcroft)
- Flexible Modeling System (FMS) (V. Balaji)
- Zonostrophic Turbulence in Two-layer Quasi-geotrophic Model (Junyi Chai)
- Roles of Zonal and Meridional Shift of the ITCZ/SPCZ and the Climatological Precipitation on the Nonlinearity in the Surface Zonal Wind Response to ENSO (Kityan Choi)
- Variations and Trends in Local and Global Radiative Fluxes, and their Relation to Processes of the Hydrological Cycle (Stephan Fueglistaler)
- Creation of GLODAPv2: A Next Generation Data Product for Model Initialization, Comparison and/or Assimilation (Robert Key)
- Ocean Mixing Processes and Parameterization (Sonya Legg)
- Urban Model Development and Surface-Atmosphere Interaction (Dan Li)
- Understand Climate Changes in the Upper Troposphere/Lower Stratosphere (Pu Lin)
- Exploring Use of Satellite and *In Situ* Measurements for Evaluating Cumulus Parameterization in GFDL Models (Zhengzhao "Johnny" Luo)
- The Fluctuation-Dissipation Theorem in a Two-Layer Model of Quasi-Geostrophic Turbulence (Nicholas Lutsko)
- Local vs. Regional Effects of Land-Use-Change Induced Heterogeneity on Historical Climate (Sergey Malyshev)
- Ozone and Secondary Organic Aerosols over Southeast U.S. (Jingqiu Mao)
- Ocean Mixing Processes and Parameterization (Benjamin D. Mater)
- Transient Eddies in the Martian Atmosphere (Todd Mooring)
- Internal Wave Mixing in Continental Slope Canyons (Robert Nazarian)
- Processes that Control Climate Change over the Southern Hemisphere (Isidoro Orlanski)
- Implementation of Nitrate Aerosols in the GFDL AM3 Model (Fabien Paulot)
- AMOC Decadal Variability and Climate Impacts (Yohan Ruprich-Robert)
- Development of an Ice-Sheet Model (Olga Sergienko)
- Towards the New GFDL Land Model LM4 (Elena Shevliakova)
- Regional Climate Studies Using the Weather Research and Forecasting Model (James Smith)
- The Response of a Turbulent Boundary Layer to a Step Change in Stabilizing Surface Heat Flux (Alexander Smits and Elie Bou-Zeid)
- Improving Microphysical Parameterization in Numerical Models (Kara J. Sulia)

Earth System Modeling and Analysis Projects continued

- Processes of Dense Water Formation and Transport in the North Atlantic and their Influences on the Climate (He Wang)
- Implementation of a Double-Moment Aerosol Microphysics Scheme (Yuxing Yun)
- Decadal Variability and Prediction (Liping Zhang)

Earth System Model Applications Projects

- Climatic Controls on Arid Midlatitude Asia (Jane Baldwin)
- Antarctic Sea Ice and the Southern Ocean Overturning Circulation (Anna FitzMaurice)
- Long Term Variability of Planktonic Ecosystems in Earth System Models (Fernando González Taboada)
- Tropical Rainfall Responses to Forced Ocean Surface Warming (Spencer Hill)
- Seasonal Predictions in a High-Resolution GFDL Climate Model (Liwei Jia)
- Drought Research and Predictions (Nathaniel Johnson)
- Climate Variability Modulates Western U.S. Ozone Air Quality in Spring via Deep Stratospheric Intrusions (Meiyun Lin)
- Exploring Emission versus Climate Drivers of Tropospheric Ozone Variability and Trends over Northern Mid-Latitudes from Space (Meiyun Lin)
- Curator Infrastructure (Serguei Nikonov)
- Regional and Global Climate Impacts of Anthropogenic Aerosols (Geeta Persad)
- Using Models to Improve our Ability to Monitor Ocean Uptake of Anthropogenic Carbon (Keith Rodgers)
- Factors Controlling Seasonal Variations in Arctic Black Carbon (Zhaoyi Shen)
- Climate Response to Saharan Dust Perturbations (Jeffrey Strong)
- Application of Seasonal to Decadal Climate Predictions for Marine Resource Management (Desiree Tommasi)
- Signal Tracking of Antarctic Open-Ocean Polynyas (Hannah Zanowski)

Progress Reports:

Earth System Modeling and Analysis

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

Principal Investigator: Alistair Adcroft (Princeton Research Oceanographer)

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

Other Participating Researchers: Gokhan Danabasoglu (NCAR), Mehmet Ilicak (Bergen, Norway), Todd Ringler (LANL)

Award Number: NA08OAR4320752
Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Ecosystem Goal: Protect, Restore, and Manage the Use of Coastal and Ocean Resources through Ecosystem-based Management (20%)
Climate Goal: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond (80%)
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

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

Methods and Results/Accomplishments:

The entire year has been devoted to model and code development with focus on i) the MOM6 ocean model code (with extensive contributions from Hallberg, Harrison, Griffies and Krasting), ii) SIS2 sea-ice model (led by Hallberg), iii) the OM4 ¼° ice-ocean configuration (with input from OWG), and iv) the CM4 physical coupled model using the ¼° ocean model (under the auspices of CWG).

MOM6 code development has mostly been in the form of adding content and comprehensiveness to the capabilities. The mesoscale eddy kinetic energy (MEKE) parameterization that controls the isopycnal thickness mixing efficiency has been further developed (see Jansen et al., 2015a), fully implemented, tuned in idealized tests and deployed in OM4 and CM4. Much attention has been paid to KPP which is provided in the form of the CVmix project (collaboration with Griffies, Danabasoglu and Ringler). There is much code development yet to be done: not all parameterizations that were available in MOM5 and GOLD have been ported over or enabled.

The majority of MOM6 and SIS2 developments have been motivated by the continuing development of OM4 and CM4. The first engineering coupled run of CM4 occurred in early the spring. We have met a milestone of a "touchstone" comprising coupling OM4 to AM2 in a CM2.5 lookalike. This "touchstone" looks as good as CM2.5 in many metrics, if not better in some. The "touchstone" was a "sanity check" and not intended to be further developed or published, even though some significant effort went into it. The intent is to use and publish with CM4 that uses AM4.

Plans have been made to begin development of 1° configurations of the ice-ocean and coupled models.

Publications:

Energy budget-based backscatter in an eddy permitting primitive equation model. Jansen, M., Held. I., Adcroft, A., and Hallberg, R.W., 2015: Ocean Modelling, submitted.

Energy budget-based Mesoscale Eddy Parameterization. Jansen, M., Adcroft, A., Hallberg, R.W., and Held. I., 2015: Ocean Modelling, submitted.

Energy flux into internal lee waves: Sensitivity to future climate changes using linear theory and a climate model. Melet, A., Hallberg, R., Adcroft, A., Nikurashin, M. and Legg, S., 2015: Journal of Climate, 28(6), http://dx.doi.org/10.1175/JCLI-D-14-00432.1.

A framework for parameterization of heterogeneous ocean convection. Ilicak, M., Adcroft, A. and Legg, S, 2014: Ocean Modelling, 82, p. 1-14, http://dx.doi.org/10.1016/j.ocemod.2014.07.002.

An Order-invariant Real-to-Integer Conversion Sum. Hallberg, R., and Adcroft, A., 2014: Parallel Computing, 40(5-6), p. 140-143, http://dx.doi.org/10.1016/j.parco.2014.04.007.

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

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

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

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

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

Award Number: NA08OAR4320752
Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Goal: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond (50%)
Weather & Water Goal: Serve Society's Needs for Weather and Water Information (50%)
Weather-Ready Nation Goal: Society is Prepared for and Responds to Weather-Related Events (50%)
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts (50%)

Objectives: Building model components and data standards consistent with the common model infrastructure FMS in support of PU/GFDL modeling activities

Methods and Results/Accomplishments:

During the past year, we accomplished the following: development of Flexible Modeling System (FMS) and FMS Runtime Environment (FRE) in support of Earth system modeling activities at PU/GFDL; development of FRE (FMS Runtime Environment) as a distributed workflow system spanning multiple sites (NCCS, NCRC, GFDL); Fully-automated seasonal forecast system delivers quasi-operational forecast starting March 2014; continued to serve as Head of Modeling Services at GFDL, including membership of the Science Board, Research Council, and Model Development Team.

Under my oversight, Modeling Services continued to maintain and deliver improvements to the Flexible Modeling System FMS, its runtime environment FRE, and the GFDL Curator model development database and data publication system. Team met 3 NOAA milestones in 2014 and in 2015. Serving as co-chair of WGCM Infrastructure Panel (WIP), I am providing input to the WGCM, to modeling groups around the world, and the Earth System Grid Federation (ESGF) on the infrastructural implications of CMIP6 design. I gave several invited talks during 2014-2015, including keynote talks at symposia in ICTP, ECMWF, and Internet-2. I served on several major review boards, including on the Science Advisory Board for the Max Planck Institute for Meteorology, Hamburg; DOE ACME Project, NASA GMAO and GISS 5-year center renewal, NCAR-Wyoming Supercomputing Center renewal, NWSC2.

Outreach: Overview talk on climate modeling and research to Princeton Plasma Theory group, May 2014

References:

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

Publications:

Jia, L., et al., 2014: Improved Seasonal Prediction of Temperature and Precipitation over Land in a High-resolution GFDL Climate Model. Journal of Climate, http://dx.doi.org/10.1175/JCLI-D-14-00112.1.

Vecchi, G., et al., 2014: On the seasonal forecasting of regional tropical cyclone activity. Journal of Climate, 27 (21), 7994–8016.

Griffies, S. M., et al., 2014: Sampling the physical ocean in CMIP6 simulations. CLIVAR Report.

Moine, M.-P., et al., 2014: Development and exploitation of a controlled vocabulary in support of climate modelling. Geoscientific Model Development, 7 (2), 479–493, 10.5194/gmd-7-479-2014.

Yang, Xiaosong, Gabriel A Vecchi, Rich Gudgel, Thomas L Delworth, Shaoqing Zhang, Anthony Rosati, Liwei Jia, William F Stern, Andrew T Wittenberg, Sarah B Kapnick, Rym Msadek, Seth Underwood, Fanrong Zeng, Whit G Anderson, and Venkatramani Balaji, in press*:* Seasonal predictability of extratropical storm tracks in GFDL's high-resolution climate prediction model**.** Journal of Climate. DOI:10.1175/JCLI-D-14-00517.1. 2/15.

Progress Report Title: **Zonostrophic Turbulence in Two-layer Quasi-geotrophic Model**

Principal Investigator: Junyi Chai (Princeton Graduate Student)

CICS/GFDL Collaborator: Isaac Held (GFDL)

Other Participating Researchers: Malte Jansen (University of Chicago), Geoffrey Vallis (Princeton/University of Exeter, UK)

Award Number: NA08OAR4320752
Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Goal: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: Prove the existence of zonostrophic regime in a baroclinic model and study its characteristics, thus providing understandings for the flows in Earth's ocean and planetary atmosphere

Methods and Results/Accomplishments:

Zonostrophic turbulence was discovered in one-layer quasi-geostrophic (QG) models forced by random stirring and has since been related to Jovian atmosphere for the appearance of strong zonal jets. This study shows that such zonostrophic turbulence can also exist in a two-layer QG model driven by baroclinic turbulence. The kinetic energy spectrum shows a clear transition from the inertial inverse cascade regime with -5/3 slope at small scales to the zonostrophic regime with -5 slope at the largest scales. The turbulent regime is characterized by two non-dimensional numbers criticality and non-dimensional surface friction. The zonostrophic regime is achieved in the corner of low friction and low criticality. A new dependency of eddy diffusivity on surface friction is founded when surface friction is low enough, that eddy diffusivity decreases with surface friction regardless of criticality. The zonal jets are found to be strong mixing barriers, especially in the upper layer, and therefore PV and tracer staircases are formed. A new scaling for eddy diffusivity is derived for the zonostrophic regime as $D \sim \beta^{-2} U^{18/7} \lambda^{-18/7} \kappa^{3/7}$ (where U is the mean thermal wind, λ is the deformation radius and κ is the surface friciton rate), which qualitatively agrees with simulations. The next step may be focusing on the role of vortices in heat transport, which co-exists with eddies and jets when surface friction is low.

References:

Thompson, A. and Young, W. (2007), Two-Layer Baroclinic Eddy Heat Fluxes: Zonal Flows and Energy Balance, J. Atmos. Sci., 64, 3214-3231.

Publications:

Chai, J. and Jansen, M. (2015), Equilibration of a baroclinic planetary atmosphere in the limit of vanishing bottom friction, in preparation.

Presentations:

Chai, J. JPL Summer School, August 31-September 4, 2015. Baroclinic turbulence in the low bottom friction regime, oral presentation.

Progress Report Title: **Roles of Zonal and Meridional Shift of the ITCZ/SPCZ and the Climatological Precipitation on the Nonlinearity in the Surface Zonal Wind Response to ENSO**

Principal Investigator: Kit-Yan Choi (Princeton Graduate Student)

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

Other Participating Researchers: Stephan Fueglistaler (Princeton)

Award Number: NA08OAR4320752
Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Goal: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: To understand the nonlinearities in the equatorial surface east-west wind feedback for ENSO

Methods and Results/Accomplishments:

Based on experiments with a shallow water model, we found that although the zonal and meridional shift of the ITCZ/SPCZ contribute comparably to the equatorial precipitation anomalies, the zonal redistribution component is responsible for most of the equatorial zonal wind response. However the meridional shift of the ITCZ/SPCZ during La Nina, enhances the nonlinearity in the zonal wind response substantially by reducing the climatological precipitation on the equator, thereby reducing the zonal redistribution and the zonal wind response to La Nina. This result highlights the role of climatological precipitation in limiting the zonal wind response to La Nina.

The GFDL CM2.5 forecast-oriented low ocean resolution model free-run simulation (FLOR; Vecchi et al 2014; Jia et al 2014) is compared to another simulation using the same model however with the surface ocean biases are corrected toward observations through flux adjustment (FLOR-FA). We found that both the linear and nonlinear equatorial zonal wind response to ENSO are improved by flux correcting the ocean surface climatologies. We also analyzed the CMIP5 models and found that there is a linear relationship between the linear zonal wind response and the climatological precipitation in the equatorial central Pacific; indicating that the climatology near the Warm Pool Edge is crucial to the equatorial Pacific atmosphere-ocean feedback. However, there is no linear relationship found between the nonlinear zonal wind response and the climatological precipitation among the models; suggesting that improvements to the representation of physical processes in the models are required by correctly capturing the nonlinearity in the zonal wind response.

References:

Vecchi, G. A., et al., 2014: On the Seasonal Forecasting of Regional Tropical Cyclone Activity. Journal of Climate, 27 (21), 7994–8016, doi:10.1175/JCLI-D-14-00158.1.

Jia, L., et al., 2015: Improved Seasonal Prediction of Temperature and Precipitation over Land in a High-Resolution GFDL Climate Model. Journal of Climate, 28 (5), 2044–2062, doi:10.1175/JCLI-D-14-00112.1.

Publications:

Choi, Kit-Yan, Gabriel A. Vecchi, and Andrew T. Wittenberg, 2015: Nonlinear zonal wind response to ENSO in the CMIP5 models: Roles of the zonal and meridional shift of the ITCZ/SPCZ and the simulated climatological precipitation. Journal of Climate (submitted).

Presentations:

Choi, Kit-Yan, Gabriel A. Vecchi, and Andrew T. Wittenberg, 2015: Nonlinear Wind Response to ENSO: Role of the zonal and meridional shift of the ITCZ/SPCZ and the climatological precipitation. ENSO Workshop Australia 2015, February 2015, Sydney, Australia.

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

Principal Investigator: Stephan Fueglistaler (Princeton Assistant Professor)

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

Award Number: NA08OAR4320752

Task III: Individual Projects

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

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

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

Methods and Results/Accomplishments:

This project provided support for AOS graduate student Claire Radley until August 2014. Claire Radley successfully defended her thesis in December 2014. The objective of the project is to improve our understanding of the relation between the distribution of localized phenomena and processes to the tropical mean, with three key results:

ENSO induces large spatial changes in the distribution of sea surface temperatures, and atmospheric convection, rainfall, clouds and circulation. Despite large local biases in the spatial distribution of rainfall and clouds (are consequently in the top of atmosphere radiative balance), atmospheric general circulation models generally capture the tropical average responses to ENSO events reasonably well. We find that for some variables such as cloud cover, model biases in the base state translate into corresponding biases in response to ENSO in such a way that the model's distribution function of the anomalies during ENSO is a scaled version of the anomalies in the observations, whereby the scaling factor is given by the tropical mean bias of the model. This scaling greatly improves the agreement between the model's and the observation's probability distribution functions of the ENSO anomalies. However, similar relations were not found for other variables (such as TOA radiative balance), and the scaling also provided a poor predictor for the model's (small) biases in the tropical mean response to ENSO. (Results published in Radley et al., 2014).

The role of convective organization for tropical high cloud amount. High cloud amount and convective mass flux are non-linearly related, with high cloud amount reaching saturation for the regions with high convective mass flux. We thus expect that high cloud amount – and associated radiative forcing – depends on the degree with which convection is focused in certain regions. Interesting, we find that the PDFs of high cloud amount vary only little in response to ENSO, such that this aspect may be explored only with models, where we can force the convective mass flux PDFs by varying the prescribed sea surface temperatures. Analysis of the response to prescribed SST modifications shows that indeed tropical high cloud amount is sensitive to the spatial organization of convection, but that the model's response is weaker than expected due to a response in high clouds in non-convective regions. This response is not fully understood at present, and remains to be further investigated. (Results published in Radley and Fueglistaler, 2014.)

Tropical temperature trends in CMIP5/AMIP model runs. We show that substantial differences in tropical average temperature trends between AMIP runs forced with identical sea surface temperatures arise due to differences in the evolution of the spatial distribution of convection over the period 1980-2008. (Manuscript in preparation.)

Publications:

Radley, C., S. Fueglistaler, The role of large-scale convective organization for tropical high cloud amount, Geophys. Res. Letts., 41, 5259-5263, 10.1002/2014GL060904.

Radley, C., S. Fueglistaler, L. Donner, Clouds and radiative balance changes in response to ENSO in observations and models, J. Clim. *27*, 3100 – 3113, doi:10.1175/JCLI-D-13-00338.1, 2014.

Conference presentations:

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

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

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

Award Number: NA08OAR4320752

Task III: Individual Projects

NOAA Sponsor: Brian Gross (GFDL)

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

Theme: Earth System Modeling and Analysis

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

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

Methods and Results/Accomplishments:

During the past year the prototype of GLODAPv2 was produced. The product now includes data from approximately 800 oceanographic cruises. The exact number is indeterminate since there is no set definition of what differentiates a cruise from a "leg". For example the Atlantic GEOSECS expedition in the 1970s included 121 stations that were gathered on 9 legs, but in the current GLODAPv2 configuration this is considered a single cruise. Similar expeditions are segregated into different cruises. The choice of grouping or separating is not done consistently, but rather depended on comparability of data between the different portions and simply on historical decisions. In the end, this is just a clerical issue. All of the cruises included in GLODAPv2 are summarized in a table currently posted at CDIAC (http://cdiac.ornl.gov/oceans/GLODAPv2/cruise_table.html). This summary table provides:

A. The identification code for each cruise, known as the Expocode,
B. The sequential cruise number used to identify data in the compiled product
C. A map of the station locations, available by clicking the Expocode
D. The large scale geographic region
E. Various aliases, section names and/or project acronyms for the cruise
F. The cruise dates and ship
G. The chief scientist and PI for various measurements included in the GLODAPv2 data product
H. The measurements that are available from each cruise. Not all measured parameters are included in the v2 data product
I. A listing of publications that have used data from each cruise. These references provide information for anyone who will be using the data and additionally help to acknowledge the efforts of those responsible for the measurements. A specific request is made for additional references. A. Kozyr of CDIAC will maintain these listings
J. A link to the individual cruise files and metadata files. There are no restrictions on use of any or all data included in v2. Note that the data in the individual cruise files has not been altered or adjusted in any manner; these are the original measurements

K. A machine readable metadata file
L. A link to the plots, notes and other evidence used to determine when any parameter from a cruise required a bias adjustment. This web site is physically located at GEOMAR in Kiel, Germany and includes a very large number of graphics resulting from both the automated crossover comparisons and the inversions used to quantify the adjustment parameters used to calibrate the various measurements.

A summary table with all the final adjustment factors has been created and is available at GEOMAR (https://carbochange.geomar.de/adjustments/list/). This site is currently password protected because minor corrections/additions are still being made. That limitation will soon be lifted and the full set of adjustment factors will be public and can be downloaded in part or total by anyone. This website also provides links to the same evidence listed (L. in the above listing) in the Cruise Summary Table. Once the adjustment table has been "frozen" anyone can download the results and alter the values as they see fit.

The initial version of the GLODAPv2 discrete data product was assembled and distributed to the working team in December, 2014. This (and subsequent) *beta* test version consisted of basin size components with one each for the Atlantic, the Pacific, the Indian and the Arctic Oceans. The Southern Ocean is currently segregated into the 3 longitudinal divisions. Combined the 4 component contain almost exactly one million individual water samples with each sample having up to 35 different measurements. The list of included parameters is a slight superset of what was in first version of GLODAP.

The steps used create each product are as follows:

A. The original data from a cruise are read and any adjustments are applied to the individual parameters.
B. Any measurements that are not "good" are deleted and the accompanying quality flag reset to "missing" (9)
C. For the most common parameters (salinity, oxygen, nitrate, silicate and phosphate) – those that are included in other large scale compilations such as WOA, missing values are vertically interpolated on a station by station basis. The distance over which interpolation is allowed is controlled and varies with depth. Interpolated parameters are flagged zero "0" to differentiate from measurements
D. The most commonly calculated parameters (depth, potential temperature, potential densities, neutral density and apparent oxygen utilization are added
E. Subsequent cruises are subjected to steps A-D, column order matched and then concatenated.
F. The concatenated product is subjected to final cursory quality control to eliminate "fliers" that managed to survive all prior tests. These values will always exist because the initial quality flag assignment was done by so many different people.

Once created the 4 basin scale products are distributed to collaborators for the final steps. These include calculation of carbon system parameters by Anton Velo (including pH at *in situ* temperature and pressure as requested by the modeling community), partial pressures for the various CFC measurements by Toste Tanhua, etc. Each of these parameters is appended as a new column. Once all of these calculations have been completed, the 4 basin scale products are concatenated, sorted by Expocode and then re-written first as a single large file and then as basin components by Steven van Heuven. Both of these will be distributed through CDIAC without limitation. Siv Lauvset will then use global file to produce gridded maps for a subset of the measured parameters. As with GLODAPv1, these maps match the levels and grid spacing used in previous efforts (1 degree by 1 degree and 33 vertical depth layers). For GLODAPv2 the DIVA gridding package will be used. We are now on our 4th beta version of the discrete products and the magnitude of the "corrections" being made is rapidly approaching the insignificant level.

To date, data from approximately 25 new cruises is being accumulated. We have devised a new methodology for preparation of future versions of the data product. The plan is to simply accept GLODAPv2 as being "correct" and adjusting new data (when necessary) to the fully qualified existing product. Roughly once per decade the entire collection may be reexamined if time/energy/funding is

available. The plan is to transfer the majority of this work from Princeton to CDIAC and have members of the GLODAPv2 team serve as an oversight committee.

Publications:

Carter, B R., J R Toggweiler, Robert M Key, and Jorge L Sarmiento, December 2014: Processes determining the marine alkalinity and carbonate saturation distributions**.** Biogeosciences**,** 11(24)**,** DOI:10.5194/bg-11-7349-2014.

A number of oral presentations and posters have been generated by this project. Drafts exist for 3 initial papers and one detailed data report. The initial publications will be submitted to ESSD and then a scientific summary paper will be submitted, probably to GBC.

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

Principal Investigator: Sonya Legg (Princeton Senior Research Oceanographer)

CICS/GFDL Collaborator: Robert Hallberg and Steve Griffies (GFDL) Alistair Adcroft, He Wang, Benjamin Mater, and Robert Nazarian (Princeton)

Other Participating Researchers: Jody Klymak (UVic), Rob Pinkel (SIO), Jennifer MacKinnon (SIO), Mathew Alford (UW), Mike Gregg (UW), Steve Jayne (WHOI), Lou St Laurent (WHOI), Kurt Polzin (WHOI), Eric Chassignet (FSU), Brian Arbic (UMich), Harper Simmons (UAlaska), Maarten Buijsman (UNO), Mehmet Ilicak (UBergen), Maxim Nikurashin (UTasmania), Angelique Melet (LEGOS), Jonas Nycander (UStockholm), Alberto Naveiro Garabato (USouthampton), Michael Meredith (BAS)

Award Number: NA08OAR4320752
Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Goal: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond
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, but also including deep convection driven by surface buoyancy loss, and mixing due to lee-waves driven by subinternal flow.

The study of tidally-generated internal waves forms a component of the Internal Wave Driven Mixing Climate Process Team, headed by Jennifer MacKinnon at Scripps Oceanographic Institution and including Legg and Robert Hallberg as team members. Legg and Hallberg have co-supervised former CPT postdoc Angelique Melet, and are now co-supervising CPT postdoc Benjamin Mater. A dominant focus of the past year has been the fate of low-mode tidally generated internal waves. A recently submitted manuscript (Melet et al 2015b) examines the impact of the breaking of low-mode internal tides on the large-scale ocean circulation, using an energetically consistent parameterization of the global internal tide, focusing on the consequences of wave breaking in different regions of the ocean. The vertical distribution of internal wave dissipation is shown to be particularly important to key aspects of ocean climate such as the strength of the thermocline, ocean heat uptake, and steric sea-level, while the horizontal location impacts circulation if dense water is modified by mixing, influencing the overturning circulation. Legg is now collaborating with Mater, Hallberg, and visiting scientist Jonas Nycander to develop a more detailed predictive model for the location of the low-mode internal tide dissipation.

In collaboration with Melet, Hallberg and others, Legg has contributed to two publications on the effect of lee-waves generated by mesoscale eddy flow over topography on ocean mixing (Melet et al 2014

and Melet et al 2015a). Other work related to the Internal Wave Driven Mixing CPT includes studies of the scattering of low-mode internal waves at continental slope topography, including simulations and theoretical work carried out by CICS/AOS graduate student Robert Nazarian under Legg's supervision, and Legg's participation in the Tasman Tidal Dissipation Experiment field program in January 2015.

