Cooperative Institute for Modeling the Earth System (CIMES)
A Proposal to the Office of Oceanic and Atmospheric Research,
National Oceanic and Atmospheric Administration (NOAA)

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1. ABSTRACT

We propose to establish a Cooperative Institute for Modeling of the Earth System (CIMES) to conduct research in support of NOAA’s mission and strategic goals in areas related to earth system science. CIMES would build on the collective knowledge and complementary resources that have been developed over the past five decades of close collaboration between Princeton University and NOAA’s Geophysical Fluid Dynamics Laboratory (GFDL), currently embodied in the Cooperative Institute for Climate Science (CICS) which ends in June 2018. Our vision for CIMES is to be a world leader in understanding and predicting the earth system, across time scales from days to decades, and from the local to global spatial scales, with particular focus on extreme events, and integrating physical, chemical, and biological components.

The earth system knowledge and resources that Princeton University and GFDL bring to CIMES are second to none in the field, thanks to GFDL’s unparalleled expertise in numerical climate modeling, and Princeton’s ability to draw on the knowledge and abilities of first rate scientists and engineers; as well as public policy experts who will shape our national and international response to earth system change and the manifold challenges it represents. Princeton also provides GFDL with a crucial element in its research enterprise, namely, a steady influx of enormously gifted graduate students and postdoctoral fellows, on whose skills and insights the future of climate science rests.

CIMES research will address the following three themes:

1. **Earth System Modeling:** Developing and improving Earth System Models (ESMs), numerical models which simulate the climate and earth system, and allow prediction of the future evolution of this system. These models include the dynamical, physical, chemical and biological components of the atmosphere-ocean-land system and the coupling between them.

2. **Seamless Prediction Across Time and Space Scales:** Applying the ESMs to predictions on time-scales from days to centuries and over spatial scales from those of extreme events to global scales, making use of the same flexible code-base. We focus on two different aspects of prediction across time and space scales, the very high-resolution modeling necessary to resolve extreme weather phenomena, and the predictability of different weather and climate phenomena.

3. **Earth System Science: Analysis and Applications:** Using ESMs to understand the impacts of environmental variations and changes on pressing problems of relevance to society, including marine ecosystems, weather extremes, drought and air quality.

The mission of CIMES is to focus the scientific talent of Princeton University at all levels from graduate students, through postdocs, and faculty, to address these research themes, providing a
bridge between NOAA-GFDL and Princeton University and the wider academic community. The direct involvement of graduate students and postdocs in CIMES research is a crucial element in achieving our goals, as well as providing outstanding opportunities to train the next generation of leaders in earth system sciences through the exceptional earth system graduate and postdoctoral programs in the Atmospheric and Oceanic Sciences (AOS) Program; and broadening the participation of underrepresented groups in earth system science through summer internships, visiting faculty exchange fellowships and increasing research collaborations with a diverse range of institutions.

Highlights:

Close alignment with NOAA priorities
CIMES goals are closely aligned with NOAA’s climate adaptation and mitigation, weather-ready nation, and healthy oceans goals. CIMES will advance NOAA’s mission by contributing to the development of world-leading computer models of the earth-system; supporting research on understanding and predicting changes in climate and oceans; sharing of information with the wider scientific community, and the broader public; and contributing to the conservation and management of marine ecosystems through research into ecosystems and climate. The cooperative institute will also work to promote a strong and more diverse scientific workforce.

Outstanding record of performance working with NOAA
Princeton’s collaboration with NOAA/GFDL extends back 50 years and has played a key role in many of the major advances in climate and earth system modeling over that time. This research partnership has resulted in hundreds of joint publications.

Nationally recognized experts
Princeton University and GFDL bring outstanding earth system knowledge and resources to CIMES, combining GFDL’s unparalleled expertise in numerical climate modeling with Princeton’s first-rate scientists, engineers, and public policy experts.

Excellent educational program with a successful record of training earth scientists
The Princeton AOS Program has awarded 113 Ph.D. degrees since the Program’s inception in 1968, with a majority of graduates going on to leading positions in academia and research, including many now employed at NOAA laboratories. The AOS postdoctoral and visiting scientist program has also been extremely successful - a total of over 350 scientists have participated and have made many important and lasting contributions to all areas of GFDL-relevant science.

Strong university support through cost-sharing
Princeton University has made its strongest-ever financial commitment to NOAA as proposed host of CIMES, more than doubling its prior cost share commitment and pledging approximately $4 million in total cost-sharing and in-kind support over the 5-year Cooperative Agreement. The partnership with GFDL/NOAA is further underscored by a letter of strong support from Princeton University President Christopher L. Eisgruber, submitted as an appendix to this proposal.
2. RESULTS FROM PRIOR RESEARCH


Below, we highlight key results from recent research funded through CICS. Details are in annual reports from the past five years. https://www.princeton.edu/cics/about-us/reviews-reports/

EARTH SYSTEM MODELING: DEVELOPMENT AND ANALYSIS

CICS scientists have played a key role in the development of all components of the earth-system model over the past few years, including ocean, atmosphere, cryosphere and land components.

Software infrastructure for climate modeling

Earth system modeling requires a robust and well-structured model architecture and workflow system. The Flexible Modeling System (FMS), developed and maintained by a team led by CICS scientist V. Balaji, enables the efficient performance of the earth system model and the coupling of the component models. The software development associated with the dynamical cores of the ocean and atmospheric models at GFDL includes significant CICS contributions: A new hybrid coordinate ocean model, MOM6, a component of the GFDL coupled climate model CM4, has been developed by a team led by CICS scientist Alistair Adcroft. CICS associate researchers Xi Chen and Linjong Zhou developed new algorithms to enable the development of the new prototype high-resolution atmospheric dynamical core contributing to the Next Generation Global Prediction System (NGGPS) for the National Weather Service (NWS). The Forecast-orientated Low Ocean Resolution (FLOR) model was developed with significant contributions from CICS scientists.

Ocean model development

The new ocean model MOM6 incorporates many advances in representation of sub-grid-scale physics contributed by CICS researchers, including new parameterizations for small-scale mixing driven by breaking internal tides (CICS scientist Sonya Legg), a new parameterization of the surface mixed layer (CICS postdoctoral researcher Brandon Reichl), and parameterizations of mesoscale eddies (CICS scientist Alistair Adcroft).

Ice sheet and ice shelf model development

CICS scientist Olga Sergienko leads the ice-sheet modeling effort at GFDL/CICS. A model of floating ice-shelves has been developed, in collaboration with CICS scientist Alistair Adcroft, allowing the ocean circulation under ice-shelves to be simulated. A significant recent focus has been the development of representations of ice-bergs in MOM6, important contributions to the ocean freshwater budget.

Land surface model development

The land-surface plays an important role in the climate system, determining water and momentum fluxes, as well as providing sources and sinks of dust and chemical components such as carbon and nitrogen. The land-surface component of an earth system model must therefore represent the feedbacks between the atmosphere and the terrestrial biosphere, as well as accounting for land-use such as cropland and urban development. The development of GFDL’s new land surface model LM4, led by a team of CICS researchers, including Stephen Pacala (