Legg's overflow-related work includes supervision of CICS/AOS graduate student He Wang, who has carried out studies of the impact of flow through the channels of the Nordic Seas and Canadian Archipelago on the North Atlantic Circulation, leading to one published manuscript, and a second soon to be submitted (Wang et al, 2015a; Wang et al 2015b). Legg is also collaborating with the DynOPO project, [lead PIs Alberto Naveiro Garabato (Southampton University) and Michael Meredith (British Antarctic Survey)] to examine the mixing in Weddell Sea Deep Water as it flows through the Orkney Passage into the Scotia Sea, performing numerical simulations to guide their 2017 field program, and compare results with climate model parameterizations of mixing in overflows.

Legg has collaborated with former CICS postdoc Mehmet Ilicak and CICS scientist Alistair Adcroft to develop a new parameterization of open ocean convection in the presence of mesoscale eddies, leading to the publication Ilicak et al 2014.

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.

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. Legg also represented CICS at the NOAA-Educational Partnership Program biannual forum, participating in judging of posters, panel discussions and mentoring sessions with undergraduate and graduate students funded by NOAA EPP. Other outreach activities include guest lectures on Climate Change to an undergraduate non-science major environmental geology class at Rider University. Legg is also active in efforts to mentor women in oceanography, including participation in MPOWIR, PWiGs, and ESWN, and serving on the steering committee for the recent Women in Oceanography issue of Oceanography magazine.

Publications:

Ilicak, M., S. Legg and A. Adcroft, 2014: A framework for parameterization of heterogeneous ocean convection. Ocean Modelling, 82, 1-14.

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

Melet , A., R. Hallberg, A. Adcroft, M. Nikurashin and S. Legg, 2015a: Energy flux into internal lee waves: sensitivity to future climate changes using linear theory and a climate model. J.Climate , 28, DOI:10.1175/JCLI-D-14-00432.1..

Melet, A., S. Legg and R. Hallberg, 2015b: Climatic impacts of parameterized local and remote tidal mixing. Submitted to J.Climate.

Wang, H., S. Legg and R. Hallberg, 2015: Representations of the Nordic Sea Overflows and their Large Scale Impact in Climate Models. Ocean Modelling, 86, doi:10.1016/j.ocemod.2014.12.005.

Wang, H., S. Legg and R. Hallberg, 2015b: The role of freshwater pathways from the Arctic to the North Atlantic on North Atlantic circulation and climate. In preparation.

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

Principal Investigator: Dan Li (Princeton Postdoctoral Research Associate)

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

Other Participating Researchers: Chris Milly (USGS)

Award Number: NA08OAR4320752
Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Goal: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

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

Methods and Results/Accomplishments:

The current LM3 does not include any urban representation. Hence it cannot represent the impacts of urbanization on the local/regional climate and is not suitable to be used to assess the impacts of climate change in urban areas. However, given the substantial expansion of urban land and the significant growth of urban population, developing an accurate urban representation in the land model is becoming imperative. I am currently implementing a state-of-the-art urban representation into GFDL's land model LM3. The urban representation is largely based on urban canopy models that have been used in numerical weather prediction models like the Weather Research and Forecasting model (Chen et al., 2011). This urban representation has been implemented and evaluated with prescribed atmospheric forcing. The next step is to study the impacts of global climate change on cities and the impacts of urbanization on local/regional climate.

In the meantime, a better understanding the interactions between the surface (e.g., urban surface) and the atmosphere is the fundamental basis for further improving our global climate and earth system models. I have been working on understanding the surface-atmosphere interaction from a turbulence perspective. In particular, the Monin-Obukhov similarity theory, which is used to parameterize surface-atmosphere interaction in almost all numerical models, is revisited from a theoretical point-of-view.

References:

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

Publications:

Li, Y., Z. Gao, D. Li, L. Wang, and H. Wang (2014), An Improved Non-iterative Surface Layer Flux Scheme for Atmospheric Stable Stratification Conditions, Geosci. Model Dev., 7(2), 515-529.

Zhang, Y., Z. Gao, D. Li, Y. Li, N. Zhang, X. Zhao and J. Chen (2014), On the Computation Of Planetary Boundary Layer Height Using the Bulk Richardson Number Method, Geosci. Model Dev., 7, 2599-2611.

Li, D., 2014: Assessing the impact of interannual variability of precipitation and potential evaporation on evapotranspiration. Advances in Water Resources, 70, 1-11. http://dx.doi.org/10.1016/j.advwatres.2014.04.012.

Yang, W. Y., D. Li, T. Sun, and G. H. Ni (2015), Saturation-excess and Infiltration-excess Runoff on Green Roofs, Ecol Eng, 74, 327–336.

Wang, L. L., Z. Gao, S. Miao, X. Guo, T. Sun, M. Liu, and D. Li (2015), Contrasting Characteristics of the Surface Energy Balance between the Urban and Rural Areas of Beijing, China, Adv. Atmos. Sci. 32(4), 505-514.

Li, D., G. G. Katul and S. Zilitinkevich (2015), Revisiting the Turbulent Prandtl Number in an Idealized Atmospheric Surface Layer, J Atmos Sci. (in press).

Zhang, N., Z. Gao, D. Li and Y. Liu (2015), Sensitivity of Climate Models to the Critical Richardson Number in the Boundary Layer Parameterization, J. Geophys. Res.: Atmospheres (in revision).

Sun, K., D. Li, L. Tao, Z. Zhao, and M. A. Zondlo (2015), Quantifying the Influence of Random Errors in Turbulence Measurements on Scalar Similarity in the Atmospheric Surface Layer, Bound. Layer Meteorol. (in revision).

Chen, C., D. Li, Z. Gao, J. Tang, Y. Gao, X. Guo, L. Wang, and B. Wan (2015), Seasonal and Inter-annual Variations of Sensible heat, Water vapor and CO2 Fluxes over a Rice-wheat Rotation System in North China Plain, Adv. Atmos. Sci. (in revision).

Li, D., G. G. Katul, and E. Bou-Zeid (2015), Turbulent Energy Spectra, Momentum and Heat Flux Co-spectra in the Stable Atmospheric Surface Layer, Bound. Layer Meteorol. (in revision).

Li, D., T. Sun, M. Liu, L. Yang, L. Wang and Z. Gao (2015) Contrasting responses of urban and rural surface energy budgets to heat waves explain synergies between urban heat islands and heat waves, Environmental Research Letters (in revision).

Li, D., and G. G. Katul (2015), The k^{-1} Scaling of Temperature Spectra in Atmospheric Surface Layer Flows, Q. J. Roy. Meteor. Soc. (to be submitted).

Progress Report Title: **Understand Climate Changes in the Upper Troposphere/Lower Stratosphere**

Principal Investigator: Pu Lin (Princeton Postdoctoral Research Associate)

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

Award Number: NA08OAR4320752
Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Goal: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: We seek to understand how the circulation and thermal structure in the upper troposphere/lower stratosphere would response to external forcings of the climate system.

Methods and Results/Accomplishments:

We diagnose the strength of the stratospheric circulation (the Brewer-Dobson circulation) simulated by GFDL general circulation models CM2.1 and CM3 with different external forcings. We find that regardless of the forcings, the strength of the lower stratospheric circulation is strongly correlated with the tropical mean surface temperature on both interannual time scales and decadal-to-multidecadel time scales. Consistent changes in the Brewer-Dobson circulation with respect to those in the tropical mean surface temperature prevail across time scales and forcings, and constitute an important attribution element of the atmospheric adjustment to global climate change. This result has been summarized into a paper accepted by *Geophysical Research Letter*.

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

Changes in the ozone concentration would alter the radiation balance of the climate system (Forster and Shine 1997), and further lead to circulation changes (Polvani et al. 2011). But due to the complexity of the ozone chemistry, most models do not include interactive ozone variations in their climate integrations, but instead prescribe a monthly time series of zonal mean ozone concentration. Recent studies suggest that prescribing ozone changes this way may lead to under-representation of the ozone depletion during the historical period (Neely et al. 2014) and may also lead to bias in the climate sensitivity estimation (Nowack et al. 2014). We develop a simple parameterization for ozone chemistry that allows models to simulate interactive ozone variations with little additional computational expense.

The implementation of this ozone parameterization in AM4 has been tested successfully. We find this simple parameterization can reproduce the climatology, seasonal cycle and long-term trends of ozone simulated by the model with full chemistry.

References:

Forster, P. M. D., and K. P. Shine, 1997: Radiative forcing and temperature trends from stratospheric ozone changes, JGR, 102, 10841-10855.

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

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

Neely, R. R., III, D. R. Marsh, K. L. Smith, S. M. Davis and L. M. Polvani, 2014: Biases in Southern Hemisphere climate trends induced by coarsely specifying the temporal resolution of stratospheric ozone, GRL, 41, 8602-8610.

Nowack, P. J., and coauthors, 2014: A large ozone-circulation feedback and its implications for global warming assessments, Nature Climate Change, 5, 41-45.

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

Publications:

Lin, P., Y. Ming and V. Ramaswamy, 2015: Tropical climate change control of the lower stratospheric circulation, GRL, 42(3), 941-948, doi:10.1002/2014GL062823.

Lin, P., D. Paynter, Y. Ming and V. Ramaswamy, 2015: Understand changes of the tropical tropopause layer under global warming, in preparation for J. Clim.

Presentations:

Lin, P., Y. Ming and V. Ramaswamy, 2014: A robust tropical bottom-up control of the shallow stratospheric circulation, invited talk at AOGS 11th Annual Meeting, AS14-A001, Sapporo, Japan.

Lin, P., D. Paynter, Y. Ming and V. Ramaswamy, 2014: Understand changes of the tropical tropopause layer under global warming, poster presentation at AGU Fall meeting, A23L-3424, San Francisco, CA.

Progress Report Title: **Exploring Use of Satellite and *In Situ* Measurements for Evaluating Cumulus Parameterization in GFDL Models**

Principal Investigator: Zhengzhao "Johnny" Luo, (Princeton Visiting Faculty; Associate Professor, City College of New York, CUNY, Sabbatical Leave)

CICS/GFDL Collaborator: Leo Donner (GFDL)

Award Number: NA08OAR4320752

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: Explore ways to use satellite and in situ observations to evaluate GCM cumulus parameterization in GFDL models

Methods and Results/Accomplishments:

During my 3-month Sabbatical visit, I interacted with a number of GFDL scientists (e.g., Drs. Leo Donner, Yi Ming, Ming Zhao, S. J. Lin, etc.) discussing ways of using satellite and in situ observations for evaluating GCM cumulus parameterizations. Since most of the satellite methods I have developed apply to convective scale phenomena such as entrainment and vertical velocity (Luo et al. 2010; Luo et al. 2014), it was decided that a comparison with the Donner scheme (Donner et al. 2001) is most meaningful. Specifically, convective vertical velocity is singled out for detailed analysis. To this end, Dr. Leo Donner and colleagues have run AM3 and saved a number of variables pertaining to the Donner parameterization scheme including vertical velocity. Although an "apple-to-apple" comparison is yet to be completed, preliminary examinations of both modeling and observational results individually suggest that a favorable comparison is expected. This line of work continues to develop and has been included in the thesis of a graduate student at CUNY.

I gave a seminar on 3/26/2014 to discuss analysis of trace gas measurements in recent field campaigns that were made near and inside convective clouds and how they can be utilized to constrain convective entrainment. The satellite related work was presented at GFDL in May 2013 so it was not repeated this time. I also participated in GFDL's Lab Review on May 20-21 2014.

References:

Donner, L. J., C. J. Seman, and R. S. Hemler (2001), A cumulus parameterization including mass fluxes, convective vertical velocities, and mesoscale effects: thermodynamic and hydrological aspects in a general circulation model, J. Climate, 14, 3444 – 3463.

Luo, Z. J., G. Y. Liu, and G. L. Stephens, 2010: Use of A-Train data to estimate convective buoyancy and entrainment rate, Geophys. Res. Letts. 37, L09804, doi 10.1029/2010GL042904.

Luo, Z. J., J. Jeyaratnam, S. Iwasaki, H. Takahashi and R. Anderson, 2014: Convective vertical velocity and cloud internal vertical structure: An A-Train perspective, Geophys. Res. Letts., 41, doi:10.1002/2013GL058922.

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

Principal Investigator: Nicholas Lutsko (Princeton Graduate Student)

CICS/GFDL Collaborator: Isaac Held (GFDL)

Other Participating Researchers: Pablo Zurita-Gotor (Universidad Complutense and Instituto de Geociencia UCM-CSIC, Madrid, Spain)

Award Number: NA08OAR4320752
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Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Goal: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: To relate the response to small perturbations of an idealized model of the mid-latitudes to the autocorrelation time-scale of annular mode variability via the Fluctuation-Dissipation Theorem (FDT). This also provides insight more generally into how the FDT can be used in a climate context.

Methods and Results/Accomplishments:

The Fluctuation-Dissipation Theorem (FDT) provides a means of calculating the response of a dynamical system to a small force by constructing a linear operator which depends only on data from the internal variability of the unperturbed system. Much effort has been devoted to understanding the internal variability, or “fluctuations", in observations and in models, so it is intriguing to be able to use this framework to predict how these systems respond to perturbations. Recently, the assumptions underlying the FDT and it applicability for the climate system have been addressed (Majda et al. 2005; Gritsun and Branstator 2007), however efforts to apply the FDT to Atmosphere-only General Circulation Models (AGCM) have produced mixed results (Gritsun and Branstator 2007; Ring and Plumb 2008).

Here we have applied the FDT to a turbulent, baroclinically unstable jet in a two-layer quasi-geostrophic (QG) model. This model is intermediate in complexity between the highly idealized models used to develop the FDT and the AGCMs which have been previously studied. The two-layer model also captures the essential features of atmospheric circulation in the midlatitudes. Most importantly there is annular mode-like variability in this model. Annular modes are the dominant mode of variability in the zonal-mean winds in the extra-tropics and a clear relationship between the autocorrelation time-scale of this mode and the response of the midlatitude circulation to forcing has been seen in idealized models (Gerber et al. (2008); Chan and Plumb (2009)). However the FDT has yet to be successfully applied to this situation (Ring and Plumb (2008); Cooper and Haynes (2013), personal communication).

The perturbations to the model we considered were of the same magnitude in each layer. In one case the perturbations had the same sign in each layer (the barotropic case) and in the other the perturbations had the opposite sign in each layer. The supercriticality of the model was also varied to test

how the FDT fared in different parameter settings. To perform the FDT calculations the data was decomposed onto Empirical Orthogonal Functions (EOFs).

In the barotropic case good qualitative estimates are obtained for all values of the supercriticality, though the FDT consistently overestimated the response, perhaps due to significant non-Gaussian behavior present in the model. Nevertheless, this adds to the evidence that the annular mode time-scale plays an important role in determining response of the mid-latitudes to small perturbations. The baroclinic case was more challenging for the FDT. However by constructing different bases with which to calculate the EOFs we have shown that the issue in this case is that the baroclinic variability is poorly sampled, not that the FDT fails. The strategies developed in order to generate these estimates may be applicable in situations in which the FDT is applied to larger systems.

Outreach Activities: Mentored Aaron Match, a Hollings Scholar at GFDL during summer 2014.

References:

Chan, C. J., and R. A. Plumb, 2009: The response of the troposphere to stratospheric perturbations and its dependence on the state of the troposphere. Journal of the Atmospheric Sciences, 66 (7), 2107–2115.

Gerber, E. P., S. Voronin, and L. M. Polvani, 2008: Testing the Annular Mode Autocorrelation Time Scale in Simple Atmospheric General Circulation Models. Monthly Weather Review, 136 (4), 1523–1535.

Gritsun, A., and G. Branstator, 2007: Climate Response Using a Three-Dimensional Operator Based on the Fluctuation–Dissipation Theorem. Journal of the Atmospheric Sciences, 64 (7), 2558–2575.

Majda, A. J., R. Abramov, and M. Grote, 2005: Information Theory and Stochastics for Multiscale Nonlinear Systems. American Mathematical Society, 133 pp.

Ring, M. J., and R. A. Plumb, 2008: The Response of a Simplified GCM to Axisymmetric Forcings: Applicability of the Fluctuation–Dissipation Theorem. Journal of the Atmospheric Sciences, 65 (12), 3880–3898.

Publications:

Lutsko, N. J., Held, I. M., and P. Zurita-Gotor, 2015: Applying the Fluctuation-Dissipation Theorem to a Two-Layer Model of 2 Quasi-Geostrophic Turbulence. Journal of the Atmospheric Sciences (In Review).

Progress Report Title: **Local vs. Regional Effects of Land-Use-Change Induced Heterogeneity on Historical Climate**

Principal Investigator: Sergey Malyshev (Princeton Professional Specialist)

CICS/GFDL Collaborator: Elena Shevliakova (Princeton), Ronald J. Stouffer (GFDL)

Other Participating Researchers: Stephen W. Pacala (Princeton)

Award Number: NA08OAR4320752
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Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Goal: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: To understand the direct influence of land surface properties change due to human land use on the local climate within different parts each grid-cell, as well as possible influence on regional climate, in the framework of GFDL's earth-system model ESM2Mb

Methods and Results/Accomplishments:

In this study we explore effects of land-use and land-cover change (LULCC) on surface climate using two ensembles (5 members each) of numerical experiments with the Geophysical Fluid Dynamics Laboratory (GFDL) comprehensive Earth System Model ESM2Mb. The experiments simulate historical climate with two different assumptions about LULCC: (1) no land use change with potential vegetation (PV) and (2) with the CMIP5 historical reconstruction of LULCC (LU).

The difference between LU and PV experiments is illustrated in Figure 1. While in PV experiments the properties of the vegetation are uniform within a land grid cell, human land use activity creates sub-grid heterogeneity in the LU simulations, where multiple sub-grid scale areas ("tiles") can have different properties due to land use activities. E.g., the properties of crops are going to be different from the properties of neighboring pastures, or natural vegetation. The model is designed to simulate interaction between land surface and the atmosphere separately for each tile, which gives it an ability to take into account non-linear processes of land-atmosphere interactions, and also allows us to look at the local climate contrast among different neighboring tiles in LU simulation. Using multiple ensemble members allows us to examine difference between LU and PV simulations with higher degree of confidence.

We used two different approached in the analysis: (1) we compare differences in LU and PV climates to evaluate the regional and global effects of LULCC, and (2) we characterize sub-grid climate differences among different land-use tiles within each grid cell in the LU experiment. Using the first method, we estimate the magnitude of LULCC effect to be similar to some previous studies. Using the second method we found a pronounced sub-grid signal of LULCC in near-surface temperature over majority of areas affected by LULCC. The signal is strongest on croplands (Figure 2), where it is detectable with 95% confidence over 68.5% of all non-glaciated land grid cells in June-July-August, compared to 8.3% in the first method. In agricultural areas, the sub-grid signal tends to be stronger than

LU-PV signal by a factor of 1.3 in tropics in both summer and winter and by 1.5 in extra-tropics in winter. Our analysis for the first time demonstrates and quantifies the local, sub-grid scale LULCC effects with a comprehensive ESM and compares it to previous global and regional approaches.

Publications:

Berg, Alexis, B R Lintner, Kirsten L Findell, S I Seneviratne, Bart van den Hurk, A Ducharne, F Cheruy, S Hagemann, D Lawrence, and Sergey Malyshev, et al., February 2015: Interannual coupling between summertime surface temperature and precipitation over land: processes and implications for climate change. Journal of Climate, 28(3), doi:10.1175/JCLI-D-14-00324.1.

Berg, Alexis, B R Lintner, Kirsten L Findell, and Sergey Malyshev, et al., November 2014: Impact of soil moisture-atmosphere interactions on surface temperature distribution. Journal of Climate, 27(21), doi:10.1175/JCLI-D-13-00591.1.

Kapnick, Sarah B., Thomas L Delworth, M Ashfaq, Sergey Malyshev, and P C D Milly, November 2014: Snowfall less sensitive to warming in Karakoram than in Himalayas due to a unique seasonal cycle. Nature Geoscience, 7(11), doi:10.1038/ngeo2269.

Lee, M, Sergey Malyshev, Elena Shevliakova, P C D Milly, and D A Jaffe, October 2014: Capturing interactions between nitrogen and hydrological cycles under historical climate and land use: Susquehanna watershed analysis with the GFDL Land Model LM3-TAN. Biogeosciences, 11(20), doi:10.5194/bg-11-5809-2014.

Lichstein, J W., Ni-Zhang Golaz, Sergey Malyshev, Elena Shevliakova, Tao Zhang, J Sheffield, R A Birdsey, Jorge L Sarmiento, and S W Pacala, June 2014: Confronting terrestrial biosphere models with forest inventory data. Ecological Applications, 24(4), doi:10.1890/13-0600.1.

Milly, P C., Sergey Malyshev, Elena Shevliakova, Krista A Dunne, Kirsten L Findell, T Gleeson, Zhi Liang, Peter Phillipps, Ronald J Stouffer, and S C Swenson, October 2014: An enhanced model of land water and energy for global hydrologic and earth-system studies. Journal of Hydrometeorology, 15(5), doi:10.1175/JHM-D-13-0162.1.

Parsons, L. A., Yin, J., Overpeck, J. T., Stouffer, R. J., and Malyshev, S. (2014): Influence of the Atlantic Meridional Overturning Circulation on the monsoon rainfall and carbon balance of the American tropics. Geophysical Research Letters, 41, 1-6, doi:10.1002/2013GL058454.

Subin, Zachary M., P C D Milly, B N Sulman, Sergey Malyshev, and Elena Shevliakova, July 2014: Resolving terrestrial ecosystem processes along a subgrid topographic gradient for an earth-system model. Hydrology and Earth System Sciences Discussions. doi:10.5194/hessd-11-8443-2014. 7/14.

Weng, E S., Sergey Malyshev, J W Lichstein, C E Farrior, R Dybzinski, T Zhang, Elena Shevliakova, and S W Pacala, Dec. 2014: Scaling from individuals to ecosystems in an Earth System Model using a mathematically tractable model of height-structured competition for light. Biogeosciences Discussions. doi:10.5194/bgd-11-17757-2014. 12/14.

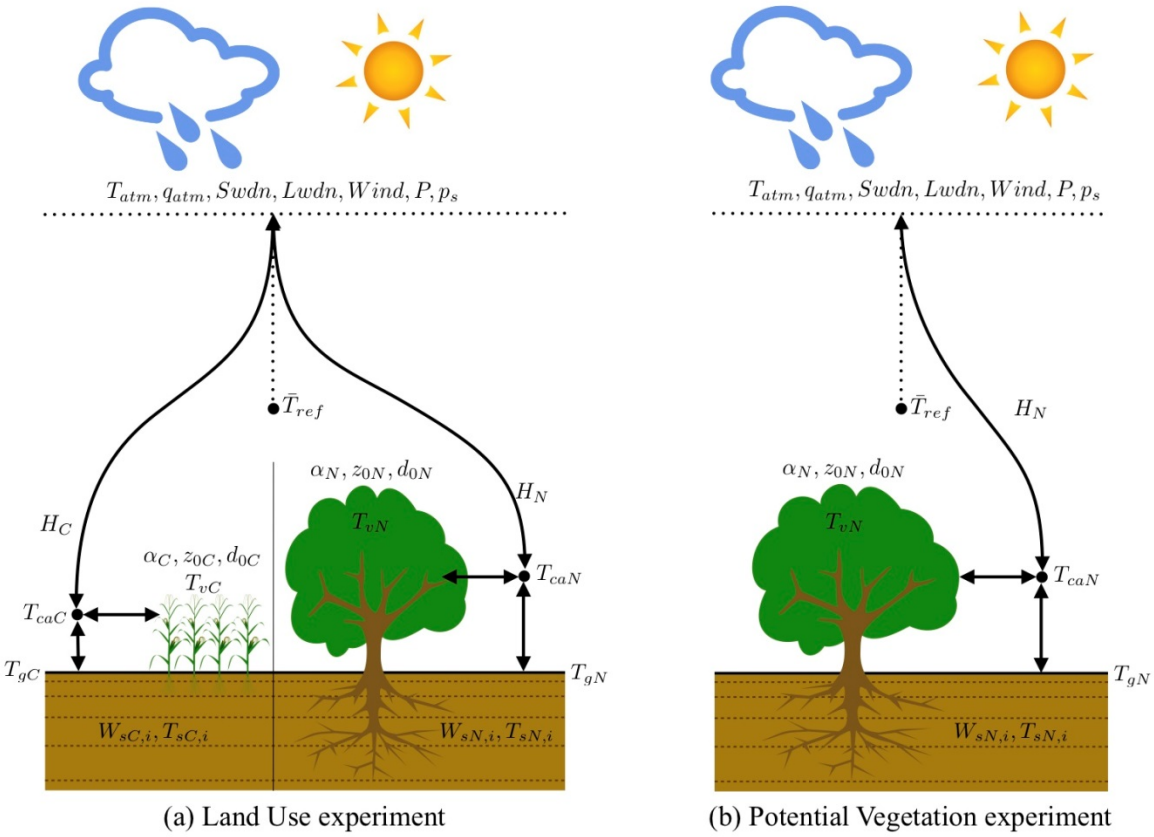


Figure 1. Schematic diagram illustrating the temperature contrasts between tiles and between experiments. For simplicity, only sensible heat fluxes are shown, and only two tiles: cropland (C) and natural (N). The left-hand side diagram shows a simplified structure of the land-atmosphere exchange in the Land Use (LU) numerical experiments, and the right-hand side – in the Potential Vegetation (PV) ones. The atmospheric inputs (temperature T_{atm}, specific humidity q_{atm}, downward short-wave and long-wave radiation fluxes $Swdn$ and $Lwdn$, precipitation P, wind, and surface pressure p_s) are the same for all tiles within the grid cell. However, the properties of the tiles (albedo α, roughness length z_0, displacement height d_0) are different. As a result, the net radiation balance (not shown) and surface fluxes H are going to be different, resulting in distinct temperatures of the canopy T_v, ground surface T_g, soil T_s, and canopy air T_{ca}, and soil water content W_s. The fluxes from all tiles are merged and passed up to the atmosphere; 2-m temperature $\bar{T}_{ref}$ is diagnosed based on canopy-air and atmospheric temperatures. Since both tiles are driven by the same atmospheric variables, the noise in the temperature difference $T_{caC} - T_{caN}$ should be much reduced compared to weather noise in individual temperatures T_{caN}, T_{caC}.

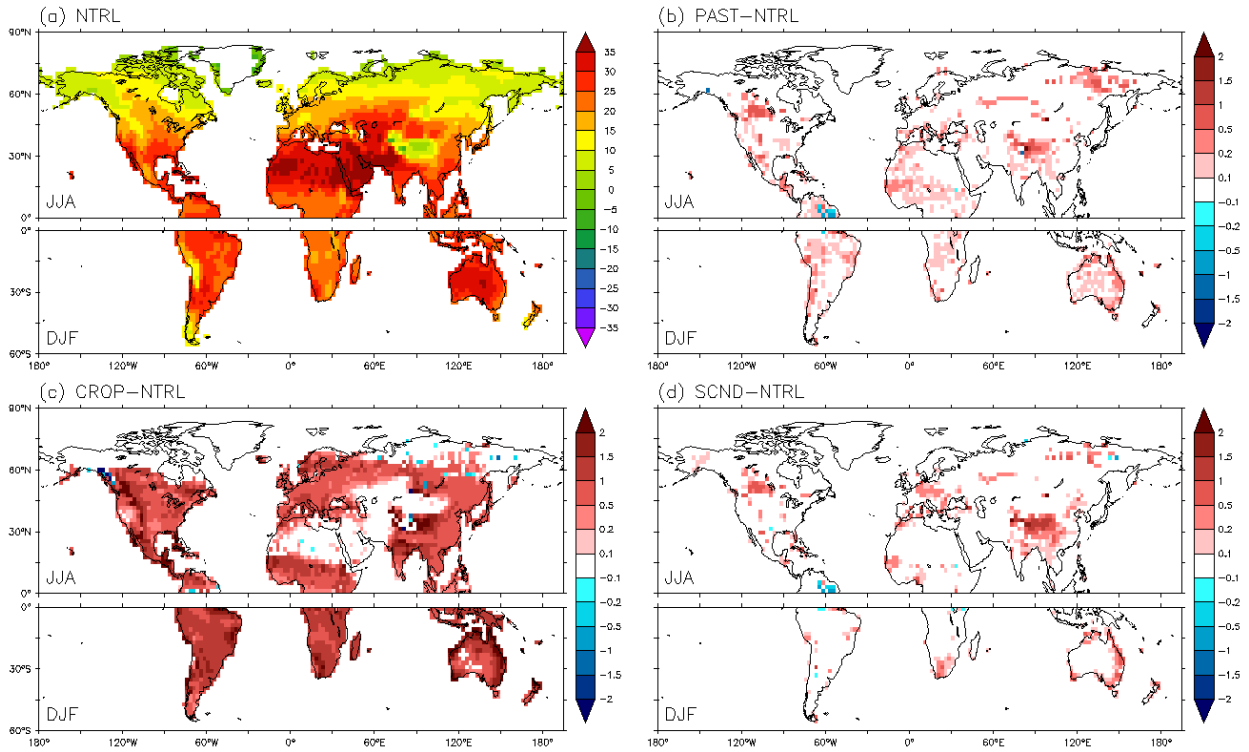


Figure 2. Ensemble mean summertime canopy air temperature averaged over the last 20-years of the historical simulation (1986-2005). For the Northern Hemisphere the figure shows boreal summer (June-July-August) average, for Southern Hemisphere — December-January-February average. Panels (b), (c), and (d) show the canopy air temperature differences between different types of land disturbed by LULCC (crops, pastures, and secondary vegetation, respectively) and natural vegetation within grid cells within the same run.

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

Principal Investigator: Jingqiu Mao (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Larry Horowitz (GFDL), Jingyi Li (Princeton)

Other Participating Researchers: Fabien Paulot (GFDL), Songmiao Fan (GFDL), Arlene Fiore (Columbia U.)

Award Number: NA08OAR4320752
Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Goal: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

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

Methods and Results/Accomplishments:

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

We have hired a postdoc (Jingyi Li) with the grant funded by NOAA Climate Program Office (Mao is the PI). Dr. Jingyi Li is now working with Mao on comparing model results to field observations in Southeast US. She has also implemented a new version of Fast-JX (v7.1) in GFDL AM3 model. She is now implementing a new module of secondary organic aerosols in GFDL AM3 model, which will be evaluated soon.

We have received a grant from NSF (Mao as PI) to organize a Southeast modeling workshop at GFDL in June of 2015. This workshop is also supported by NOAA and EPA. The major focus of this workshop will be on how to constrain models with recent measurements on gas-phase and aerosol-phase species during SAS, to improve modeling capabilities on ozone and particulate matter (PM) over the Southeast US.

We have started a new project on coupling land model (LM3) with biogenic emission (MGEAN). This project will help us to understand the future biogenic emissions with dynamic vegetation.

Simulation of SENEX aircraft campaign with GFDL AM3 model. The data is now submitted to the archive of NOAA ESRL server. We are working on two papers for the ozone chemistry over Southeast US.

During the course of this work, one proposal has been submitted to EPA and is still under programmatic review, and I have published over ten papers, three of them as first-author.

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

Publications:

Mao, J., Fan, S., and Horowitz, L. W. (2014), Fe speciation in aerosols sustained by HO_2 uptake, submitted.

Emmons, L. K., Arnold, S. R., Monks, S. A., Huijnen, V., Tilmes, S., Law, K. S., Thomas, J. L., Raut, J.-C., Bouarar, I., Turquety, S., Long, Y., Duncan, B., Steenrod, S., Strode, S., Flemming, J., Mao, J., Langner, J., Thompson, A. M., Tarasick, D., Apel, E. C., Blake, D. R., Cohen, R. C., Dibb, J., Diskin, G. S., Fried, A., Hall, S. R., Huey, L. G., Weinheimer, A. J., Wisthaler, A., Mikoviny, T., Nowak, J., Peischl, J., Roberts, J. M., Ryerson, T., Warneke, C., and Helmig, D.: The POLARCAT Model Intercomparison Project (POLMIP): overview and evaluation with observations, Atmos. Chem. Phys. Discuss., 14, 29331-29393, 2014.

S.R. Arnold, L.K. Emmons, S.A. Monks, K.S. Law, D.A. Ridley, S. Turquety, S. Tilmes, J.L. Thomas, I. Bouarar, J. Flemming, V. Huijnen, J. Mao, B.N. Duncan, S. Steenrod, Y. Yoshida, J. Langner, and Y. Long (2014): Biomass burning influence on high latitude tropospheric ozone and reactive nitrogen in summer 2008: a multi-model analysis based on POLMIP simulations, Atmos. Chem. Phys. Discuss., 14, 24573-24621.

S.A. Monks, S.R. Arnold, L.K. Emmons, K.S. Law, S. Turquety, B.N. Duncan, J. Flemming, V. Huijnen, S. Tilmes, J. Langner, J. Mao, Y. Long, J.L. Thomas, S.D. Steenrod, J.C. Raut, C. Wilson, M.P. Chipperfield, H. Schlager, and G. Ancellet (2014): Multi-model study of chemical and physical controls on transport of anthropogenic and biomass burning pollution to the Arctic, Atmos. Chem. Phys. Discuss., 14, 25281-25350.

T. Fu, Y. Zheng, F. Paulot, J. Mao, R. M. Yantosca (2014): Sensitivity of Southeast U.S. surface ozone to large-scale warming is positive but variable, Nature Climate Change, Accepted.

Fischer, E.V., Jacob, D. J., Yantosca, R. M., Sulprizio, M. P., Millet, D. B., Mao, J., Paulot, F., Singh, H. W., Roiger, A.-E., Ries, L., Talbot, R.W., Dzepina, K., and S. Pandey Deolal (2014), Atmospheric peroxyacetyl nitrate (PAN): a global budget and source attribution, Atmos. Chem. Phys., 14, 2679-2698.

Presentations:

(Invited) Nitrate Radicals and Biogenic Volatile Organic Compounds (VOCs): Oxidation, Mechanisms and Organic Aerosol, Georgia Institute of Technology, Atlanta, GA (06/2015)

(Invited) Atmospheric Chemistry Center for Observational Research and Data (ACCORD) workshop (03/2015)

(Invited) American Chemical Society spring meeting, symposium "Transformations of Matter in the Troposphere", Denver, CO (03/2015)

(Invited) University of California Riverside, Riverside, CA (02/2015)

(Invited) NOAA Earth System Research Laboratory, Boulder, CO (01/2015)

Atmospheric chemical mechanism meeting, Davis, California (12/2014)

(Invited) 13th Annual CMAS Conference, Chapel Hill, NC (10/2014)

(Invited) OH Reactivity Specialists Uniting Meeting (ORSUM), Max Plank Institute for Chemistry, Mainz, Germany (10/2014)

(Invited) NESDIS - community CrIS trace gas data user workshop (9/2014)

GFDL lab review, Princeton, NJ (05/4014)

SENEX/SOAS/NOMADSS workshop, Boulder, CO (04/2014)

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

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

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

Other Participating Researchers: Jonas Nycander (Stockholm University), Jennifer MacKinnon (SIO)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (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 due to internal waves, develop parameterizations of wave-driven 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:

Mater arrived in August 2014 to conduct work on internal wave-driven mixing as part of the Internal Wave Driven Mixing Climate Process Team headed by Jennifer MacKinnon. Thus far, research has entailed the development and implementation of a numerical scheme that parameterizes the propagation of baroclinic tidal energy within GFDL's MOM6 ocean model. The baroclinic, or "internal" tides, are of significant importance to understanding climate variability due to the role these long internal waves plays in transporting a large proportion (roughly half) of the energy that drives turbulent mixing, and in turn, large-scale overturning in the deep ocean. To date, this redistribution of energy by the internal tides is largely unaccounted for in ocean climate models despite the potential climatic impacts (Melet et al., 2015). Because current climate models do not fully resolve dynamics at the scales of the internal tides, tidal processes must be parameterized. Specifically, their generation (i.e. conversion from barotropic to baroclinic energy forms), propagation, and dissipation (i.e. conversion to turbulence) must all be represented in terms of grid-scale quantities in a physically meaningful manner.

The propagation problem has been of early focus in this work. Using well-established ideas of internal wave ray-tracing, a working numerical module has been developed that parameterizes the two-dimensional propagation, refraction, and reflection of internal tidal energy for simplified test cases in MOM6. The simplified nature of the test cases allows for the direct comparison of model results with exact analytical descriptions of energy refraction under the influence of planetary rotation, depth, and stratification. Performance of the parameterization under different advection schemes has been a large part of the work and remains an area open to continued refinement.

Future work on this subject will involve the incorporation of existing parameterizations for the generation of internal tides (e.g. Nycander, 2005; Falahat et al., 2013) as well as the development and implementation of new parameterizations for the processes leading to the dissipation of internal tides into turbulent mixing. Recent CICS-affiliated research (e.g. Legg, 2014; Melet et al., 2013, 2015) will be called upon as part of this work. In accord with the stated objectives, parameterizations will be implemented in GFDL's global climate models to investigate the sensitivity of these large-scale models to more physically-based spatial distributions of mixing.

References:

Falahat, Saeed, Jonas Nycander, Fabien Roquet, and Moundheur Zarroug, 2014: Global calculation of tidal energy conversion into vertical normal modes. J. Phys. Oceanogr., 44, 3225–3244. doi: http://dx.doi.org/10.1175/JPO-D-14-0002.1.

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

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

Melet, Angelique, Sonya Legg, and Robert W Hallberg, 2015, submitted: Climatic impacts of parameterized local and remote tidal mixing. Journal of Physical Oceanography.

Nycander, Jonas, 2005. "Generation of internal waves in the deep ocean by tides."Journal of Geophysical Research: Oceans (1978–2012) 110.C10.

Progress Report Title: **Transient Eddies in the Martian Atmosphere**

Principal Investigator: Todd Mooring (Princeton Graduate Student)

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

Other Participating Researchers: Geoffrey Vallis (Princeton/Exeter)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: Improve our knowledge of the empirical properties and underlying physical mechanisms of transient eddy activity in the Martian atmosphere

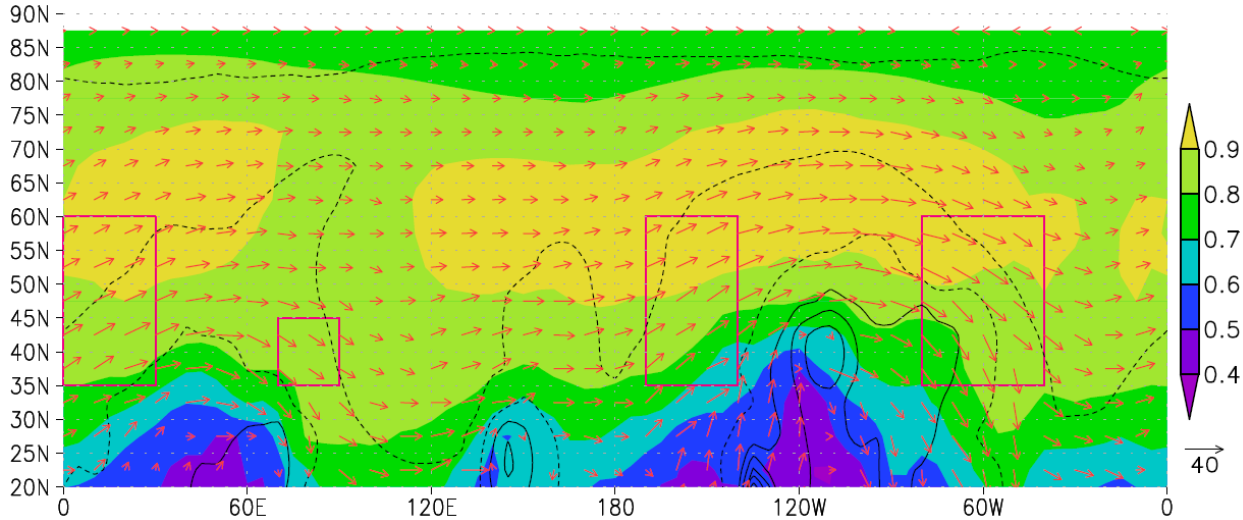
Methods and Results/Accomplishments:

For my PhD I am investigating several aspects of the dynamics of transient eddies in the Martian atmosphere. This project employs two major research methods: diagnosis of a Martian reanalysis dataset to better understand what Martian transient eddies are actually like, and idealized general circulation model experiments to facilitate identification of the physical causes of Martian eddy behaviors. My use of an idealized general circulation model to attempt to explain why transient eddy activity on Mars can be so regular (e.g., Ryan et al. 1978) has been described in previous versions of this annual progress report. Because this project examines transient eddies in a relatively unfamiliar context, it advances knowledge of them as a general phenomenon rather than merely as a feature of the current terrestrial atmosphere. In principle, enhanced theoretical understanding of such eddies could conceivably make it easier to evaluate the realism of their behavior in simulations of future terrestrial climates.

This year's activities focused principally on surveying transient eddy activity in the Mars Analysis Correction Data Assimilation (MACDA) reanalysis dataset (Lewis et al. 2007, Montabone et al. 2014). Specifically, we examined eddy variance and covariance (storm track) fields and maps of eddy phase velocity. This work is novel because previous attempts to study Martian eddy variance and covariance fields have either used pure model output (e.g., Hollingsworth et al. 1996) or were restricted to examining the temperature field (e.g., Banfield et al. 2004). We showed that the eddy variance-covariance fields are zonally modulated and that their spatial structures possess considerable interannual repeatability.

We also computed eddy phase velocities using a teleconnection map-based technique (Wallace et al. 1988). A sample phase velocity map constructed from eddy surface pressure fields is shown on the next page. There is a prominent tendency for eddy propagation to follow topographic contours, which is diminished at higher altitudes (not shown).

Outreach Activities: I participated in the Ocean Fun Days event held May 18, 2014 at Sandy Hook, New Jersey, helping with a fluid dynamics experiment illustrating different phenomena that can occur when water masses of different densities are allowed to interact. Phenomena included sinking of denser water to the bottom of the tank and the generation of internal waves.



Eddy phase velocities computed from eddy surface pressure data are shown. Units are m s^{-1}, with a scale arrow located in the lower right corner of the plot. Black solid and dashed lines are topographic contours spaced 2 km apart, with dashed lines at lower elevations than solid lines. Propagation of the eddies around topography is evident, particularly in the four regions outlined in magenta. The background shading indicates the maximum correlations on the lagged teleconnection maps used to compute the eddy phase velocities—larger values mean that the eddies are more coherent in time (Wallace et al. 1988).

References:

Banfield, D., B. J. Conrath, P. J. Gierasch, R. J. Wilson, and M. D. Smith (2004), Traveling waves in the Martian atmosphere from MGS TES nadir data, Icarus, 170 (2), 365-403, doi:10.1016/j.icarus.2004.03.015.

Hollingsworth, J. L., R. M. Haberle, J. R. Barnes, A. F. C. Bridger, J. B. Pollack, H. Lee, and J. Schaeffer(1996), Orographic control of storm zones on Mars, Nature, 380 (6573), 413-416, doi:10.1038/380413a0.

Lewis, S. R., P. L. Read, B. J. Conrath, J. C. Pearl, and M. D. Smith (2007), Assimilation of Thermal Emission Spectrometer atmospheric data during the Mars Global Surveyor aerobraking period, Icarus, 192 (2), 327-347, doi:10.1016/j.icarus.2007.08.009.

Montabone, L., K. Marsh, S. R. Lewis, P. L. Read, M. D. Smith, J. Holmes, A. Spiga, D. Lowe, and A.Pamment (2014), The Mars Analysis Correction Data Assimilation (MACDA) dataset v1.0, Geosci. Data J., 1 (2), 129-139, doi:10.1002/gdj3.13.

Ryan, J. A., R. M. Henry, S. L. Hess, C. B. Leovy, J. E. Tillman, and C. Walcek (1978) Marsmeteorology: Three seasons at the surface, Geophys. Res. Lett., 5 (8), 715-718, doi:10.1029/GL005i008p00715.

Wallace, J. M., G.-H. Lim, and M. L. Blackmon (1988), Relationship between cyclone tracks, anticyclone tracks and baroclinic waveguides, J. Atmos. Sci., 45 (3), 439-462, doi:10.1175/1520-0469(1988)045<0439:RBCTAT>2.0.CO;2.

Publications:

Mooring, T. A. and R. J. Wilson (2015), Transient eddies in the MACDA Mars reanalysis, J. Geophys.Res., in preparation.

Presentations:

Mooring, T. A. and R. J. Wilson (2014), Climatology of transient eddy activity in the MACDA reanalysis, paper presented at the 8th International Conference on Mars, Pasadena, California, 14-18 July, available at http://www.hou.usra.edu/meetings/8thmars2014/pdf/1045.pdf.

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)

Award Number: NA08OAR4320752
Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Goal: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

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

Methods and Results/Accomplishments:

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

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

From this two-pronged approach, we have made a number of interesting conclusions over the past year. Using a suite of low-resolution, hydrostatic simulations covering the entire parameter space, we have found that, in the net, critical slope V-shaped canyons dissipate the most energy from the incoming internal wave while, taken relative to the control simulations, flat-bottomed V-shaped canyons dissipate relatively more energy. This discrepancy is due to the fact that flat-bottomed V-shape canyons can lead to wave trapping and ray convergence, which is impossible in the control of purely vertical sidewalls, in which the only dissipation occurs in a shallow boundary layer and all rays are reflected away from the topography. Using the non-dimensional Richardson number, which indicates whether the stratification (potential energy) is strong enough to suppress to shear (kinetic energy), we have also indicated a broad region over both types of canyons where instability is possible. From additional high-resolution, non-

hydrostatic simulations, we have found that the main means of energy dissipation in the V-shaped canyon is overturning and convective instability while for flat-bottom V-shaped canyons the main means of instability stems from shear instability. Additional high-resolution, non-hydrostatic simulations will be conducted at certain intervals in the parameter space should future ray tracing suggest other regions of the parameter space where enhanced wave trapping occurs.

Once this parameter space study has been finished and published in a peer-reviewed journal, and the driving parameters of internal wave-driven mixing in canyon regions are identified, we will formalize the appropriate parameterization for ocean global circulation models and implement it in one of GFDLs ocean models.

Outreach Activities: *TASK:* Weekly tutoring in the broad areas of mathematics and science for adult students working towards their high school degree. Over the past academic year, two of my students have graduated. I have also taken part in curriculum development for TAKS's Adult Education Program, as well as overseeing educational field trips. *Princeton:* I have mentored undergraduate Paul Yi, who will work under my co-supervision for the remainder of his career at Princeton (Junior & Senior years). We have worked together, as well as with co-adviser Prof. Sonya Legg, to come up with a research topic and have secured funding through PEI. *College of the Holy Cross*: On March 16, I gave an outreach talk at my alma mater, The College of the Holy Cross on the work in the Princeton AOS Program (including my research) and NOAA GFDL. This talk was aimed at Physics and Mathematics majors interested in pursuing a graduate career in the applied aspects of their disciplines.

Conference Presentations:

Nazarian, R.: A parameter space study of internal wave dynamics in continental slope canyons, poster, German Society of Physics Summer School on Physical Oceanography, September, 2014.

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

Principal Investigator: Isidoro Orlanski (Princeton Senior Meteorologist)

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

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

Award Number: NA08OAR4320752
Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Goal: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

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

Methods and Results/Accomplishments:

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

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

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

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

Publications:

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

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

Climate Change over the Extra-tropics of the Southern Hemisphere: The tail of a reanalyzes ensemble. Isidoro Orlanski and Silvina Solman. (to be submitted)

Progress Report Title: **Implementation of Nitrate Aerosols in the GFDL AM3 Model**

Principal Investigator: Fabien Paulot (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Larry Horowitz and Paul Ginoux (GFDL)

Award Number: NA08OAR4320752
Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Goal: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: The development of a fully interactive nitrogen cycle within the GFDL Earth System Model. My primary focus is on improving our understanding of the fate of atmospheric nitrogen, with an emphasis on particulate matter and nitrogen deposition.

Methods and Results/Accomplishments:

Over the last year, my research has primarily focused on the development and evaluation of the simulation of nitrate aerosols in AM3, including their contribution to aerosol optical depth. Nitrate aerosols were not included in radiative calculations in previous AM3 simulations.

I have first performed a comprehensive evaluation of AM3 against atmospheric observations of reactive nitrogen including surface concentrations (NH_3, HNO_3 , NH_4^+ , NO_3^-), wet deposition fluxes (NH_4^+ , NO_3^-), and aerosol optical depth (MODIS, MISR, AERONET). I have also carried out the first evaluation of AM3 against vertical profiles of aerosol dry extinction collected by NOAA ESRL.

This evaluation of AM3 in a configuration similar to that used for ACMIP or CMIP5 has revealed important seasonal biases in the simulation of sulfate and nitrate aerosols. These biases have motivated the development of a new configuration of AM3 (AM3N) with a revised treatment of aerosol removal by snow and convective precipitation and a more detailed representation of the thermodynamic equilibrium between sulfate, nitrate, and ammonia. AM3N better captures the spatial and temporal distributions of nitrate and sulfate and improves the simulation of the aerosol optical depth (Fig. 1).

I used AM3N to characterize the sensitivity of NO_3^- aerosols to projected changes in anthropogenic emissions. In contrast with recent studies, AM3N only simulates a modest increase of NO_3^- optical depth in response to changes in emissions alone. Further analysis suggests that the flux of NH_3 to the free troposphere (e.g., from convective transport or biomass burning) may exert a strong control on future NO_3^- aerosols.

The improved parameterizations of aerosol chemistry and wet deposition in AM3N will be included in the next version of the GFDL atmospheric model (AM4) to help better characterize chemistry climate interactions.

Publications:

Sensitivity of nitrate aerosols to ammonia emissions and to nitrate chemistry: implications for present and future nitrate optical depth. Paulot et al. (in preparation).

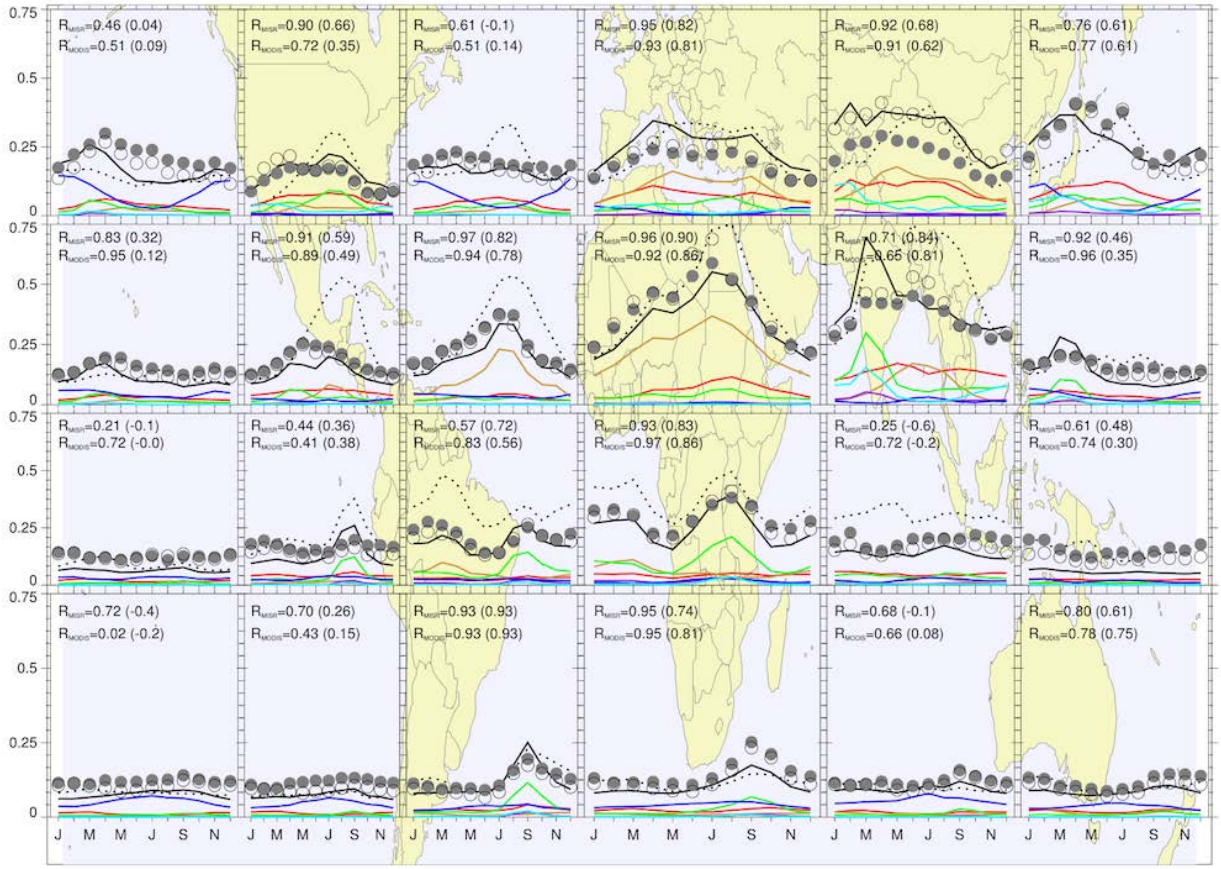


Figure 1: Observed and simulated monthly AOD at 550nm in different regions averaged over the 2008-2010 period. Circles show observations from MODIS (open circles) and MISR (filled circles). The solid and dash black line show the AOD simulated by AM3N and AM3 respectively. We also show the simulated optical depth of sulfate (red), nitrate (cyan), dust (brown), organic carbon (green), black carbon (purple), and sea salt (blue) in AM3N. The model is sampled to match the location and time of valid measurements by both MODIS and MISR in each region. Correlations between simulated and observed AOD are shown inset for AM3N and AM3 (in parenthesis).

Progress Report Title: **AMOC Decadal Variability and Climate Impacts**

Principal Investigator: Yohan Ruprich-Robert (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Rym Msadek (GFDL), Tom Delworth (GFDL)

Award Number: NA08OAR4320752
Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Goal: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: The Atlantic Meridional Overturning Circulation (or AMOC) plays a crucial role in the climate energetic balance, transporting a substantial amount of heat from tropical latitudes to the northern pole. Many studies have shown that the AMOC predominantly varies at multidecadal timescale, leading to modulation of temperature and precipitations over many area of the globe at this timescale. However, the physical processes leading to those teleconnections are still uncertain and so far no consensus exists on the mechanisms governing such preferential timescale of the AMOC variability. The main goals of this postdoctoral research are to improve our knowledge of the AMOC variability both in terms of physical mechanisms and climate impacts.

Methods and Results/Accomplishments:

Over the last year, we have studied the physical mechanisms responsible for the AMOC variability in a suite of GFDL coupled models. Using multi-millennial pre-industrial simulations of three models (CM2.1, CM3, and FLOR), we have investigated the robustness of the AMOC decadal variability characteristics. All models share similar oceanic resolution (~1°) and ocean mesoscale eddy parameterizations, but have different atmospheric resolution and physics. We find that the mechanism of AMOC variability in the three models is similar, but the preferred timescale of variability is different (periods of 20yr, 17yr, and 27yr for CM2.1, CM3, and FLOR, respectively; see Figure 1). In all three models, the AMOC variability mechanism involves an increase of the Labrador Sea deep convection in response to a cooling induced by the winter positive North Atlantic Oscillation. This drives an acceleration of the AMOC over the subpolar region that propagates southward (consistently with the mechanism proposed by Zhang 2010), which in turn yields an increased northward heat transport. At the same time, by geostrophic balance, the positive density anomalies over the Labrador Sea favor an acceleration of the subpolar gyre circulation, which leads to the creation of positive temperature anomalies over the subpolar gyre and the Labrador Sea regions, eventually contributing to a reversal of the oscillation.

This study shows that models that exhibit similar AMOC decadal mechanisms can have different characteristic timescales. Because the skill in decadal predictions mainly comes from oceanic variations, the existence of these different timescales can influence our ability to predict the climate: 5 years following initialization, the predictable signal could be shifted up to 5 years depending on the model used for the prediction. Further analyses are ongoing to better understand the origin of this discrepancy.

The climate impacts of the AMOC variability have been studied through its hypothesized Sea Surface Temperature (SST) fingerprint: the so-called Atlantic Multidecadal Variability (or AMV). We performed experiments based on the GFDL CM2.1 model in which SSTs in the North Atlantic sector are restored to the observed AMV pattern (following Ting et al. (2009)'s definition), while other basins are left fully coupled. In order to explore and isolate the potential AMV impacts and maximize the signal-to-noise ratio, we use an ensemble simulation of 100 members that are run for 11 years. We find that a positive AMV leads to the set-up of a negative Pacific Decadal Variability pattern that is characterized by cold anomalies in the tropical Pacific and warm anomalies in the western Pacific mid-latitudes. The response of the tropical Pacific Ocean to a positive phase of the AMV is similar to that observed during a development of La Niña event. However, the AMV-induced anomalies are not stationary and our results suggest that the AMV can modulate ENSO on interdecadal timescale. We investigate the frequency of occurrence of El Niño and La Niña events and find that the probability of La Niña events increase by about 15% during the first 3 years of the simulation and is followed by an increase of El Niño events for the following 2 years (see Figure 2). We propose a physical mechanism to explain this modulation of ENSO by the North Atlantic variability.

This work will be continued in the coming year by focusing on the climate impacts of the AMV simulated by a higher-resolution model than the one used in this year's experiments. We will also investigate the influence of climate mean state on the representation of these climate anomalies.

a) AMOC 8yr low-pass filtered EOF1 **b) AMOC 8yr low-pass filtered EOF2** **c) PC1/PC2 cross-correlation**

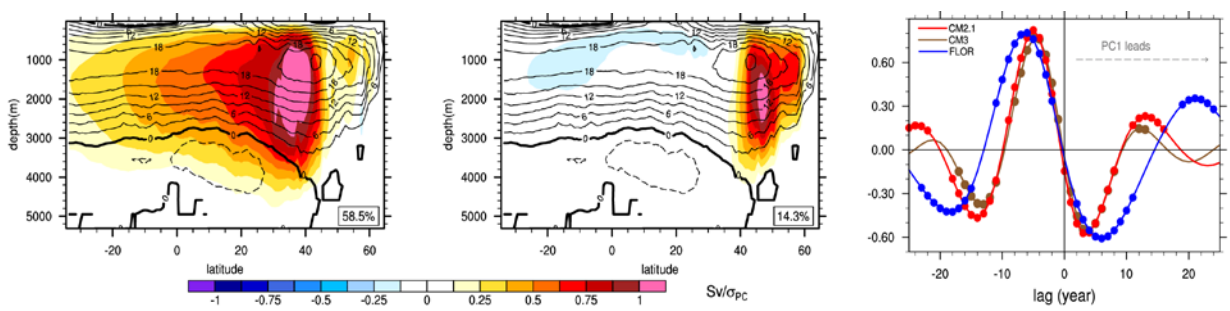


Figure 1: Solid contours show time-mean AMOC in the GFDL CM2.1 model, while color shading shows the amplitude of the first (a) and second (b) EOFs. The spatial patterns of the two leading EOFs from two additional models (CM3 and FLOR) are very similar, and not shown. (c) Lagged correlations between the time series corresponding to EOF1 and EOF2 from the CM2.1, CM3, and FLOR models. The length of time between successive minima in the correlation functions indicates the dominant timescale of variability. The CM2.1 and CM3 models have similar correlation structures, indicating similar timescales of variability (~17-20 years). The different structure for the FLOR model indicates a longer timescale of variability (~27 years). However, for each model EOF2 leads EOF1 in time by roughly one-quarter of the dominant timescale of AMOC variability.

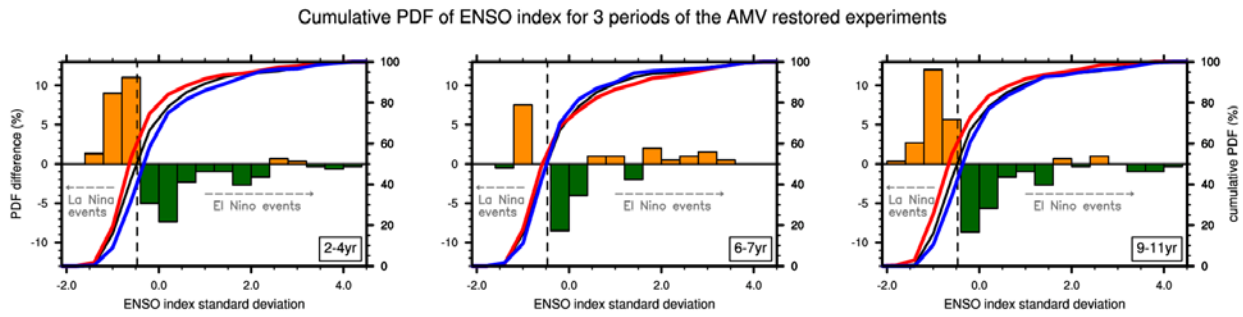


Figure 2: Cumulative PDF of ENSO index for different periods of North Atlantic SST restored simulations: period 2-4yr, 6-7yr and 9-11yr from left to right. The black, red and blue lines indicate the control, the AMV+ and the AMV- simulations, respectively. The histograms stand for the ENSO index PDF difference between the AMV+ and AMV- simulations. Over the periods 2-4yr and 9-11yr, there are about 20% more La Niña events in AMV+ compare to AMV-, whereas the period 6-7yr shows the opposite tendency.

References:

Zhang, R., 2010: Latitudinal dependence of Atlantic meridional overturning circulation (AMOC) variations, Geophysical Research Letters, 37, L16703, doi:10.1029/2010GL044474

Ting M, Kushnir Y, Seager R, Li C (2009) Forced and internal twentieth-century SST in the North Atlantic. J Clim 22: 1469-1881. doi: 10.1175/2008JCLI2561.1

Publications:

Ruprich-Robert Y., Msadek R. and Delworth T. (in preparation) Intradecadal modulation of ENSO induced by North Atlantic multidecadal variability.

Ruprich-Robert Y., Msadek R. and Delworth T. (in preparation) Consistency of AMOC decadal variability in a suite of GFDL models: what sets the timescale?

Conferences:

Ruprich-Robert Y., Msadek R. and Delworth T. (poster) Consistency of AMOC decadal variability in a suite of GFDL models: what sets the timescale?, US AMOC meeting, September 2014, Seattle.

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

Principal Investigator: Olga Sergienko (Princeton Research Glaciologist)

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

Award Number: NA08OAR4320752
Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Goal: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: Improve understanding of the fundamental mechanisms governing ice sheets behavior, processes controlling their short and long-term changes and the effects of ice sheets interactions with other components of the climate system

Methods and Results/Accomplishments:

The rate of ice transport from the interior of ice sheets to their margins, and hence the rate with which it contributes to sea level, is determined by the balance of driving stress, basal resistance, and ice internal deformation. The recent high-resolution observations of the Antarctic and Greenland ice sheets surface and bed elevations allow to compute driving stress (Fig. 1) and ice deformation velocities with unprecedentedly high spatial resolution (~ 1 km). Using observations of ice-sheet surface velocities it is possible to infer basal traction by inverse techniques. The results reveal broad-scale organization in 5–20 km band-like patterns in both the driving and basal shear stresses located in zones with substantial basal sliding (Sergienko et al., 2014). Both ice sheets experience basal sliding over areas substantially larger than previously recognized. The likely cause of the spatial patterns is the development of a band-like structure in the basal shear stress distribution that is the results of pattern-forming instabilities related to subglacial water. The similarity of patterns on the Greenland and Antarctic ice sheets suggests that the flow of ice sheets is controlled by the same fundamental processes operating at their base, which control ice sheet sliding and are highly variable on relatively short spatial and temporal scales, with poor predictability.

In order to investigate the effects of thermodynamic coupling of the ocean circulation and Antarctic ice shelves, the global ocean circulation model MOM 6 and sea-ice model SIS have been configured to resolve the ocean circulation in the ice shelves' cavities and to account for the thermodynamic interactions with ice shelves. The results show that the thermodynamic coupling has strong effects on the ocean water masses modifications and on the sea-ice formation: sea-ice thickness is consistently larger in simulations accounting for the thermodynamic coupling compared to the simulations without the coupling.

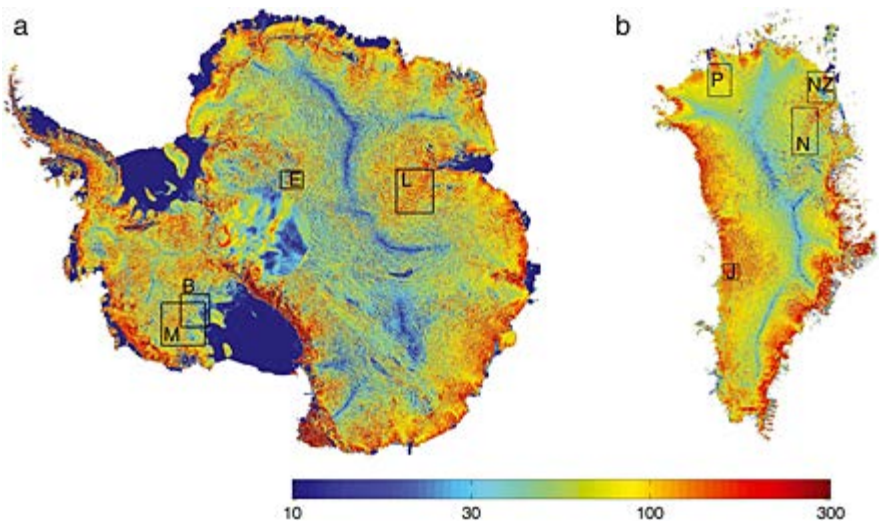


Figure 1.Driving stress (kPa) of (a) Antarctic ice sheet and (b) Greenland ice sheet.

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

References:

Sergienko, O. V. 2014. A vertically integrated treatment of ice stream and ice shelf thermodynamics, J. Geophys. Res. Earth Surf., 119, doi:10.1002/2013JF002908.

Publications:

Sergienko, O. V. 2014. A vertically integrated treatment of ice stream and ice shelf thermodynamics, J. Geophys. Res. Earth Surf., 119, doi:10.1002/2013JF002908.

Goldberg D. N., C. Schoof and O. V. Sergienko. 2014. Stick-slip motion of an Antarctic Ice Stream: The effects of viscoelasticity, J. Geophys. Res. Earth Surf., 119, 1564-1580, doi:10.1002/2014JF003132.

Sergienko, O. V., T. T. Creyts, and R. C. A. Hindmarsh *(*2014*)*, Similarity of organized patterns in driving and basal stresses of Antarctic and Greenland ice sheets beneath extensive areas of basal sliding, Geophys. Res. Lett., 41, 3925–3932, doi:10.1002/2014GL059976.

Conference Abstracts:

Sergienko O. and R. C. A. Hindmarsh (2014). Organized band-like structures in driving and basal stresses of the Antarctic and Greenland ice sheets. IGS Symposium on Contribution of Glaciers and Ice Sheets to Sea-Level Change, Chamonix, France, May 25 – 30.

Sergienko O. (2014). Ice-shelf melt channels as a pattern-formation process and their sensitivity to oceanic and glaciological forcings IGS Symposium on Contribution of Glaciers and Ice Sheets to Sea-Level Change, Chamonix, France, May 25 – 30.

Sergienko O., M. Harrison and R. Hallberg (2014). The effects of Antarctic ice-shelf/ocean interactions in a global sea-ice-ocean isopycnal model AGU Fall Meeting, San Francisco, CA December 9-13, 2014.

Progress Report Title: **Towards the New GFDL Land Model LM4**

Principal Investigator: Elena Shevliakova (Princeton Senior Climate Modeler)

CICS/GFDL Collaborator: Sergey Malyshev (Princeton), Ronald Stouffer (GFDL), Chris Milly (GFDL), Ben Sulman (Indiana University), Minjin Lee (Princeton), Zack Subin (Princeton), John Krasting (GFDL)

Other Participating Researchers: Steve Pacala (Princeton)

Award Number: NA08OAR4320752
Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Goal: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

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

Methods and Results/Accomplishments:

During 2014, I have co-led with Chris Milly the development of the new GFDL land model capabilities for the next generation LM4 model. The new modeling capabilities were implemented in the LM3 framework and tested in the global and regional stand-alone simulations: (1) a first global computer model of soil carbon and its interactions with plant roots and the soil microbial community and global multi-century simulations with the new LM3-CORPSE model (Sulman et al 2014). This will allow important plant-soil interaction processes to be included in future climate assessments. (2) a fully coupled terrestrial –aquatic carbon–nitrogen dynamics model LM3-TAN, which was applied to simulate water quality dynamics in the Susquehanna River (Lee et al 2014). This will allow us to connect terrestrial BGC processes with the ocean ones and build a land-ocean BGC exchange. (3) a first global land model which captures sub-grid hydrological variability topographic spatial variability LM3-TiHi (Subin et al 2014). This capability enables GFDL land models to better capture the dynamics of the soil water table and prognostic wetland area simulations. (4) an improved soil and snow physics version of LM3 model LM3.1 (Milly et al 2014) (5) a prototype for a new, age-height structured dynamic vegetation model LM3-PPA (Weng et al, 2014) (6) a new parameterization of photosynthetic and respiratory acclimation which was implemented in LM3 model and evaluated at a number of sites (Smith et al, in review). This will allow us to reduce plants' sensitivity to temperature variations in line with observations.

Additionally, a number of other land model improvements are underway, including a new daily fire model, a sub-grid urban area tile, and coupled carbon-nitrogen-microbial dynamic and methane capabilities.

In collaboration with the GFDL scientists, I contributed to the analysis of implications of different CO_2 emissions paths for carbon cycling and transient climate changes (Krasting et al 2014), and am

preparing another manuscript on the analysis of implications of land use land cover change for effective terrestrial carbon sensitivity to climate and CO_2.

Outreach Activities: I participated in the January 2014 NOAA Science Day and in the Climate Science Day in Washington, D.C., a non-partisan opportunity for scientists of many disciplines to build relationships and provide members of Congress access to the best possible climate science information.

Publications:

Malyshev, Sergey, Elena Shevliakova, Ronald J Stouffer, and S W Pacala, in press: Contrasting Local vs. Regional Effects of Land-Use-Change Induced Heterogeneity on Historical Climate: Analysis with the GFDL Earth System Model**.** Journal of Climate. DOI:10.1175/JCLI-D-14-00586.1.

Sulman, B., R Phillips, A Oishi, E. Shevliakova, S Pacala (2014), Microbe-driven turnover offsets mineral-mediated storage of soil carbon under elevated CO2, Nature Climate Change 4.12 (2014): 1099-1102.

Lee, M, S Malyshev, E Shevliakova, PCD Milly and PR Jaffé. (2014) Capturing interactions between nitrogen and hydrological cycles under historical climate and land use: Susquehanna watershed analysis with the GFDL Land Model LM3-TAN. Biogeosciences, 11, 5809-5826, 2014.

Lichstein, J W., Ni-Zhang Golaz, Sergey Malyshev, Elena Shevliakova, Tao Zhang, J Sheffield, R A Birdsey, Jorge L Sarmiento, and S W Pacala, June 2014: Confronting terrestrial biosphere models with forest inventory data. Ecological Applications, 24(4), doi:10.1890/13-0600.1.

Subin, ZM, PCD Milly, BN Sulman, S Malyshev, and E. Shevliakova. (2014) Resolving terrestrial ecosystem processes along a subgrid topographic gradient for an earth-system model. Hydrology and Earth System Sciences Discussions 11, no. 7: 8443-8492.

Milly, PCD, SL Malyshev, E Shevliakova**,** KA Dunne, KL Findell, T Gleeson, Z Liang, P Phillipps, RJ Stouffer, and S. Swenson, 2014. An enhanced model of land water and energy for global hydrologic and earth-system studies. Journal of Hydrometeorology, 15, 1739-1761, DOI: 10.1175/JHM-D-13-0162.1. (2014) An enhanced model of land water and energy for global hydrologic and earth-system studies. J. of Hydrometeorology, 15, 1739–1761.

Weng, E. S., S. Malyshev, J. W. Lichstein, C. E. Farrior, R. Dybzinski, T. Zhang, E. Shevliakova, and S. W. Pacala. Scaling from individuals to ecosystems in an Earth System Model using a mathematically tractable model of height-structured competition for light. Biogeosciences Discussions 11, no. 12 (2014): 17757-17860.

Smith, N, S Malyshev, E. Shevliakova, J. Kattge, and JS Dukes. Models without foliar temperature acclimation underestimate the terrestrial carbon sink, Nature Climate Change (in review).

Krasting, JP, JP Dunne, E Shevliakova, and R. J. Stouffer. Trajectory sensitivity of the transient climate response to cumulative carbon emissions. GRL 41, no. 7 (2014): 2520-2527.

Progress Report Title: **Regional Climate Studies Using the Weather Research and Forecasting Model**

Principal Investigator: James A. Smith (Princeton Professor, Civil and Environmental Engineering)

CICS/GFDL Collaborator: Maofeng Liu (Princeton)

Other Participating Researchers: Ping Lu (Princeton), Mary Lynn Baeck (Princeton), Tim Marchok (GFDL), Gabe Vecchi (GFDL), Tom Knutson (GFDL)

Award Number: NA08OAR4320752

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

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

Objectives: The objectives of this project are: 1) to characterize the regional precipitation and flood climatologies of the US through combined modeling and observational studies and 2) to assess the error structure of regional climate model simulations using the Weather Research and Forecasting (WRF) model. Analyses focus on urban impacts on precipitation, landfalling tropical cyclones and heavy rainfall from mesoscale convective systems.

Methods and Results/Accomplishments:

We have carried out climatological assessments of urban impacts on regional climate based on observational analyses and studies based on numerical experiments using WRF. The climatology of water vapor flux in the Baltimore-Washington metropolitan region was examined using high-resolution (15-minute, and approximately 200 meter vertical resolution) water vapor flux time series derived from GPS precipitable water observations and VAD wind profiles derived from Doppler velocity observations for the Sterling, VA WSR-88D radar (Ryu et al. 2015a). Analyses are used to characterize the striking seasonal and diurnal variation of water vapor flux profiles and to compare these results with reanalysis fields. Numerical experiments are carried out in Ryu et al. 2015b to examine the interrelated effects of the bay breeze circulation and urban heat island circulation on intense convection in the Baltimore-Washington metropolitan region. The Princeton Urban Canopy Model (PUCM) provides the best representation of surface fluxes over the region and the best representation of convective rainfall. In Yeung et al. 2015, Lagrangian analyses of storm structure and motion are carried out for the 50 most intense convective "days" during the period 2000-2009 (based on cloud-to-ground lightning flash density). Analyses highlight the modification of heavy rainfall (and convective evolution) over the New York City metropolitan area. There is, however, no evidence of "storm splitting" around the City as reported in previous studies.

Analyses of tropical cyclones have continued in collaboration with the Hurricane Research Group at GFDL. We have examined the role of extratropical transition on rainfall distribution from landfalling tropical cyclones through case study analyses (including Hurricane; Liu et al. 2015) and through analyses of climate model simulations using the GFDL FLOR model. For the FLOR analyses, we have implemented a version of Hart's cyclone phase space diagram that can be computed using only the model

levels available for the FLOR simulations and shown that the algorithm performs well. Preliminary analyses have been carried out for 1990 control simulations and provide realistic representations of the climatology of extratropical transition over the Atlantic basin. We have examined the frequency of landfalling tropical cyclones and associated rainfall properties over the eastern United States using the GFDL Zetac model (Wright et al. 2015). The frequency of occurrence of post-landfall tropical cyclones during the 21st century shows little net change over much of the eastern U.S. despite a decrease in frequency over the ocean. This reflects a greater landfalling fraction in the warmer climate in CMIP5 projections, which is not seen in CMIP3-based projections. Tropical cyclone rainfall over land averaged within 500 km of the storm center is enhanced by 8 to 17%. This is at least as much as expected from the Clausius-Clapeyron relation.

Publications:

Liu, M., J. A. Smith and G. Vecchi, Extreme rainfall from landfalling tropical cycloes: Hurricane Irene case study, in preparation, 2014.

Ryu, Y-H., J. A. Smith, and E. Bou-Zeid, On the climatology of precipitable water and water vapor flux in the mid-Atlantic region of the US, J. Hydrometeor, 16, 70–87.

Ryu, Y-H., J. A. Smith, E. Bou-Zeidand M. L. Baeck, The influence of land-surface heterogeneities on heavy convective rainfall in the Baltimore-Washington area, in preparation, 2015b.

Thorndahl, S., J. A. Smith, M. L. Baeck, and W. F. Krajewski, Analyses of the Temporal and Spatial Structure of Heavy Rainfall from a Catalog of High-Resolution Radar Rainfall fields, Atmospheric Research,144(1), 111-125.

Villarini, Gabriele, Radoslaw Goska, James A. Smith, and Gabriel A. Vecchi, 2014: North Atlantic Tropical Cyclones and U.S. Flooding. Bull. Amer. Meteor. Soc., 95, 1381–1388.

Wright, Daniel B., James A. Smith, Gabriele Villarini, and Mary Lynn Baeck, 2014. Long-Term High-Resolution Radar Rainfall Fields for Urban Hydrology. Journal of the American Water Resources Association (JAWRA) 50*(3)*: 713-734. DOI: 10.1111/jawr.12139.

Wright, D. B., J. A. Smith and M. L. Baeck, A critical examination of areal reduction factors, J. of Hydrological Engineering, 19(4), 769–776.

Wright, D. B., T. R. Knutson and J. A. Smith, Regional climate model projections of rainfall from landfalling tropical cyclones, Climate Dynamics, 1-15, March 2015.

Yeung, J. K., J. A. Smith, M. L. Baeck and G. Villarini, Lagrangian analyses of rainfall structure and evolution for organized thunderstorms in the urban corridor of the northeastern US, J. of Hydrometeorology, in press, 2015.

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

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

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

Other Participating Researchers: Owen Williams, Mostafa Momen, and Abel-John Buchner (Princeton)

Award Number: NA08OAR4320752

Task III: Individual Projects

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

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

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

Methods and Results/Accomplishments:

In our experimental work, we have completed the studies of thermally stratified turbulent boundary layers with homogeneous boundary conditions. We have studied smooth wall and rough wall flows, with constant temperature and constant heat flux conditions. For the rough wall, we used a woven mesh, with a geometric maximum height of k = 4.1 mm, corresponding to k^+ = 11 to 50, and δ/k=30 to 31. The experiments were conducted at nine velocities for each of eight wall temperatures, including the neutrally stable case. The corresponding Richardson number and Reynolds number ranges for the smooth wall were:
$0<Ri_\delta<0.52$ and $400<Re_\theta<1650$, and for the rough wall they were $0<Ri_\delta<0.7$ and $900<Re_\theta<2500$.

The collapse in the turbulent stresses with increasing Richardson number is evident from Figure 1. The main difference observed between the smooth and rough cases was the Richardson number at which the turbulent shear stress levels collapses, and effectively where turbulent production ceases. For the smooth case, this occurred at a bulk Richardson number of 0.1 while in the rough case it was 0.15.

The experiments on step changes in roughness and wall temperature are in progress. The low-speed wind tunnel was used to generate a rough wall boundary layer at Reynolds numbers based on momentum thickness of up to 1500. The upstream part of the tunnel wall was heated to introduce a step change in wall temperature to the boundary layer. Particle image velocimetry and a thermocouple rake were used to measure the fluctuating velocity field and mean temperature profile at three locations downstream of the step change. Results on the rate of growth of the internal boundary layer and the corresponding evolution of the turbulent stresses, were presented at the 67th Meeting of the APS/DFD Meeting in November of 2014.

Concomitantly, we finished the large eddy simulations of such transitions going from stable to more stable and from stable to unstable and vice-versa. In the latest phase of the analyses we focused on

understanding the various terms of the TKE budget. In figure 2, we show the turbulent kinetic energy over such a sequence of patches and, as illustrated, the advection of TKE plays a major role and can result in very strong turbulence over the cold patches despite the locally elevated Richardson number. This implies that the cryosphere-atmosphere coupling over such variables surfaces in polar regions (leads and polynyas) will be much stronger than simple surface similarity theories would imply. This complements our results from last year where we get a regionally-averaged heat flux of 200W/m^2, a very significant value, even when the regionally-averaged surface temperature is equal to the air temperature. Over the past year we have also conducted LES with an unsteady synoptic forcing and under baroclinic conditions to better understand the influence of these influences on the response of turbulent boundary layers.

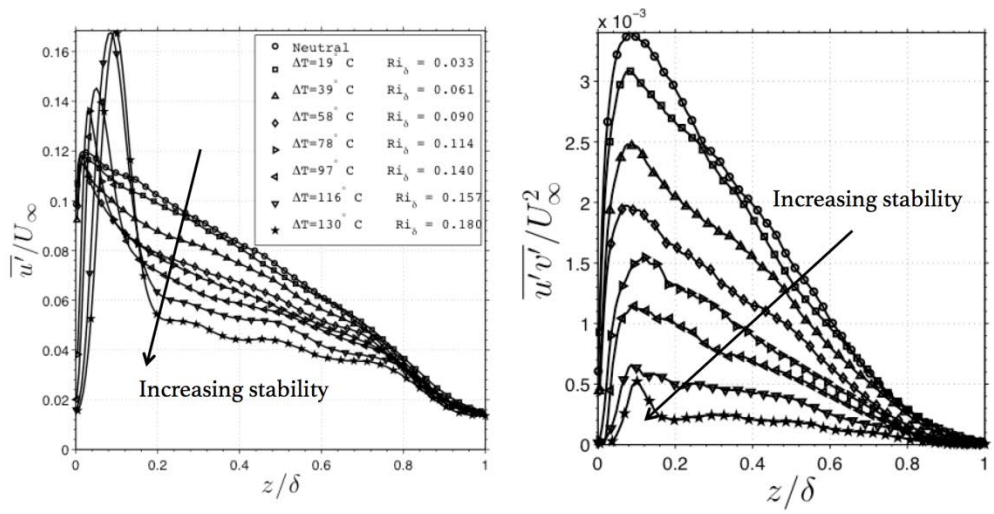


Figure 1. Rough wall. Effect of increasing Richardson number on instantaneous velocity fields, for Re_θ=990 to 1550, and Ri_δ=0 to 0.18.

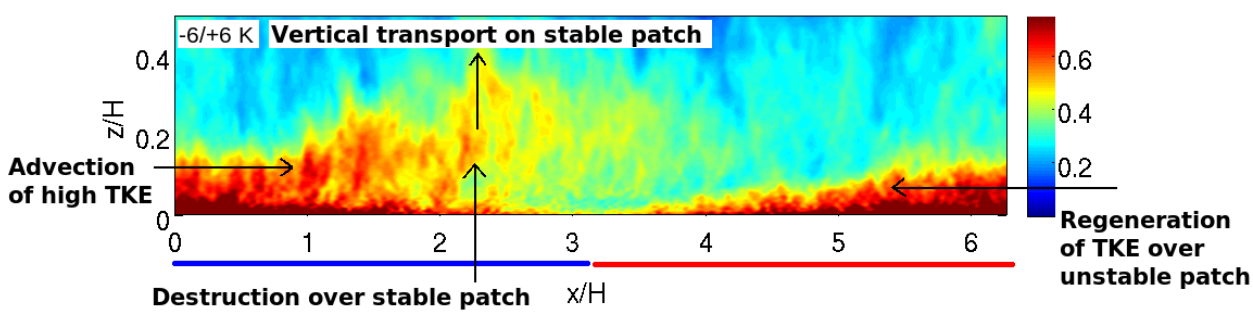


Figure 2. TKE fields from a periodic simulation (the flow is from left to right and the flow that exits at the right side boundary is recirculated as inflow at the left side boundary).

Publications:

Momen M. and Bou-Zeid E. (2015) "Large Eddy Simulations and Damped-Oscillator Models of the Unsteady Ekman", the Journal of Atmospheric Sciences, under review.

Owen Williams, "Density effects on turbulent boundary layer structure: from the atmosphere to hypersonic flow" (PhD, 2014; Postdoc, University of Maryland).

Williams, O. H., Van Buren, T. and Smits, A. J. "Measuring turbulent heat fluxes using PIV and fast response cold-wires." Under review, Experiments in Fluids.

Presentations:

Bou-Zeid E. and Shah S. (2014) "Probing the role of buoyancy in the stable atmospheric boundary layer: direct and large-eddy simulations" 21st Symposium on Boundary Layers and Turbulence, Leeds, UK.

Bou-Zeid E. and Shah S. (2014) "Probing the role of buoyancy in the stable atmospheric boundary layer: direct and large-eddy simulations" 67th Meeting of the American Physical Society Division of Fluid Dynamics, San Francisco, CA, November 23-25.

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

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

Tyler Van Buren, Owen J. Williams, Alexander J. Smits, Laboratory investigation of a thermally stable boundary layer subject to a step change in wall temperature. Paper R32.00001, 67th Meeting of the American Physical Society Division of Fluid Dynamics, San Francisco, CA, November 23-25, 2014.

Owen J. Williams, Tyler Van Buren, Alexander J. Smits, Turbulent heat flux measurements in thermally stable boundary layers. Paper L26.00007, 67th Meeting of the American Physical Society Division of Fluid Dynamics, San Francisco, CA, November 23-25, 2014.

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

Principal Investigator: Kara Sulia (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Chris Golaz (GFDL)

Award Number: NA08OAR4320752
Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Goal: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: To improve microphysical representation within the GFDL Atmospheric Model (V3) and to understand these impacts on the larger scale

Methods and Results/Accomplishments:

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

Within the enumerable process that can occur on the micro scale, the growth of ice crystals can play an important role in the prediction and evolution of the water phase. A new method of ice crystal growth has been developed in which the particle shape history is tracked in an accurate sense to glean a better representation of depositional growth. This effect directly impacts the liquid and ice phase, and indirectly effects cloud lifetime and the radiative budget. The method was developed and refined within the Weather Research and Forecasting Model and was implemented into AM3 during my tenure as a postdoctoral research associate.

Initial three-year results containing the new adaptive habit microphysics scheme reveals a strong sensitivity to the ice-snow autoconversion threshold and also indicates the need for prognostic snow. The model with the new microphysics scheme improves predicted ice water path as compared to the Morrison-Gettleman scheme and likewise for the predicted LWP. Further tests were completed to assess radiative sensitivities and climate effects on a longer time-scale. These tests are still underway.

References:

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

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

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

Publications:

Sulia, K., H. Morrison, and J. Y. Harrington, 2014: Dynamic and microphysical evolution during mixed-phase cloud glaciation simulated using the bulk adaptive habit prediction model. J. Atmos. Sci, 71, 4158-4180.

Progress Report Title: **Processes of Dense Water Formation and Transport in the North Atlantic and their Influences on the Climate**

Principal Investigator: He Wang (Princeton Graduate Student)

CICS/GFDL Collaborator: Sonya Legg (Princeton), Robert Hallberg (GFDL), Thomas Delworth (GFDL)

Award Number: NA08OAR4320752
Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Goal: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: Using climate models to understand the impacts on the AMOC and climate of the processes in the North Atlantic dense water formation regions, including overflows, freshwater transport and shear-driven diapycnal mixing

Methods and Results/Accomplishments:

The sinking branch of the Atlantic Meridional Overturning Circulation (AMOC) consists of dense water formations in the North Atlantic including the Nordic Seas and Labrador Sea. Representations of the dense water formations processes are important to the realistic simulation of the AMOC's mean state and variability in climate models. Here we apply GFDL's two sets of climate models (CM2G and CM2M), which differ only in their ocean components to study the sensitivity of the AMOC on the North Atlantic dense water formation processes. We focus on three processes, including the Nordic Seas dense water overflows, freshwater transport into the Labrador Sea and shear-driven diapycnal mixing.

In the first project, we study the impact of the overflows on the AMOC and climate. We test the response of the climate to different treatments of the overflows in CM2G and CM2M, whose ocean components differ in both horizontal and vertical gridding. We find that the horizontal gyre circulation and North Atlantic climate are sensitive to the existence of the Iceland-Scotland channels overflow, and the vertical structure of AMOC is sensitive to the diapycnal diffusivity in the overflows' immediate downstream region. These findings indicate that the overflow representation in climate models is important to the simulated large scale circulations and climate. The results are published on Ocean Modelling.

In the second project, we study the effect of the freshwater transport through Canadian Arctic Archipelago (CAA) on the AMOC. Freshwater transport from the Arctic acts as a cap to the ocean surface and impacts the air-sea interaction and dense water formation rate there. The freshwater has two routes entering the Labrador Sea, channels through CAA and Fram Strait. The relative roles of these two pathways are studied in CM2G and CM2M by modifying the channels width of CAA. In both coupled models, the Labrador Sea convection is found to be sensitive to the partition of the freshwater import between CAA and Fram Strait. Freshwater entering the North Atlantic via CAA mostly stays along the western boundary and has little effect on the Labrador Sea convection; while freshwater via Fram Strait

circumnavigating the Greenland Coast has a stronger interaction with the center of the Labrador Sea and is more capable of suppressing the convection. The AMOC, on the other hand, does not necessarily follow the modification of Labrador Sea convection caused by freshwater anomaly. Because of the response of gyre circulation and feedbacks on surface density, convection in other regions (Irminger Sea, south of the Labrador Sea) always tends to compensate to the change in Labrador Sea convection. This work is under preparation for publication.

In the currently ongoing third project, we study the impact of shear-driven mixing. Shear-driven mixing influences the produce water of overflows (Nordic Seas and Antarctica). The Antarctic overflows and overturning circulation are found to be sensitive to the critical Richardson number.

Publications:

Wang, H., Legg, S. A., Hallberg, R. W., 2015. Representations of the Nordic Seas overflows and their large scale climate impact in coupled models. Ocean Modelling. 86 (0), 76 -92.

Progress Report Title: **Implementation of a Double-Moment Aerosol Microphysics Scheme**

Principal Investigator: Yuxing Yun (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Yi Ming (GFDL)

Award Number: NA08OAR4320752
Award Number: NA14OAR4320106

Other Participating Researchers: Chien Wang (MIT)

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Goal: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: Implement a double-moment aerosol microphysics scheme to predict aerosol number and size distribution

Methods and Results/Accomplishments:

A double moment aerosol microphysics scheme is implemented in to GFDL-AM4. The scheme predicts mass and number concentration for sulfate, black carbon, and organic carbon aerosols (Wilson et al. 2001, Ekman et al. 2006, Kim et al. 2008). There are three size modes for sulfate: nucleation, Aitken, and accumulation. Black carbon and organic carbon are all in accumulation modes. The internal and external mixture of black/organic carbon and sulfate are explicated tracked. Externally mixed black/organic carbon are transferred to internal mixture with sulfate from the condensation of gas phase H_2SO_4. There are 9 added mass tracers: 3 for each sulfate modes, 2 for internally and externally mixed black carbon, 2 for internally and externally mixed organic carbon, and 2 for the black/organic carbon in the internal mixture. There are 7 added number tracers, one for added each mass tracer except for black/organic carbon in the internal mixture, since the number is the same as the internally mixture itself. The three modes of sulfate aerosols also coagulate with each other and onto black/organic carbon aerosols. The production of gas phase H_2SO_4 comes from the oxidation of SO_2 and OH. The aqueous phase reaction of SO_2 and H_2O_2 and SO_2 and O_3 produces sulfate aerosols that directly go to the accumulation mode. Nucleation mode sulfate are formed by the binary nucleation of H_2SO_4.

After the implementation, the updated GFDL-AM4 model was evaluated against other models and field observations. The number and mass concentrations of sulfate, black carbon, and organic carbon aerosols are comparable to the CAM5-MAM7 model, which has its own double moment aerosol scheme. The black carbon vertical profiles of several remote locations were compared to the HIPPO observation. The black carbon seasonal cycle and sulfate seasonal cycle were also compared to in situ observations. The comparison was found to depend on the tuning of wet and dry removal of the aerosols.

References:

Ekman, A., C. Wang, J. Ström, and R. Krejci (2006), Explicit simulation of aerosol physics in a cloud- resolving model: Aerosol transport and processing in the free troposphere, J. Atmos. Sci., 63, 682-

696, doi:10.1175/JAS3645.1.

Kim, D., C. Wang, A. M. L. Ekman, M. C. Barth, and P. J. Rasch (2008), Distribution and direct radiative forcing of carbonaceous and sulfate aerosols in an interactive size-resolving aerosol-climate model, J. of Geophys. Res., 113(D16), doi:10.1029/2007jd009756.

Wilson, J., C. Cuvelier, and F. Raes (2001), A modeling study of global mixed aerosol fields, J. Geophys. Res., 106, 34081-34108.

Publications:

Yuxing Yun, Songmiao Fan, Yi Ming, Paul Ginoux, and Po-lun Ma, The implementation of a double moment aerosol microphysics scheme in GFDL-AM4. (in preparation).

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

Principal Investigator: Liping Zhang (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Tom Delworth (GFDL)

Award Number: NA08OAR4320752
Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Modeling and Analysis

NOAA Goals:
Climate Goal: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

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

Methods and Results/Accomplishments:

North Pacific decadal oscillation (PDO) (Figure 1) is examined in a suite of coupled climate models developed at the Geophysical Fluid Dynamics Laboratory (GFDL) (Delworth et al. 2006; Delworth et al. 2012). Simulated SST anomalies in the Kuroshio Oyashio Extension (KOE) region exhibit a significant spectral peak at approximately 20 years (Zhang and Delworth 2015). We use sensitivity experiments to show that: (i) the simulated PDO mechanism involves extratropical air-sea interaction and oceanic Rossby wave propagation, (ii) the oscillation can exist independent of interactions with the Tropics, but that such interactions can enhance the PDO, and (iii) ocean to atmosphere feedback in the extratropics is critical for establishing the approximately 20-year timescale of the PDO. The simulated PDO has a realistic association with precipitation variations over North America, with a warm phase of the PDO generally associated with positive precipitation anomalies over regions of the western United States.

A suite of initialized hindcast and forecast ensemble experiments using fully coupled GFDL CM2.1 model are used to examine the PDO prediction time scale. Our results suggest that the PDO has a much shorter prediction skill in the initialized system than that in the North Atlantic Ocean. The SST variability associated with the PDO can only be predictable up to 1 year at the 90% significance level when the prediction skill is verified against the independent observational datasets. Consistent with previous studies, the upper ocean heat content associated with the PDO has a longer prediction skill than the SST, however, its prediction skill only extends to 2 year at the 90% significance level. The short prediction timescale is largely associated with the PDO characteristics which are closely related with the upper layer wind-driven ocean circulation and mid-latitude air-sea feedback. The underestimated mid-latitude air-sea coupling in the GFDL model and strong stochastic characteristics of mid-latitude wind may hinder the real prediction scale of PDO.

References:

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

Delworth, T. L. et al., 2012: Simulated climate and climate change in the GFDL CM2.5 high

resolution coupled climate model. J. Climate., 25(8), 2755-2781.

Publications:

Liping Zhang and Tom Delworth 2015: Analysis of characteristics and mechanisms of the Pacific decadal oscillation in a suite of coupled models from the Geophysical Fluid Dynamics Laboratory. submitted to Journal of climate (in revision).

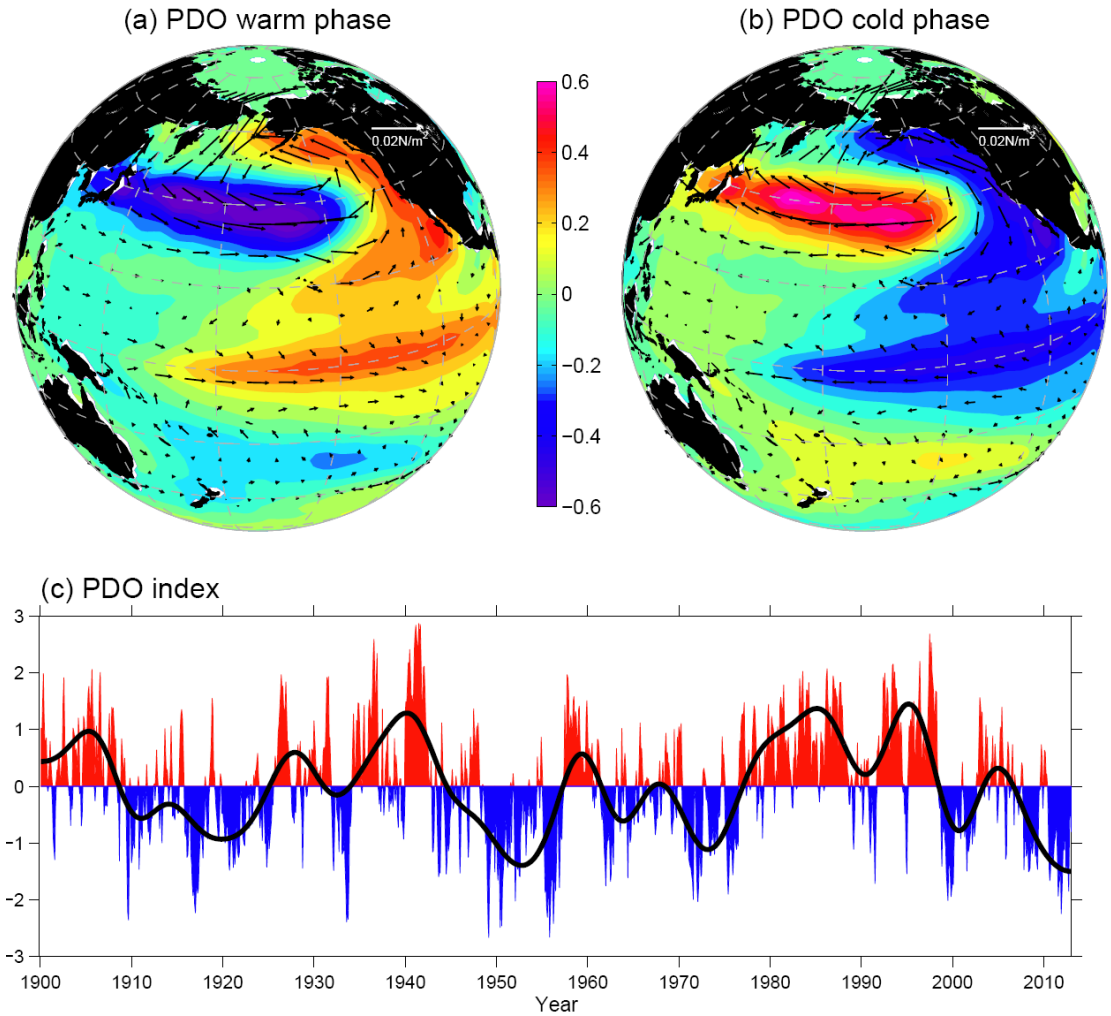


Figure 1: Shown are the PDO behaviors in observations. (a-b) Regression of SST (^{o}C) and surface wind stress (N/m^2) against the (c) PDO index which is defined as the principal component time series of leading EOF over the North Pacific Ocean (20°N-60°N). (a) represents the PDO warm phase and (b) represents the PDO cold phase. The principal component time series (c) is normalized by its standard deviation, thus the amplitudes in (a) and (b) correspond to one standard deviation change of the corresponding principal component time series.

Progress Reports:

Earth System Model Applications

Progress Report Title: **Climatic Controls on Arid Midlatitude Asia**

Principal Investigator: Jane Baldwin (Princeton Graduate Student)

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

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

Award Number: NA08OAR4320752
Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

NOAA Goals:
Climate Goal: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

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

Methods and Results/Accomplishments:

This year we investigated, or have begun to investigate, four influences on the climate of Arid Midlatitude Asia (AMA):

Tianshan Mountains: AMA is bisected by an area of greater precipitation at the Tianshan Mountains into an East desert (including the Gobi, Taklamakan, etc) and a West desert (located at Central Asia around the Aral Sea). The East and West deserts are differentiated both spatially and by their climatology: precipitation peaks in the summer in the East and the winter in the West. Last spring, we ran CM2.5-FLOR, which has a 50 km atmosphere/land and a 1 degree ocean, with the Tianshan mountains removed to determine the influence of these mountains on the area and climatology of this arid region. We found that the Tianshan have a range of local and remote effects on climate, including reducing winter precipitation in the East desert, but significantly enhancing the East Asian monsoon. Our work this year has focused on establishing the statistical significance of these results, and investigating the physical mechanisms behind the Tianshan's climatic influences via moisture balance and energy decomposition analyses. We have also written these results up in a paper to be submitted in the next few months.

Tibetan Plateau and the Himalayas: A number of prior studies have investigated the effect of the Tibetan Plateau on climate (i.e. Manabe and Broccoli 1990, Boos and Kuang 2010). CM2.5-FLOR captures AMA and the Indian Monsoon more precisely and accurately than the models used in these previous studies. We ran a series of CM2.5-FLOR experiments without the Tibetan Plateau or Himalayas, including a run with dynamic vegetation. Changes to the deserts are generally in keeping with prior work—AMA disappears or moves southward without the Tibetan Plateau. However, while prior work suggested that Indian monsoon strength decreases everywhere without the Tibetan Plateau, monsoon changes in our experiment vary spatially including increases in precipitation over Southern India if South

India topography remains intact. We are still in the process of analyzing these experiments, particularly the dynamic vegetation results and physical mechanisms for the observed changes.

Remote Monsoon Effects: Rodwell and Hoskins 1996 suggested that the monsoon high over Asia generates a Rossby wave, which in turn promotes subsidence and drying at western Asia and the Sahara. This result was found with an initialized model that did not have fully developed baroclinic instability. We are currently exploring the dynamical controls on this westward extent in a steady-state framework with developed baroclinic instability using GFDL's idealized dynamical core forced with an Indian monsoon-like heating. Thus far we have programmed the model forcing to be monsoon-like and have generated a series of model runs to display the sensitivity of the circulation to different forcing parameters. We are currently in the process of analyzing these model runs.

Evaporation Climatology: In both CM2.1 and CM2.5-FLOR, East desert precipitation and evaporation peak simultaneously in the summer. In contrast, for the West desert CM2.1 precipitation and evaporation both peak in the winter, while in CM2.5-FLOR precipitation peaks in the winter but evaporation peaks a few months later in the early spring. Reanalysis suggests that lagged evaporation is more realistic for the West desert, though analysis of more observations is necessary to confirm this result. Preliminary analysis suggests that a more advanced land model in CM2.5-FLOR (LM3) allows lagged evaporation in this region via deeper soil moisture layers and plants that draw on these deeper layers. Further analysis will focus on confirming this result, and exploring the implications of the West vs. East precipitation-evaporation lag for both climate and desertification.

Outreach Activities: Mentored undergraduates especially women interested in science research as resident graduate student in Princeton University's Rockefeller College. Activities included helping revise graduate school application statements, holding discussions about women in science, writing recommendations for students applying to research programs, organizing groups to go to science lectures on campus, and organizing "boot camps" to assist students writing senior theses.

References:

Manabe, S. and Broccoli, A. (1990). Mountains and arid climates of middle latitudes. Science, 247(4939):192–195.

Rodwell, M. J. and Hoskins, B. J. (1996). Monsoons and the dynamics of deserts. Quarterly Journal of the Royal Meteorological Society, 122(534):1385–1404.

Boos, W. R. and Kuang, Z. (2010). Dominant control of the south Asian monsoon by orographic insulation versus plateau heating. Nature, 463(7278):218–222.

Presentations:

Baldwin, Jane and Gabriel A. Vecchi. Influence of the Tianshan Mountains on Arid Central Asia. American Geophysical Union 2014, San Francisco, California.

Progress Report Title: **Antarctic Sea Ice and the Southern Ocean Overturning Circulation**

Principal Investigator: Anna FitzMaurice (Princeton Graduate Student)

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

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (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: Principally, to understand the robustness and causality (if any) of the correlation currently observed between the Antarctic sea ice extent and the Southern Ocean overturning cell divide; more broadly, to understand the relationship between sea ice, surface buoyancy fluxes, and deep water formation in the Southern Ocean

Methods and Results/Accomplishments:

Recent publications have noted a correspondence between the latitude of the cell divide of the Southern Ocean overturning circulation and the Antarctic sea ice extent (Ferrari *et. al.*, 2014; Marshall & Speer, 2012). It has been suggested that this correlation may be causal, although the direction of the causality, if it exists, is not immediately obvious. Ferrari *et. al.* argue that sea ice acts to modulate the latitude at which the annual surface buoyancy flux in the Southern Ocean changes sign, and that this in turn dictates where the cell divide must occur. Conversely, Marshall & Speer suggest that the location of the overturning cell divide may act to constrain the maximum sea ice extent via its influence on near-surface temperatures.

As part of this project, we have tested the robustness and possible causality of the correlation between the Antarctic sea ice extent and the Southern Ocean overturning cell divide using the coupled climate model CM2G. Two perturbation experiments were performed, one in which the overturning circulation was perturbed without directly affecting the sea ice extent, and one in which the sea ice extent was perturbed without directly altering the overturning circulation. Our results suggest that the overturning cell divide does not act as a strict constraint on the sea ice extent. Also, whilst sea ice does exert a strong seasonal influence on surface buoyancy fluxes, which in turn impact the Southern Ocean overturning circulation, a direct relationship does not exist between the latitudinal change in sign of annual surface buoyancy fluxes as determined by the sea ice extent, and the Southern Ocean overturning circulation cell divide. Further work will focus on better describing the nuanced and seasonally varying relationship between sea ice, surface buoyancy fluxes, deep water formation, and the Southern Ocean overturning circulation.

References:

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

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

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

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

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

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

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

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

Methods and Results/Accomplishments:

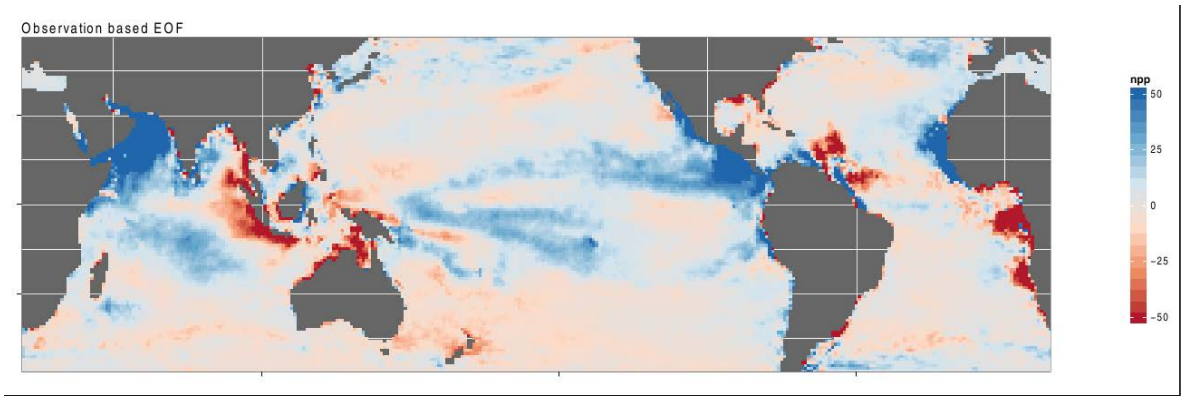
We are using statistical methods to characterize long term, spatial-temporal variability in physical (surface temperature, photosynthetic active radiation, upwelling and ocean circulation) and biological variables (chlorophyll, net primary and secondary production). We conduct parallel analysis on observational data and on simulations of the Carbon, Ocean Biogeochemistry and Lower Trophics (COBALT) planktonic ecosystem model coupled to GFDL ESM2M (Stock et al. 2014). This approach allows us to assess the ability of COBALT to reproduce observed patterns of variation from regional to wide scale, biogeographical gradients. Furthermore, COBALT simulations allow the analysis of the propagation of variability from lower to upper trophic levels, and thus to analyze patterns of variability beyond current observational constraints.

Work since November 2014 is still on an initial phase, but preliminary results indicate that ESM2M and COBALT capture large scale, decadal forcing on biological variables associated to climate modes like El Niño Southern Oscillation (Fig. 1). Our analyses revealed as well the ability of COBALT to represent a longer persistence of perturbations on higher trophic levels (Fig. 2). This suggests that the model might be able to represent as well large amplitude regime shifts in living marine resources linked to the planktonic trophic web. Future plans include the refinement of these analyses and the extension to other variables and modes of variation.

References:

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

a)



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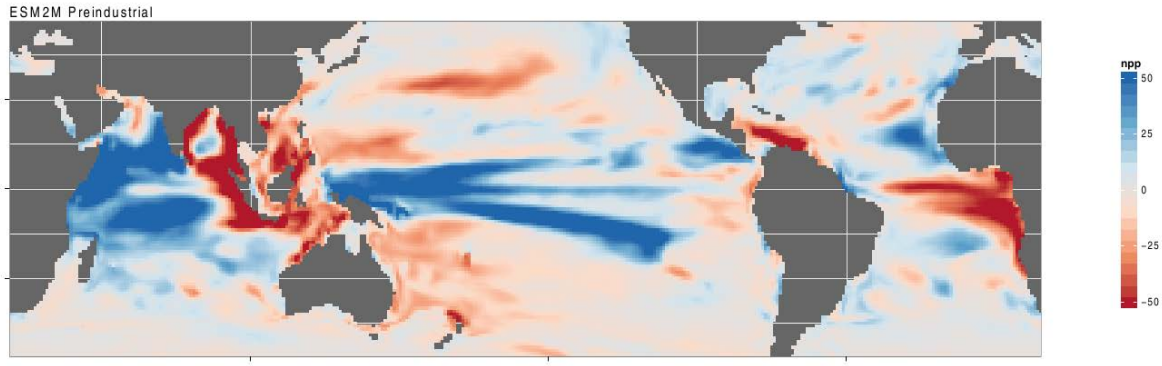


Figure 1. First Empirical Orthogonal Function (EOF) of primary production anomalies (mg C m^{-2} day^{-1}) for (a) estimates derived from remote sensing data using Eppley's model (data from www.science.oregonstate.edu/ocean.productivity), and for (b) COBALT based predictions in a preindustrial model run.

a) b)

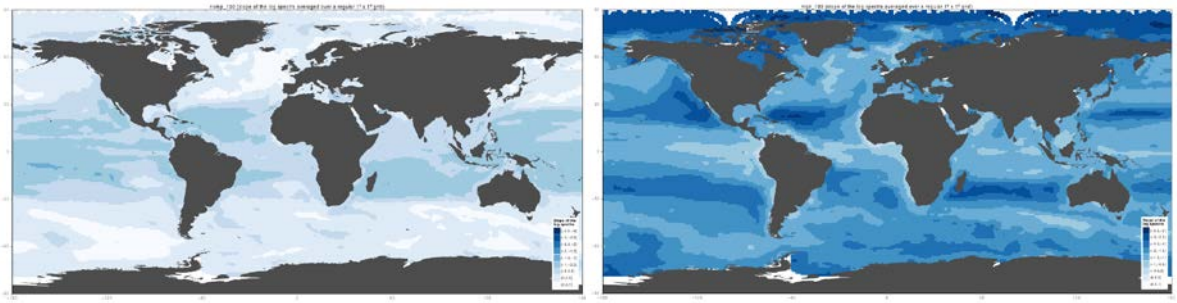


Figure 2. Slope of the logarithm of the power spectra density of time series of (a) small phytoplankton and (b) large zooplankton in a COBALT preindustrial run. Larger, negative values (darker tones) correspond to time series with more memory.

Progress Report Title: **Tropical Rainfall Responses to Forced Ocean Surface Warming**

Principal Investigator: Spencer Hill (Princeton Graduate Student)

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

Award Number: NA08OAR4320752

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

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

Objectives: Understand the precise physical mechanisms underlying the tight relationship in models and observations between the Intertropical Convergence Zone position and meridional energy fluxes; reduce the spread among atmospheric general circulation models in how precipitation in the Sahel region of Africa responds to uniformly warmed sea surface temperatures

Methods and Results/Accomplishments:

We use GFDL atmospheric models to investigate how rainfall in the Tropics responds to imposed sea surface temperature (SST) changes. For the zonal mean rainfall, we examined the physical processes involved in movements of the Intertropical Convergence Zone (ITCZ). Based on numerous idealized SST perturbation experiments in the AM2.1 model, we developed a theoretical justification for the well documented correlation in the literature between the ITCZ position and meridional energy fluxes at the equator.

More recently, we have examined how rainfall in the Sahel region of Africa responds to uniform +2 Kelvin SST warming in four of GFDL's atmospheric models – AM2.1, AM3, HiRAM, and c48-HiRAM. We have demonstrated that local cloud radiative processes play an important role in the Sahel rainfall response, and by comparison with observations we are close to being able to falsify some of the model projections and thereby reduce the uncertainty in the region's future rainfall.

Outreach Activities: 45 minute presentation by Spencer Hill and fellow Princeton AOS student Sarah Schlunegger on climate science to 7th grade students at Forrestdale Middle School in Rumson, NJ, scheduled for April 10, 2015

Publications:

Hill, S. A., Y. Ming, and I. M. Held (2015). "Mechanisms of forced tropical meridional energy flux change." J. Climate 28, no 5, p. 1725-1742. Doi:10.1175/JCLI-D-14-00165.1

Hill, S. A., Y. Ming, I. M. Held, and M. Zhao (2015). "The Sahel rainfall response to uniform ocean surface warming." In preparation for submission to PNAS.

Presentations:

Hill, S. A., Y. Ming, and I. M. Held "Mechanisms of forced tropical meridional energy flux change. Latsis Symposium, Poster presentation, ETH Zurich, June 2014.

Hill, S. A., Y. Ming, I. M. Held, and M. Zhao. "The Sahel rainfall response to uniform ocean surface warming." Invited oral presentation, Yale University, October 2014.

Hill, S. A., Y. Ming, I. M. Held, and M. Zhao. “The Sahel rainfall response to uniform ocean surface warming.” Poster presentation, AGU Fall Meeting, December 2014.

Hill, S. A., Y. Ming, I. M. Held, and M. Zhao. “The Sahel rainfall response to uniform ocean surface warming.” Poster presentation, AMS Annual Meeting, January 2015.

Hill, S. A., Y. Ming, I. M. Held, and M. Zhao. “The Sahel rainfall response to uniform ocean surface warming.” Oral presentation, NYU CAOS program student seminar series, March 2015.

Hill, S. A., Y. Ming, I. M. Held, and M. Zhao. “The Sahel rainfall response to uniform ocean surface warming.” Oral presentation, Princeton AOS dynamics seminar series, March 2015.

Progress Report Title: **Seasonal Predictions in a High-Resolution GFDL Climate Model**

Principal Investigator: Liwei Jia (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Gabriel Vecchi (GFDL)

Other Participating Researchers: Xiaosong Yang (UCAR)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (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: Investigate predictive skill on seasonal scales in a high-resolution model; explore the impact of increasing atmospheric and land resolution on seasonal predictions

Methods and Results/Accomplishments:

I studied the seasonal predictive skill of 2m air temperature and precipitation over land in a high-resolution FLOR model (~50KM in atmosphere and land, ~1 degree in the ocean and sea ice), and investigated the mechanism of the skill. A statistical optimization method was used to diagnose predictable components in the model. The seasonal skill of temperature and precipitation has been significantly improved in the FLOR model compared to the lower-resolution CM2.1 model. The two most predictable components of temperature are characterized by a component that is likely due to changes in external radiative forcing in boreal winter and summer and an ENSO-related pattern in boreal winter. The most predictable components of precipitation in both seasons are very likely ENSO-related. These components of temperature and precipitation can be predicted with significant correlation skill at least 9 months in advance.

I am also studying the role of sea surface temperature (SST) in extreme events, e.g., U.S. summer heat wave in 2012. Preliminary results have shown that SSTs play an important role in 2012 U.S. heat wave, in contrast to the 2006 U.S. heat wave, in which other mechanisms than SSTs play a role.

Publications:

Liwei Jia, Xiaosong Yang, Gabriel A. Vecchi, Richard G. Gudgel, Thomas L. Delworth, Anthony Rosati, William F. Stern, Andrew T. Wittenberg, Lakshmi Krishnamurthy, Shaoqing Zhang, Rym Msadek, Sarah Kapnick, Seth Underwood, Fanrong Zeng, Whit G. Anderson, Venkatramani Balaji, and Keith Dixon, 2015: Improved Seasonal Prediction of Temperature and Precipitation over Land in a High-Resolution GFDL Climate Model. J. Climate, 28, 2044–2062.

Xiaosong Yang, Gabriel A. Vecchi, Rich G. Gudgel, Thomas L. Delworth, Shaoqing Zhang, Anthony Rosati, Liwei Jia, William F. Stern, Andrew T. Wittenberg, Sarah Kapnick, Rym Msadek, Seth D. Underwood, Fanrong Zeng, Whit Anderson, Venkatramani Balaji, 2015, Seasonal predictability of extratropical storm tracks in GFDL's high-resolution climate prediction model. J. Climate, in press.

G. A. Vecchi, T. Delworth, R. Gudgel, S. Kapnick, A. Rosati, A. T. Wittenberg, F. Zeng, W. Anderson, V. Balaji, K. Dixon, L. Jia, H.-S. Kim, L. Krishnamurthy, R. Msadek, W. F. Stern, S. D. Underwood, G. Villarini, X. Yang, and S. Zhang, 2014: On the Seasonal Forecasting of Regional Tropical Cyclone Activity. J. Climate, 27, 7994–8016.

Progress Report Title: **Drought Research and Predictions**

Principal Investigator: Nathaniel Johnson (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Gabriel Vecchi (GFDL), Andrew Wittenberg (GFDL), Sarah Kapnick (GFDL), Xiaosong Yang (GFDL), Liwei Jia (Princeton)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

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

Objectives: The primary objectives of this project are to improve our understanding of the causes and predictability of regional droughts on seasonal to interannual timescales, to develop improved monitoring approaches for regional droughts, and to develop improved drought prediction methods.

Methods and Results/Accomplishments:

Since arriving on December 1, 2014, I have been investigating sources of North American precipitation biases in GFDL's climate models with the hope that such knowledge can translate into improved understanding of factors influencing North American drought. Specifically, I have examined differences between free-running and flux-adjusted versions of the Forecast-oriented Low Ocean Resolution (FLOR) models in an attempt to decipher why positive precipitation biases over western North America are substantially reduced in the flux-adjusted version. Preliminary results suggest that sea surface temperature biases in the North Pacific of the free-running version may be a key factor resulting in the strong precipitation biases.

During these first few months of my time at Princeton University, I also have been actively involved in NOAA's efforts to develop forecast products for lead times of 15-30 days. In February I delivered a webinar on the prospects and current efforts to initiate forecast products at these lead times as part of the ongoing NOAA Modeling, Analysis, Predictions, and Projections (MAPP) Webinar series. Beginning in April, I will contribute to the implementation of forecast guidance for the Climate Prediction Center based on my previous research.

Publications:

Johnson, N. C., Xie, S.-P, & Deser, C. (December 2014). Probabilistic representations of regional climate change in the CESM Large Ensemble. Poster presented at the 2014 AGU Fall Meeting, San Francisco, CA.

Johnson, N. C., Kosaka, Y., & Xie, S.-P. (January 2015). Increasing temperature extremes during the recent global warming hiatus. Oral presentation at the 95th AMS Annual Meeting, Phoenix, AZ.

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

Progress Report Title: **Climate Variability Modulates Western U.S. Ozone Air Quality in Spring via Deep Stratospheric Intrusions**

Principal Investigator: Meiyun Lin (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Larry Horowitz (GFDL)

Other Participating Researchers: Arlene Fiore (Columbia), Andrew Langford (NOAA ESRL), Samuel Oltmans (NOAA ESRL), David Tarasick (Environment Canada), Harald Rieder (University of Graz-Austria)

Award Number: NA08OAR4320752

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

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

Objectives: There is mounting evidence that deep stratospheric intrusions can elevate western U.S. surface ozone to unhealthy levels during spring. These intrusions can be classified as "exceptional events", which do not count towards regulatory determinations. Understanding the factors driving their year-to-year variability is thus relevant for effective implementation of the U.S. ozone air quality standard.

Methods and Results/Accomplishments:

Here we use observations and chemistry-climate model simulations to demonstrate a linkage between Western U.S. surface ozone and modes of climate variability. We show more frequent late spring stratospheric intrusions when the polar jet meanders towards the western USA, as occurs following strong La Niña winters (Niño3.4 < -1.0ºC). While El Niño leads to enhancements of upper tropospheric ozone, we find this influence does not reach surface air. Fewer and weaker intrusion events follow in the two springs after the 1991 volcanic eruption of Mt Pinatubo. The linkage between La Niña and Western U.S. stratospheric intrusion frequency can be exploited to provide a few months of lead time during which preparations could be made to deploy targeted measurements aimed at identifying these exceptional events.

Publications:

Lin, Meiyun, A.M. Fiore, L.W. Horowitz, A.O. Langford, S. J. Oltmans, D. Tarasick, H.E. Reider: Climate variability modulates western U.S. ozone air quality in spring via deep stratospheric intrusions, Nature Communications, in press, 2015.

R. Fine, M.B Miller; J. Burley; D. Jaffe; R. B. Pierce; M. Lin; M. S Gustin. Variability and sources of surface ozone at rural sites in Nevada, USA: Results from two years of the Nevada Rural Ozone Initiative (NVROI), Science of the Total Environment, doi:10.1016/j.scitotenv.2014.12.027.

B. Brown-Steiner, P.G. Hess, M. Lin. On the capabilities and limitations of GCCM Simulations of Summertime Regional Air Quality: A Diagnostic Analysis of Ozone and Temperature Simulations in the U.S. Using CESM and CAM-Chem, Atmospheric Environment, doi:10.1016/j.atmosenv.2014.11.001.

A.O. Langford, C.J. Senff, R.J. Alvarez II, J. Brioude, O.R. Cooper, J.S. Holloway, M.Y. Lin, R.D. Marchbanks, R.B. Pierce, S.P. Sandberg, A.M. Weickmann , E.J. Williams. An overview of the 2013 Las Vegas Ozone Study (LVOS): Impact of stratospheric intrusions and long-range transport on surface air quality. Atmospheric Environment, doi: 10.1016/j.atmosenv.2014.08.040.

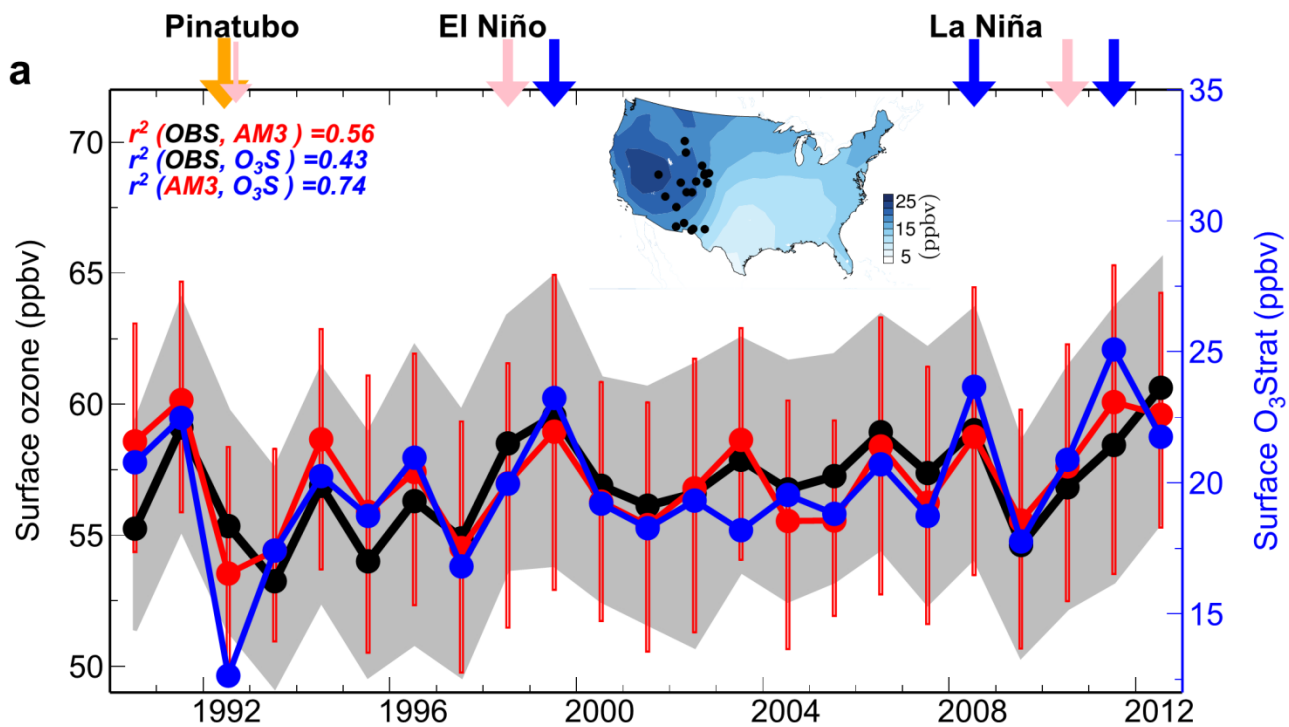
A.M. Fiore, J.T. Oberman, M.Y. Lin, L. Zhang, O.E. Clifton, D.J. Jacob, V. Naik, L.W. Horowitz, J.P. Pinto (2014): Estimating North American background ozone in U.S. surface air with two independent global models: Variability, uncertainties, and recommendations, Atmos. Environ, V96, Pages 284-300, DOI: 10.1016/j.atmosenv.2014.07.045, 2014.

Zoogman, P., Jacob, D. J., Chance, K., Liu, X., Lin, M., Fiore, A., and Travis, K. (2014). Monitoring high-ozone events in the US Intermountain West using TEMPO geostationary satellite observations, Atmos. Chem. Phys., 14, 6261-6271, doi:10.5194/acp-14-6261-2014, 2014.

B.N. Duncan, A. I Prados, L. Lamsal, Y. Liu, D. Streets, P. Gupta, E. Hilsenrath, R. Kahn, JE Nielsen, A. Beyersdorf, S. Burton, AM Fiore, J Fishman, D Henze, C Hostetler, NA Krotkov, P. Lee, M. Lin, S. Pawson, G. Pfister, KE Pickering, B. Pierce, Y. Yoshida, L. Ziemba (2014). Satellite data of atmospheric pollution for U.S. air quality applications: Examples of applications, summary of data end-user resources, answers to FAQs, and common mistakes to avoid. Atmospheric Environment, V94, Pages 647–662, DOI: 10.1016/j.atmosenv.2014.05.061

Invited Presentations:

June 2014, NASA Air Quality Applied Sciences Team (AQAST) Meeting, Harvard University: Year-to-year variability in Western U.S. high-ozone events tied to stratospheric influence: Implications for seasonal prediction to aid regional air quality planning.



Strong stratospheric influence on inter-annual variability of springtime Western U.S. surface ozone is documented in this figure. Median of maximum daily 8-hour average ozone at 22 high-elevation sites (black filled circles on map) during April-May from year 1990 to 2012 as observed (black) and simulated (red) by the GFDL AM3 model with fixed anthropogenic emissions; grey shading and red bars, respectively, represent the 25th - 75th percentiles. The median stratospheric influence (O_3Strat) for each year (blue; right axis) and 23-year climatology (inset map) is shown. **Figure from Meiyun Lin et al (Nature Communications, in press, 2015)**

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

Principal Investigator: Meiyun Lin (Princeton Associate Research Scholar)

CICS/GFDL Collaborator: Larry Horowitz (GFDL)

Other Participating Researchers: Owen Cooper (NOAA ESRL)

Award Number: NA14OAR4320106

Task III: Individual Projects

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

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

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

Methods and Results/Accomplishments:

We conduct a suite of 1980-2012 hindcast simulations with the Geophysical Fluid Dynamic Laboratory global chemistry climate model (GFDL AM3) designed to isolate the response of ozone to historical changes in human-induced emissions of non-methane ozone precursors from Asia versus North America, stratosphere/troposphere exchange, methane, wildfires and meteorology. We have carefully evaluated these multi-decadal hindcast simulations using available observations from satellite instruments, ozonesondes, and ground-based networks. For example, Figure 1 shows surface ozone trends over 1988-2012 at 52 rural monitoring sites across the U.S. as observed and simulated by the GFDL AM3 model with both emissions and meteorology varying over time. The model captures key features of observed surface O_3 trends, including the overall increase in the western USA, the significant reduction of high-ozone events (95th percentile) in the eastern USA, and larger decreases in median ozone at southeast vs northeast U.S. regions. The model indicates that background ozone that flows into the western U.S. in the 2000s has increased ~6 ppb in spring and ~4 ppb in summer compared to the 1980s, counteracting the effects of U.S. domestic emission controls. Springtime ozone mixing ratios over the western U.S. are highly variable in space and time depending on the location and meandering of mid-latitude jet. We find that sparse in-situ sampling and short observational records in light of large meteorological variability from year to year can complicate the attribution of observed trends. These results have been presented by PI Meiyun Lin in a number of conferences. Two manuscripts are currently in preparation for submission to a peer-reviewed journal.

Invited Presentations:

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

Feb-19, 2015, CENRS Air Quality Research Subcommittee, Washington DC: Key drivers of Western U.S. surface ozone variability over recent decades: Stratospheric intrusions, Asian pollution, and climate (Meiyun Lin, Invited)

Dec-15, 2014, American Geophysical Union Fall Meeting, California: Key drivers of Western U.S. surface ozone variability from 1980-2050: From extreme events to background trends (Meiyun Lin, Invited)

Dec-19, 2014, American Geophysical Union Fall Meeting, California: Role of climate variability on tropospheric ozone (Meiyun Lin, Invited)

May 2014, IGAC/SPARC Chemistry-Climate Model Initiative Workshop, Lancaster, UK: Tropospheric ozone variability at Mauna Loa Observatory tied to decadal climate variability (Meiyun Lin, Invited)

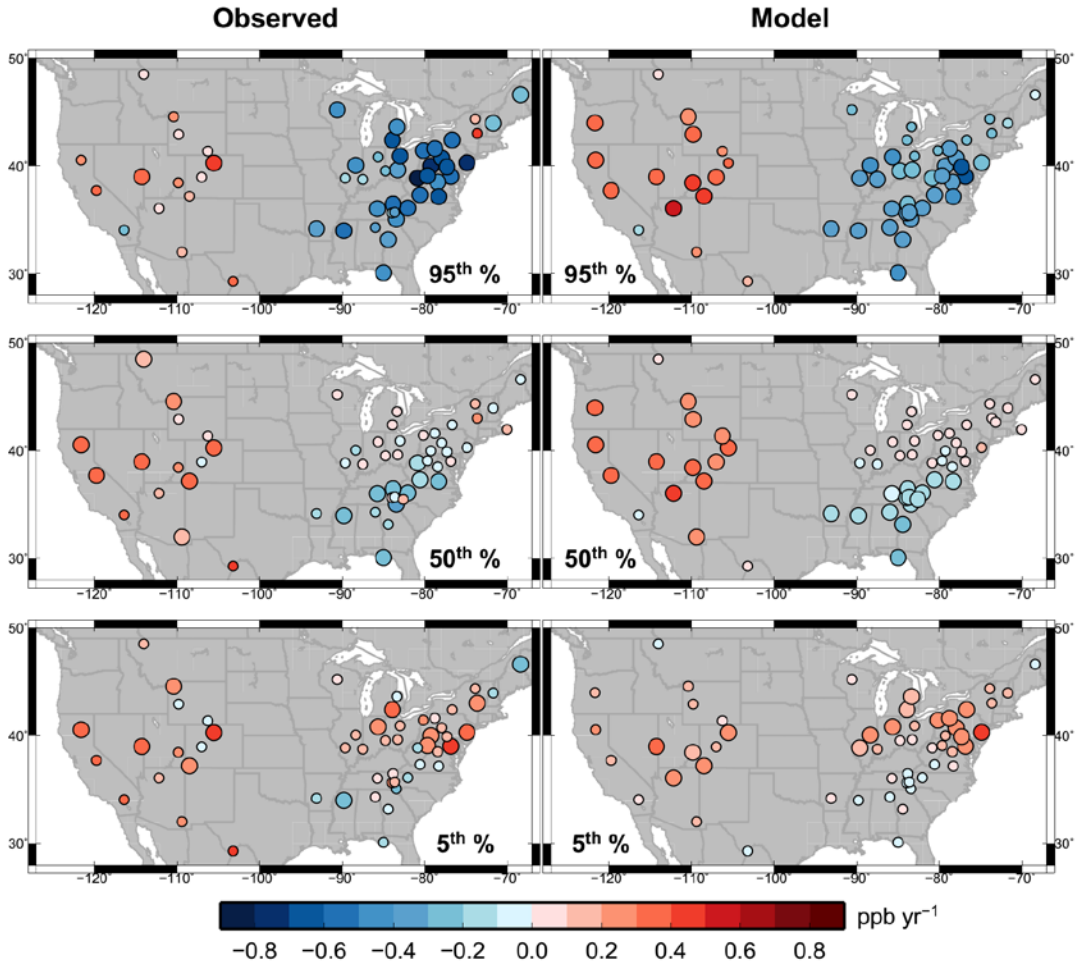


Figure 1: Springtime trends in maximum daily 8-hour surface ozone (ppb yr^{-1}) at U.S. rural sites for the 95th, 50th, and 5th percentiles over 1988-2012 as observed and simulated in the GFDL AM3 model. Indicated are sites with statistically significant (large symbols) and insignificant (small symbols) trends. (**Credit: Meiyun Lin**)

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

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

CICS/GFDL Collaborator: John Dunne (GFDL)

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

Award Number: NA08OAR4320752
Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

NOAA Goals:
Ecosystem Goal: Protect, Restore, and Manage the Use of Coastal and Ocean Resources through Ecosystem-based Management (50%)
Climate Goal : Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond (50%)
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: Assess sensitivity of global coral reefs to climate warming and ocean acidification

Methods and Results/Accomplishments:

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

We then applied a suite of alternative algorithms with respect to underlying assumptions of coral acclimation and adaptation to changes in thermal stress both historically and under future climate change projections using downscaled output from GFDL's Earth System Model (ESM2M; Logan et al., 2014). These physiologically derived bleaching prediction methods refine future bleaching projections, and advance population and community modeling efforts. We use bias-corrected global SST output from ESM2M to evaluate implications of the new representative concentration pathways (RCPs) used by the 5th IPCC Assessment to coral bleaching trajectories. Results provide a range of future bleaching frequencies, some of which dramatically improve the outlook for reef-building corals (Logan et al., 2014).

We are currently expanding upon our projections of coral reef bleaching frequency based on output from GFDL's Earth System Models. We are using a more mechanistic bleaching prediction method that will allow us to incorporate genetic diversity of algal symbionts to modulate coral adaptation to changing thermal stress after the work of Baskett et al. (2009). We also plan to include the effects of ocean acidification in the model by decreasing calcification rates as aragonite saturation state decreases. This will allow us to additionally assess trajectories of coral cover within reefs and estimate the frequency of

thermal stress to coral reefs, the rate of recovery from bleaching events, the combined effects of temperature and ocean acidification, and the resulting trajectories of coral cover. The results will represent a range of possible futures for each local coral reef "grid cell", subject to uncertainty in the factors governing reef resistance and resilience and in future climate projections.

References:

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

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

Logan, C. A., J. P. Dunne, C. M. Eakin, and S. D. Donner, 2014: Incorporating adaptive responses into future projections of coral bleaching. Global Change Biology. doi: 10.1111/gcb.12390

Publications:

Logan, C. A., J. P. Dunne, C. M. Eakin, and S. D. Donner, 2014: Incorporating adaptive responses into future projections of coral bleaching. Global Change Biology. doi: 10.1111/gcb.12390

Presentations:

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

Progress Report Title: **Curator Infrastructure**

Principal Investigator: Serguei Nikonov (Princeton Professional Technical Specialist)

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

Award Number: NA08OAR4320752
Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

NOAA Goals
Climate Goal: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: Developing means for data publications in Curator and ESGF. It included ensembles of climate model realizations, CMIP6 project preparation, and publication of datasets of various projects.

Methods and Results/Accomplishments:

The Curator system was improved by adding the capability to process ensemble of realization in one pass, putting them into DB. This improvement was propagated to all backend subsystems - mapper, fremetar, deletion tool.

Data of set of projects using newly developed ensemble-capable functionality were published; among them, the NMME project which contains 85 000 files and 9 TB of data.

The program of measures for CMIP6 preparation was elaborated and launched for execution. A part of the tasks enlisted there are completed.

The Metadata synchronization tool as part of ESGF software stack was designed and developed. It is used for the validation of metadata of published data on ESGF data nodes.

Presentations:

GFDL Model Data Requirements and ESGF. S. Nikonov, V.Balaji, A. Radhakrishnan, H. Vahlenkamp. ESGF/UV-CDAT Conference Dec 9-11, 2014. Livermore, Ca.

From "Inspiration-driven" Research to "Industrial-strength" Research: Applying User-developed Climate Analytics at Large scale. A. Radhakrishnan, E. Mason, A. Langenhorst,
V. Balaji, S. Nikonov. AGU 2014 Fall Meeting. Dec 15-19, 2014. San Francisco, Ca.

Progress Report Title: **Regional and Global Climate Impacts of Anthropogenic Aerosols**

Principal Investigator: Geeta Persad (Princeton Graduate Student)

CICS/GFDL Collaborator: Yi Ming (GFDL), V. Ramaswamy (GFDL), Paul Ginoux (GFDL), Tom Delworth (GFDL), David Paynter (GFDL), Vaishali Naik (GFDL)

Other Participating Researchers: Michael Oppenheimer (Princeton)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

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

Objectives: The objective of the projects listed here is to better understand the role of anthropogenic aerosols in the climate system, particularly how the vertical and horizontal structure of aerosol radiative forcing influences its climate impact at regional and global scales.

Methods and Results/Accomplishments:

Recent studies suggest that, despite distinct geographical distributions of top-of-the-atmosphere radiative forcing, anthropogenic greenhouse gases and aerosols give rise to similar patterns of climate response in fully coupled general circulation model simulations (though of opposite sign) [e.g. Levy et al., 2013; Xie et al., 2013]. The surface energy flux perturbation, a crucial pathway by which atmospheric forcing is communicated to the ocean, may be a vital link in explaining the spatial similarities in the fully coupled responses to disparate forcings. We analyze model-simulated, fast, atmosphere-only change in surface energy flux caused by present-day greenhouse gases versus aerosols in GFDL's AM2.1 and AM3 to elucidate the role of surface energy flux perturbations in shaping the subsequent slow, coupled response. We find that, although the two forcings are largely uncorrelated at the top-of-the-atmosphere, their surface energy flux perturbation patterns are significantly anti-correlated (Figure 1). Our analysis highlights the common modes of atmospheric circulation and surface energy adjustment that are triggered by both greenhouse gas and aerosol forcings and produce antisymmetric spatial patterns of surface sensible and latent heat flux variations in response to the two forcers, particularly over the winter-hemisphere oceans. I presented this work at the 2014 AGU Fall Meeting for which I received an Outstanding Student Paper Award. The manuscript of this work has undergone GFDL internal review and is currently being revised for submission to *Nature Geosciences.*

At a regional scale, East Asia—a region of global dynamical importance with large anthropogenic aerosol emissions—has experienced strong, aerosol-driven reductions in surface solar radiation (SSR) over the last several decades, colloquially referred to as "solar dimming" [e.g. Wild, 2012]. The regional climate response to this dimming can be expected to differ depending on whether the attenuated solar radiation is being trapped within the atmosphere (i.e. absorbed) or reflected back out of the surface-atmosphere system (i.e. scattered), but few studies have analyzed the relative contribution to dimming from aerosol absorption versus aerosol scattering. We recently demonstrated in GFDL's AM2.1 and AM3 models, however, that as much as half of the clear-sky SSR trend over East Asia is attributable to increased aerosol absorption [Persad et al., 2014]. That work has now been published in *Journal of*

Geophysical Research-Atmospheres and was presented as an invited talk at the 2014 EGU Annual Meeting.

In the current stage of the project, we are analyzing the regional climate response to this absorption-driven dimming over East Asia in AM3, using both realistic aerosol simulations and idealized simulations designed to isolate the effects of the absorption from that of the dimming. We find that, although the aerosol absorption constitutes a large, positive radiative perturbation in the atmosphere, the SSR-driven surface cooling dominates the response of the regional circulation, suppressing large-scale ascent and convection and reducing the land-sea contrast and monsoonal on-shore flow. This can be contrasted with past AGCM studies over ocean surfaces, which found that aerosol absorption promoted large-scale ascent due to increased atmospheric heating in the presence of fixed sea surface temperatures [e.g. Chung et al., 2002]. This work sheds new light on the relative importance of absorbing aerosols' atmospheric vs. surface radiative perturbation for regional circulation changes. I presented this research at the *27th Conference on Climate Variability and Change* at the 2015 AMS Annual Meeting for which I was awarded 2nd Place in the Student Oral Presentation Competition.

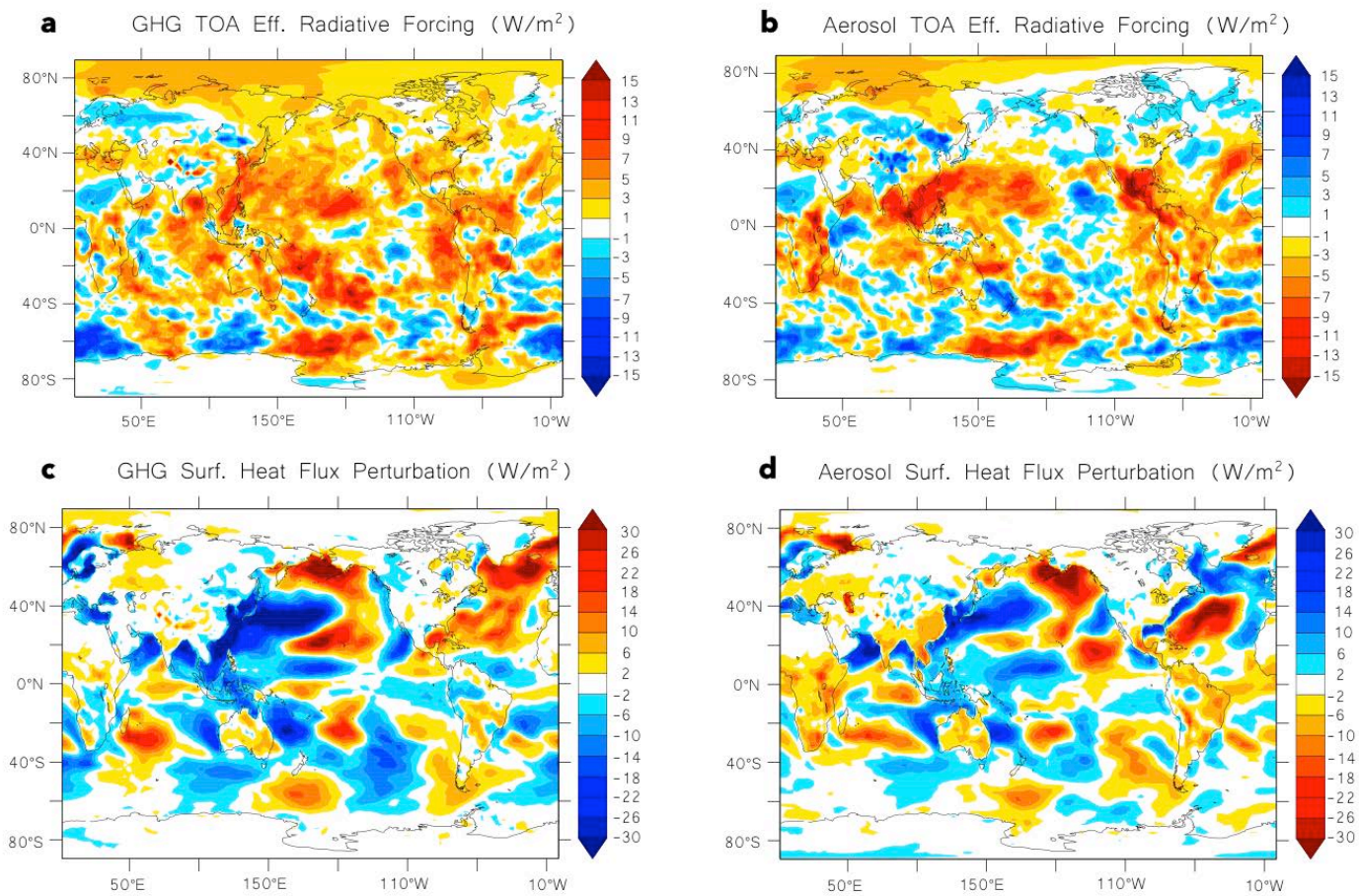


Figure 2:| The spatial pattern of Top-of-Atmosphere Effective Radiative Forcing due to present-day Greenhouse Gases (a) and Aerosols (b) is poorly correlated (R = -0.42) compared to that of the Surface Flux Perturbation (R=-0.57), the latent and sensible heat flux component of which is shown for present-day Greenhouse Gases (c) and Aerosols (d).

Outreach Activities: Mentor to NOAA/GFDL Hollings Scholar summer interns; Ran workshop for all NOAA/GFDL and Princeton AOS summer interns on applying to graduate programs in the Earth Sciences; Presented invited talk and discussion on Climate Science and Policy at Princeton Day School; Organizer and moderator of Princeton Energy Table, university-wide dinner discussion group focused on engaging undergraduates on issues of energy and the environment; Resident Graduate Student in Princeton University Butler Undergraduate College: providing informal mentorship and organizing academically and culturally enriching events for Butler College undergraduate residents; Organizer of Princeton Women in Geosciences Initiative dedicated to promoting and supporting women in pursuit of careers in Geoscience at Princeton and beyond, includes: year-round women's mentoring program, career dinner discussions with visiting senior women scientists, 2-day workshop with Brown University Professor Meredith Hastings on Unconscious Bias, Work/Life Balance, and Career/Job Negotiation; Multi-departmental forum on Diversity in Science; Served on Princeton's Women in STEM Leadership Council providing advisement to The Graduate School administration on graduate Women in STEM needs and initiatives.

References:

Chung, C. E., V. Ramanathan, and J. T. Kiehl. "Effects of the South Asian Absorbing Haze on the Northeast Monsoon and Surface-Air Heat Exchange." Journal of Climate 15, no. 17 (2002): 2462–76.

Levy, Hiram, Larry W. Horowitz, M. Daniel Schwarzkopf, Yi Ming, Jean-Christophe Golaz, Vaishali Naik, & V. Ramaswamy. The Roles of Aerosol Direct and Indirect Effects in Past and Future Climate Change. Journal of Geophysical Research: Atmospheres 118, 4521–32 (2013).

Xie, Shang-Ping, Bo Lu, & Baoqiang Xiang. Similar Spatial Patterns of Climate Responses to Aerosol and Greenhouse Gas Changes. Nature Geoscience 6, 828–32 (2013).

Wild, M. (2012), Enlightening global dimming and brightening, Bull. Am. Meteorol. Soc., 93(1), 27–37, doi:10.1175/BAMS-D-11-00074.1.

Publications:

Persad, G.G., Y. Ming, and V. Ramaswamy 2015: Spatially Similar Surface Energy Flux Perturbations due to Greenhouse Gases and Aerosols. Completed GFDL internal review for submission to Nat. Geosci.

Persad, G. G., Y. Ming, and V. Ramaswamy, 2014: The Role of Aerosol Absorption in Driving Solar Dimming over East Asia. J. Geophys. Res. Atmos., 119, 10, 410–24, doi:10.1002/2014JD021577.

Presentations:

Persad, G., D. Paynter, Y. Ming, and V. Ramaswamy, 2015: The Regional Climate Response to Absorption-Driven Solar Dimming over East Asia. 27th Conference on Climate Variability and Change at 95th AMS Annual Meeting, Phoenix, AZ. (Awarded 2nd Place in AMS Student Oral Presentation Competition).

Persad, G., Y. Ming, and V. Ramaswamy, 2014: Similarities in the Spatial Pattern of the Surface Flux Response to Present-Day Greenhouse Gases and Aerosols. American Geophysical Union Fall Meetings, San Francisco, CA. (Awarded AGU Outstanding Student Paper Award).

Persad, G., Y. Ming (presenter), and V. Ramaswamy, 2014: The Role of Aerosol Absorption in Solar Dimming over East Asia and Its Implications for Regional Climate. European Geosciences Union General Assembly, Vienna, Austria. (Invited).

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

Principal Investigator: Keith Rodgers (Princeton Research Oceanographer)

CICS/GFDL Collaborator: John Dunne (GFDL)

Award Number: NA08OAR4320752
Award Number: NA14OAR4320106

Task III: Individual Projects

NOAA Sponsor: David Legler (Ocean Climate Observation Program)

Theme: Earth System Model Applications

NOAA Goals:
Ecosystem Goal: Protect, Restore, and Manage the Use of Coastal and Ocean Resources through Ecosystem-based Management (25%)
Climate Goal: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond (75%)
Climate Adaptation and Mitigation Goal: An informed Society Anticipating and Responding to Climate and its Impacts

Objectives: The main objective of this research is to use models to interpret observations, and to aid in the optimization of ocean observing strategies. Although an important focus is ocean uptake of carbon, the analysis also has implications for ocean acidification and ocean ecosystems.

Methods and Results/Accomplishments:

Over the last year, I published a modeling study as first author (Rodgers et al., Biogeosciences) testing the hypothesis that winds have an important role in determining the rate of exchange of CO2 between the atmosphere and the ocean through wind stirring over the Southern Ocean. This was tested through a sensitivity study using an ad hoc parameterization of wind stirring in an ocean carbon cycle model, where the objective was to identify the way in which perturbations to the vertical density structure of the planetary boundary layer of the ocean impact the ocean carbon cycle and ocean biogeochemistry. An important part of this study was the application of Atmospheric Potential Oxygen (APO) ratios measured at Scripps through the support of the NOAA Climate Program Office to assess uncertainties in ocean carbon uptake over the Southern Ocean. This was achieved through collaboration with Ralph Keeling at Scripps, as well as with Rik Wanninkhof at NOAA.

Also, two separate collaborations with Joe Majkut (a graduate student of Jorge Sarmiento's at Princeton) resulted in publications in 2014 (Majkut et al.., 2014, Global Biogeochemical Cycles; Majkut et al, 2014, Royal Society). The first of these was concerned with the production of a global gridded pCO2 product spanning multiple decades. The second was concerned with the optimal design of an observing system over the Southern Ocean for monitoring carbon uptake.

Additionally, I have submitted a paper (Rodgers et al., 2014, Biogeosciences Discussions) where a 30 member ensemble suite with GFDL's Earth System Model ESM2M has been applied to the question of emergence of ecosystem stressors and observing system design.

Outreach Activities: During the summer of 2014, I hosted two summer undergraduate summer interns through the Princeton Environmental Institute's Grand Challenges Program. The students, Paul Yi and

Jonathan Lin, are undergraduates at Princeton. The work with Jonathan Lin has led to the submission of a manuscript submitted to a peer-reviewed journal (Rodgers et al., Biogeosciences Discussions).

Publications:

Rodgers, K.B., O. Aumont, S.E. Mikaloff Fletcher, Y. Plancherel, L. Bopp, C. de Boyer Montégut, D. Iudicone, R.F. Keeling, G. Madec, and R. Wanninkhof (2014a), Strong sensitivity of Southern Ocean carbon uptake and nutrient cycling to wind stirring, Biogeosciences, 11 4077-4098.

Ishii, M., R.A. Feely, K.B. Rodgers, G.-H. Park, R. Wanninkhof, D. Sasano, H. Sugimoto, C.E. Cosca, S. Nakaoka, M. Telszewski, Y. Nofiri, S.E. Mikaloff Fletcher, Y. Niwa, P.K. Patra, V. Valsala, H. Nakano, I. Lima, S.C. Doney, E.T. Buitenhuis, O. Aumont, J.P. Dunne, A. Lenton, and T. Takahashi (2014), Air-sea CO_2 flux in the Pacific Ocean for the period 1990-2009, Biogeosciences, 11, 709-234.

Majkut, J.D., J.L. Sarmiento, and K.B. Rodgers (2014a), A growing oceanic carbon uptake: Results from an inversion study of surface pCO_2 data, Global Biogeochem. Cycles, 28, doi:10.1002/2013GB004585.

Majkut, J.D., B.R. Carter, T.L. Frölicher, C.O. Dufour, K.B. Rodgers, and J.L. Sarmiento (2014b), An observing system simulation for Southern Ocean carbon dioxide uptake, Phil. Trans. R. Soc. A, 372, 20130046.

Rodgers, K.B. J. Lin, and T.L. Frölicher (2014b), Emergence of multiple ecosystem driver in a large ensemble suite with an Earth System Model, Biogeosciences Discuss., 11, 18189-18227.

Under Review:

Iudicone, D., K.B. Rodgers, Y. Plancherel, O. Aumont, T. Ito, R. Key, G. Madec, and M. Ishii (2015), The formation of the ocean's anthropogenic carbon reservoir, re-submitted to Proceedings of the National Academy of Sciences.

Presentations:

Rodgers, K.B., Feb 2015: A water mass framework for understanding carbon uptake by the ocean at the kickoff SOCOM workshop in Tsukuba Japan.

Rodgers, K.B.,Jan 2015: Strong sensitivity of Southern Ocean carbon uptake and nutrient cycling to wind stirring, in Brest, France.

Rodgers, K.B., Dec 2014: Time of emergence of multiple ocean ecosystem stressors in a large ensemble with an Earth System Model, at the MRI, in Tsukuba, Japan.

Progress Report Title: **Factors Controlling Seasonal Variations in Arctic Black Carbon**

Principal Investigator: Zhaoyi Shen (Princeton Graduate Student)

CICS/GFDL Collaborator: Larry Horowitz, Yi Ming, Isaac Held, and Venkatachalam Ramaswamy (GFDL)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (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: Improve the ability of AM3 to simulate Arctic black carbon, and evaluate the factors controlling its seasonal cycle

Methods and Results/Accomplishments:

Observations show that Arctic black carbon (BC) has a distinct seasonal cycle with higher concentrations in late winter and early spring [Quinn et al., 2007]. The inclusion of new parameterizations of BC chemical and physical processes [Liu et al., 2011] significant improve the ability of AM3 to simulate Arctic BC. We find that Arctic BC has a seasonal cycle with higher concentrations in Dec-Apr and lower concentrations in June-Oct, which is mainly affected by BC flux into the Arctic, hydrophilic BC (BCpi) fraction, and BCpi wet deposition rate.

In Aug-Oct, Arctic BC is low partially because BC transport is less efficient, but overall BCpi fraction and BCpi wet deposition rate are more important in determining the seasonal cycle. BCpi fraction is larger in mid spring-mid autumn, which is determined by the seasonal cycle of BC aging time near source regions. BCpi wet deposition rate is larger in summer and autumn, which is affected by much larger removal efficiency of liquid clouds than ice clouds. Both high BCpi fraction and high BCpi wet deposition rate account for much lower BC in the summer than winter. The decrease of BC in early summer is due to the increase in BCpi wet deposition rate, while the recovery of BC in late autumn is mainly caused by a sharp decrease in BCpi fraction.

References:

Liu, J., et al.,: Evaluation of factors controlling long-range transport of black carbon to the Arctic, Journal of Geophysical Research, 116, D04 307, doi:10.1029/2010JD015145.

Quinn, P. K., et al.,: Arctic haze: current trends and knowledge gaps, Tellus B, 59, 99–114, doi:10.1111/j.1600-0889.2006.00238.x.

Publications:

Shen, Z., Liu, J., Horowitz, L. W., Henze, D. K., Fan, S., H., Levy II, Mauzerall, D. L., Lin, J.-T., and Tao, S.: Analysis of transpacific transport of black carbon during HIPPO-3: implications for black carbon aging, Atmos. Chem. Phys., 14, 6315-6327, doi:10.5194/acp-14-6315-2014, 2014.

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

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

CICS/GFDL Collaborator: Gabriel Vecchi (GFDL)

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

Award Number: NA08OAR4320752
Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

NOAA Goals:
Climate Goal: Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond
Climate Adaptation and Mitigation Goal: An Informed Society Anticipating and Responding to Climate and its Impacts

Objectives: To understand the sensitivity of the climate system to realistic variations in both the atmospheric loading of Saharan-borne mineral dust and its optical properties with particular emphasis on the effects to tropical cyclone genesis and development.

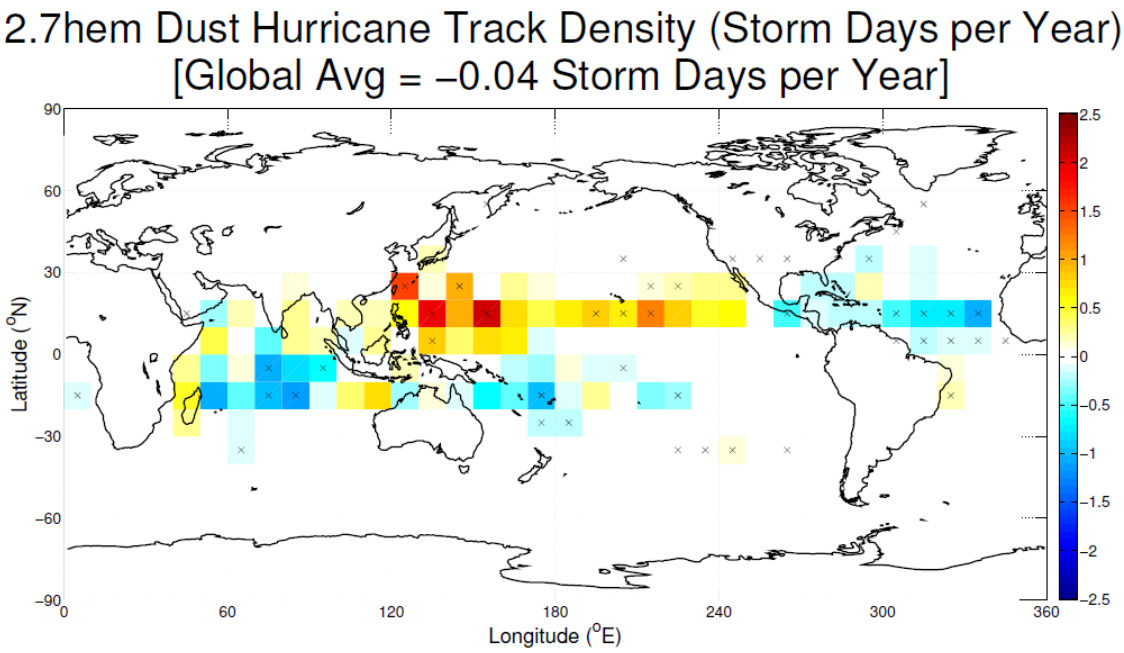
Methods and Results/Accomplishments:

North Africa is the largest source of global dust, contributing 55% of the total 6-30 Tg of global annual dust load (Huneeus et al., 2011; Ginoux et al., 2012). These large concentrations of mineral dust can be transported thousands of miles from their source regions (Adams et al. 2012) and strongly influence the radiative balance in the regional climate (Miller et al., 2014). This far transport can also influence the development of Atlantic tropical cyclones (Dunion & Velden, 2004; Braun, 2010; Wang et al., 2012). However, North Africa undergoes significant multidecadal scale fluctuations in emissions with nearly a 5x increase in dust emissions between the 1960's and the 1980's followed by a more recent decrease in emissions (Mahowald et al., 2010). Simultaneously, the heterogeneous nature of African dust mineralogy can considerably affect the interactions of dust with radiation (Sokolik and Toon, 1999).

Using the GFDL's CM2.1 and CM2.5_FLOR models, we have investigated how these variations in atmospheric loading and optical properties of North African mineral dust affect the climate system, with particular emphasis on West Africa and the tropical North Atlantic Ocean. A series of eight experiments have been conducted: Several multi-centenial free-running controls (2 for CM2.1 and 6 for CM2.5_FLOR) with constant insolation, atmospheric gases, and land cover values representative of 1990 conditions alongside an ensemble of perturbation runs from their respective control run (21 members each for CM2.1 and 2 members each for CM2.5_FLOR). The forcing consisted of reducing atmospheric dust loading to simulate an 80% decrease in dust emissions over North Africa. Each set of experiments used different optical properties ranging from the older CM2.1 standard, predominantly absorbing optical properties, to an inflated, newer, predominantly scattering optical regime, with a series of sensitivities in between.

The regional climate shows considerable sensitivity to the various optical properties and has been documented by Strong, Vecchi, and Ginoux (2015, *in review*). To understand the effect on tropical cyclone development, we examine the same forcing scenarios in the CM2.5_FLOR model which has a

higher resolution atmosphere capable of resolving tropical cyclones. The initial results are fairly intuitive in the near field in that almost every case has a decrease in tropical cyclone density over the North Atlantic (Fig 1). However, it appears as though there is some non-linearity in terms of the optical properties as the middle sensitivity regimes have lower responses than the more extreme regimes. This is currently under investigation as well as the apparent significance of any far field response in tropical cyclone counts.



Outreach Activities: Teaching Assistant position for Princeton undergraduate class entitled GEO 202: Ocean, Atmosphere, and Climate for February 2015 - May 2015, and co-taught graduate student led class entitled Weather and Climate to introduce graduate students to the linkages between meteorology and climate in Summer 2014

References:

Adams, A. M., J. M. Prospero, and C. Zhang, 2012: CALIPSO-derived three-dimensional structure of aerosol over the Atlantic basin and adjacent continents. J. Climate, 25, 6862–6879, doi:10.1175/JCLI-D-11-00672.1.

Braun, S. A., 2010: Reevaluating the role of the Saharan air layer in Atlantic tropical cyclogenesis and evolution Mon. Wea. Rev., 138, 2007–2037, doi:10.1175/2009MWR3135.1.

Dunion, J. P. and C. S. Velden, 2004: The impact of the Saharan air layer on Atlantic tropical cyclone activity. Bull. Amer. Meteor. Soc., 85, 353-365, doi:10.1175/BAMS-85-3-353.

Ginoux, P., J. M. Prospero, T. E. Gill, N. C. Hsu, and M. Zhao, 2012: Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS Deep Blue aerosol products. Rev. Geophys., 50 (RG3005), 36 pp., doi:10.1029/2012RG000388.

Huneeus, N., et al., 2011: Global dust model intercomparison in AeroCom phase I. Atmos. Chem. Phys., 11, 7781–7816, doi:10.5194/acp-11-7781-2011.

Miller, R. L., P. Knippertz, C. P. Garcia-Pando, J. P. Perlwitz, and I. Tegen, 2014: Impact of dust radiative forcing upon climate. Mineral dust: A key player in the Earth system, P. Knippertz and J.-B. W. Stuut, Eds., Springer Netherlands, 327–357, doi: 10.1007/978/94/017/8978-3_13.

Mahowald, N. M., et al., 2010: Observed 20th century desert dust variability: Impact on climate and biogeochemistry. Atmos. Chem. Phys., 10, 10875-10893, doi:10.5194/acp-10-10875-2010.

Sokolik, I. N. and O. B. Toon, 1999: Incorporation of mineralogical composition into models of the radiative properties of mineral aerosol from UV to IR wavelengths. J. Geophys. Res., 104 (D8), 9423-9444, doi:10.1029/1998JD200048.

Wang, C., S. Dong, A. T. Eva, G. R. Foltz, and S.-K. Lee, 2012: Multidecadal covariability of North Atlantic sea surface temperature, African dust, Sahel rainfall, and Atlantic hurricanes. J. Climate, 25, 5404-5415, doi:10.1175/JCLI-D-11-00413.1.

Publications:

Strong, J. D. O., G. A. Vecchi, and P. Ginoux, 2015: The Response of the Tropical Atlantic and West African Climate to Saharan Dust in a Fully Coupled GCM (In Review). J. Climate.

Progress Report Title: **Application of Seasonal to Decadal Climate Predictions for Marine Resource Management**

Principal Investigator: Desiree Tommasi (Princeton Postdoctoral Research Associate)

CICS/GFDL Collaborator: Charles Stock (GFDL)

Other Participating Researchers: Mike Alexander (ESRL), Kathy Pegion (George Mason University), Nick Bond (University of Washington – JISAO), Yan Xue (NOAA CPC), Gabriel Vecchi (GFDL), Trond Kristiansen (Institute of Marine Research, Bergen, Norway)

Award Number: NA14OAR4320106

Task II: Cooperative Research Projects and Education

NOAA Sponsor: Brian Gross (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 utility of present seasonal to decadal climate predictions for marine resource management, and develop proof of concept applications on the use of climate forecast systems in the fisheries management framework

Methods and Results/Accomplishments:

State of the art dynamical global forecast systems now exists that allow for projections of climate variables at a seasonal and decadal scale. During the initial phase of this project, we demonstrated that the NOAA's Geophysical Fluid Dynamics Laboratory (GFDL CM 2.5-FLOR) and the National Center for Environmental Prediction (NCEP CFSv2) climate forecast systems produce skillful projections of sea surface temperature (SST) anomalies both at a temporally "fishery relevant" scale, monthly to inter-annual, and at a spatially "fishery relevant" scale, the coastal shelf. These results have been collated in a manuscript to be submitted to Progress in Oceanography.

It is well established that environmental fluctuations affect the productivity of numerous fish stocks. As a Princeton Postdoctoral Research Associate, I'm assessing the utility of seasonal SST anomalies projections for the fisheries management process using the case study of Pacific sardine (*Sardinops sagax caerulea*). This fishery was selected because it is one of the few to already incorporate environmental information into the management framework, through an SST dependent harvest guideline, and for which there is a well-established recruitment-SST relationship. I will quantify the effectiveness of management, namely high and stable catch and high and stable long term stock biomass, under alternative harvest control rules: the status quo with no future information, one including perfect future information, one incorporating dynamic forecast future information, and one including persistence forecast future information. Other proof of concept applications of seasonal and decadal scale climate forecast systems in a marine resource management context I am exploring are: 1) improving spatial management strategies of Gulf of Mexico bluefin tuna (*Thunnus thynnus*) by forecasting dynamic, SST-dependent area closures to reduce bluefin tuna bycatch, and 2) using decadal SST anomaly forecasts to more effectively manage Barents and Norwegian sea cod (*Gadus morhua*), whose recruitment is largely influenced by SST variability, and 3) using seasonal forecasts of air temperature and precipitation to proactively manage river herring (*Alosa pseudoharengus* and *A. aestivalis*) spawning habitat. This last case study is a follow

up to a previous project I was involved in while at GFDL prior to this appointment that elucidated environment-freshwater survival links for river herring (Tommasi et al., In press).

Initial results from these case studies will be presented at a workshop I am organizing June 3-5 2015 at Princeton University. The focus of this workshop is on the application of seasonal to decadal climate predictions for marine resource management. There will be strong representation from both fisheries and climate science to allow for a holistic examination of the challenges associated with the application of seasonal scale forecasts in a fisheries management context and how to meet them.

Outreach Activities: Supervised a Princeton Fall Junior Paper in fall 2014 (in collaboration with Rebecca Asch). The student is following up the Junior Paper with a Spring Junior Independent Research Project.

Publications: Tommasi, D., J. Nye, C. Stock, J. A. Hare, M. Alexander, and K. Drew, 2015. Effect of environmental conditions on juvenile recruitment of alewife (*Alosa pseudoharengus*) and blueback herring (*A. aestivalis*) in freshwater: a coastwide perspective. Canadian Journal of Fisheries and Aquatic Sciences.

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

Principal Investigator: Hannah Zanowski (Princeton Graduate Student)

CICS/GFDL Collaborator: Jorge Sarmiento (Princeton), Robert Hallberg (GFDL)

Award Number: NA08OAR4320752

Task III: Individual Projects

NOAA Sponsor: Brian Gross (GFDL)

Theme: Earth System Model Applications

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

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

Methods and Results/Accomplishments:

In order to answer the above questions we analyze output from GFDL's coupled climate model, CM2G. Using a 2000-year time series of volume averaged Weddell Sea temperature, we have constructed two composite polynyas (figure 1) by averaging more than 30 individual polynyas occurring throughout the time series. The composite polynyas are used to gauge the typical magnitudes and timescales of abyssal ocean changes associated with a polynya. We use the cooling composite (figure 1a) to understand the timescales associated with the spreading of the polynya signal, and we use the warming composite (figure 1b) to determine the magnitudes of the temperature and salinity changes that occur in the abyssal oceans after cessation of the polynya.

For the time period following the cooling composite polynya cessation, termed the 'recovery,' decadal mean warming between 0.002˚C and 0.021˚C occurs below 4200m in the Southern Ocean basins (figure 2). Consistent with Johnson and Doney, 2006; Johnson et al., 2007; and Purkey and Johnson, 2010, these temperature changes are amplified in the south, with the strongest changes confined to the Southern Ocean and the South Atlantic. Comparison of the model results with abyssal temperature observations from Purkey and Johnson 2010 reveals that the composite polynya recovery signal could account for as much as 1/4 of the recent warming in the deep Southern Ocean.

Outreach Activities: PPPL Young Women's Conference (3/19/15) and Ocean Fun Days (May 2014)

References:

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

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

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

Publications:

Zanowski, H.M., R.W. Hallberg, and J.L. Sarmiento: Abyssal ocean warming and salinification associated with Weddell Polynyas in GFDL-CM2G (in prep).

Presentations:

Zanowski, H.M., Hallberg, R.W., Sarmiento, J.L.: Evidence for long-term, large-scale climate impacts associated with the Weddell Sea polynya. Poster session presented at: Cryosphere. 8th Graduate Climate Conference, 2015 Oct 31-Nov 2; Pack Forest, WA.

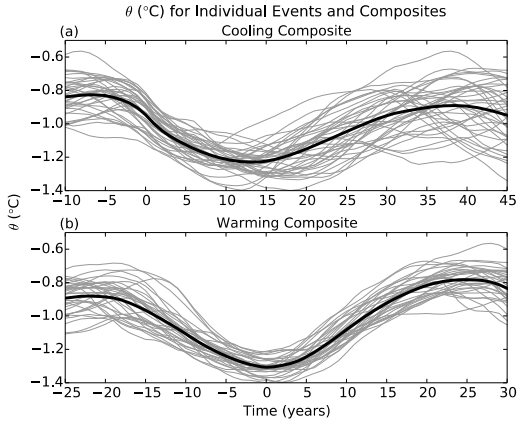


Figure 1. Time series of annually averaged, volume averaged potential temperature in the Weddell Sea for single polynyas (thin grey lines) and the composite (thick black line). The volume average is taken from 1.5km to 2.5km depth in the Weddell Sea (77S:60S, 60W:0W). In a), year 0 corresponds to the time when temperature is decreasing the fastest. We refer to this composite as the cooling composite. In b) year 0 corresponds to the time when temperature reaches a minimum in the Weddell Sea. We refer to this composite as the warming composite. Polynyas with post-zero-year mean warming trends (calculated as the mean of the temperature for each event from years 0 to 30 in b) divided by the time) greater than two standard deviations from the total mean warming trend (calculated by averaging the mean warming trend for the total number of events) are not included in the warming composite.

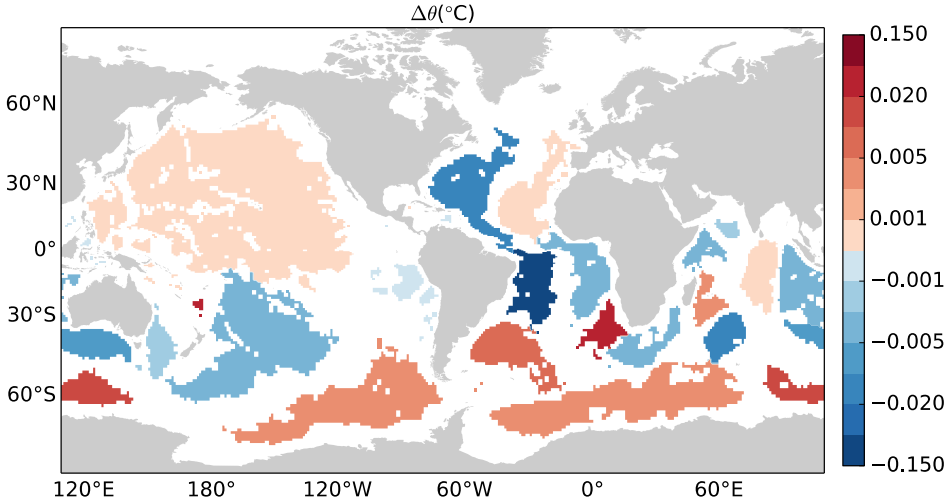


Figure 2. Basin mean temperature change averaged below 4200m for the warming composite. Changes are calculated by summing the yearly rate of basin mean temperature change over a 10-year period from years 8 to 18. All of the deep Southern Ocean basins exhibit warming between 0.002˚C and 0.021˚C. Strong warming signals are also present in the Argentine, Cape, Madagascar-Mascarene, and South Fiji basins.

	JI Lead Author							NOAA Lead Author							Other Lead Author						
	FY 09	FY 10	FY 11	FY 12	FY 13	FY 14	FY 15	FY 09	FY 10	FY 11	FY 12	FY 13	FY 14	FY 15	FY 09	FY 10	FY 11	FY 12	FY 13	FY 14	FY 15
Peer-reviewed	14	31	30	30	34	32	22	2	3	2	5	8	9	7	6	21	29	31	28	31	27
Non Peer-reviewed	14	13	3	41*	64*	64*	60*	2	4	2	2*			1*	2	7	2	2*	4*	8*	2*
Chapters in books	1	1																			
Ph.D. Thesis		2	3	2	1	2	2														

**Including Presentations*

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
Administrative Assistant, CICS
Phone: 609-258-6047
Fax: 609-258-2850
jcurcio@princeton.edu

Task I: Administrative Activities and Outreach Supported Personnel

Name	**Rank**
Alejandra Sanchez-Franks	MPOWIR Summer Intern
Nathan Serota	Summer Intern
Sarmiento, Jorge L.	CICS Director
Legg, Sonya	CICS Associate Director
Laura Rossi	CICS Administrator

Departures - Task II and Task III

Kara Sulia – 8/31/14: State University of New York at Albany

Yuxing Yun – 2/28/15: PNNL

Malte Jansen – 12/31/14: University of Chicago

Cheryl Logan – 1/31/15: California State University at Monterey Bay (Short-term Professional)

Zhengzhao Luo – 5/31/14: City College of New York (Visiting Research Scholar)

Ph.D. Defenses

Student: Claire Radley - November 2014

Advisor: Stephan Fueglistaler
Dissertation: Understanding the Dependence of Tropical High Cloud Amount and Radiative Flux on Sea Surface Temperature

Current Affiliation: McKinsey & Co.

Student: Owen Williams - November 2014

Advisor: Alexander Smits
Dissertation: Density effects on turbulent boundary layer structure: from the atmosphere to hypersonic flow

Current Affiliation: University of Maryland

Task II: Cooperative Research Projects and Education Supported Personnel

Name	**Rank**	**Host**
Adcroft, Alistair	Research Oceanographer	GFDL Director
Balaji, V.	Sr. Professional Specialist	GFDL Director
Baldwin, Jane	Graduate Student	Vecchi
Chai, Junyi	Graduate Student	Held/Vallis
Choi, Kityan	Graduate Student	Vecchi
FitzMaurice, Anna	Graduate Student	Hallberg
Gonzalez-Taboada, Fernando	Postdoctoral Research Associate	Dunne/Stock
Hill, Spencer	Graduate Student	Ming
Jia, Liwei	Associate Research Scholar	Vecchi
Johnson, Nathaniel	Associate Research Scholar	Vecchi/Wittenberg
Legg, Sonya	Senior Research Oceanographer	GFDL Director
Li, Dan	Postdoctoral Research Associate	Shevliakova/Milly
Lin, Meiyun	Associate Research Scholar	Horowitz
Lin, Pu	Postdoctoral Research Associate	Ming
Logan, Cheryl	Professor at CSUMB	Dunne
Luo, Zhengzhao (Johnny)	Professor at City College of New York	Donner
Lutsko, Nicholas	Graduate Student	Held
Malyshev, Sergey	Professional Specialist	Pacala
Mao, Jingqiu	Associate Research Scholar	Horowitz
Mater, Benjamin	Postdoctoral Research Associate	Hallberg/Legg
Mooring, Todd	Graduate Student	Held
Muhling, Barbara	Associate Research Scholar	Saba/Stock
Nazarian, Robert	Graduate Student	Legg
Nikonov, Sergey	Professional Specialist	Balaji
Orlanski, Isidoro	Sr. Research Meteorologist	GFDL Director
Paulot, Fabien	Associate Research Scholar	Horowitz
Persad, Geeta	Graduate Student	Ramaswamy
Ruprich-Robert, Yohan	Postdoctoral Research Associate	Delworth
Sergienko, Olga	Research Glaciologist	Hallberg
Shen, Zhaoyi	Graduate Student	Horowtiz
Shevliakova, Elena	Professional Specialist	Pacala
Strong, Jeffrey	Graduate Student	Vecchi
Sulia, Kara	Postdoctoral Research Associate	Golaz
Tommasi, Desiree	Postdoctoral Research Associate	Stock
Wang, He	Graduate Student	Legg
Yun, Yuxing	Postdoctoral Research Associate	GFDL Director
Zhang, Liping	Postdoctoral Research Associate	Delworth

Task II: Cooperative Research Projects Supported Personnel – RECENT HIRES

Name	**Rank**	**Advisor**
Barton, Andrew	Associate Research Scholar	Stock/Dunne
Laufkotter, Charlotte	Postdoctoral Research Associate	Stock/Dunne
Li, Dawei	Postdoctoral Research Associate	Zhang/Knutson
Ray, Sulagna	Associate Research Scholar	Wittenberg
Ward, Daniel	Postdoctoral Research Associate	Dunne/Shevliakova

Task III: Individual Research Projects Supported Personnel

Name	**Rank**	**Advisor**
Buchner, Abel-John	Visiting Student Research Collaborator	Smits
Key, Robert M.	Research Oceanographer	Sarmiento
Lin, Meiyun	Associate Research Scholar	Horowitz
Lin, Xiaohua	Research Assistant	Key
Liu, Maofeng	Graduate Student	Smith
Momen, Mostafa	Graduate Student	Bou-Zied
Radley, Claire	Graduate Student	Fueglistaler
Rodgers, Keith	Research Oceanographer	Sarmiento
Williams, Owen	Graduate Student	Smits
Zanowski, Hannah	Graduate Student	Sarmiento

Personnel				
Category	Number	B.S.	M.S.	Ph.D.
Faculty	3	-	-	3
Research Scientist	6	-	-	6
Visiting Scientist	1	-	-	1
Postdoctoral Research Associate	12	-	-	12
Professional Technical Staff	5	-	1	4
Associate Research Scholar	8	-	-	8
Administrative	1	-	-	-
Total (≥ 50% support)	**27**			**27**
Undergraduates	-	-	-	-
Graduate Students	19	2	15	2
Employees that receive < 50% NOAA funding (not including graduate students)	9	-	-	9
Located at the Lab (include name of lab)	GFDL-38	1	9	28
Obtained NOAA employment within the last year	-	-	-	-

CICS FY'15 List of Awards for Institutional Award NA14OAR4320106

Amount	PI	Project Title
$ 73,886[*0]	Jorge L. Sarmiento	CICS-YR 6 (Administration – Task I) *GFDL/Brian Gross*
$2,479,025[*0]	Jorge L. Sarmiento	CICS-YR 6 (Research/Education–Task II) *GFDL/Brian Gross*
$ 103,000[*0]	Jorge L. Sarmiento	CICS-YR 6 (Research – Task III) *GFDL/Brian Gross*
$ 40,144 [*1]	Keith Rodgers	Using Models to improve our ability to monitor ocean uptake of anthropogenic carbon (Task III) *COD-Joel Levy*
$ 69,655[*2]	Meiyun Lin	Exploring emission versus climate drivers of tropospheric ozone variability and trends over northern midlatitudes *(Task III) ESRL/NASA-Owen Cooper*
$ 137,636[*3/6]	Jorge L. Sarmiento	CICS-YR 6 (Administration – Task I) *GFDL/Brian Gross*
$5,377,273[*3/6]	Jorge L. Sarmiento	CICS-YR 6 (Research/Education–Task II) *GFDL/Brian Gross*
$ 636,077[*3/6]	Jorge L. Sarmiento	CICS-YR 6 (Research – Task III) *GFDL/Brian Gross*
$ 28,139[*4]	Jorge L. Sarmiento	CICS-YR 7 Supplemental (Administration – Task I) *GFDL/Brian Gross*
$ 625,313[*4]	Jorge L. Sarmiento	CICS-YR 7 Supplemental (Research/Education – Task II) *GFDL/Brian Gross*
$ 66,731[*5]	Jorge L. Sarmiento	CICS-YR 6 Supplemental (Administration – Task I) *GFDL/Brian Gross*

Amendment No./PI	Amount	Project Title
Amendment #0 Jorge L. Sarmiento	$2,655,911	Cooperative Institute for Climate Science – Year 6
Amendment #1 PI: Keith Rodgers	$ 40,144	Using Models to Improve our Ability to Monitor Ocean Uptake of Anthropogenic Carbon
Amendment #2 Meiyun Lin	$ 69,655	Exploring emission versus climate drivers of tropospheric ozone variability and trends over northern midlatitudes
Amendment #3/6 Jorge L. Sarmiento	$6,150,986	Cooperative Institute for Climate Science – Year 7 ***(SAC did not allow Princeton to draw down funds until budget detail was submitted and approved. This approval was obtained on April 9, 2015, amendment #6)***
Amendment #4 Jorge L. Sarmiento	$ 653,452	Cooperative Institute for Climate Sciences – Supplemental Funding – Year 7
Amendment #5 Jorge L. Sarmiento	$ 66,731	Cooperative Institute for Climate Sciences – Task I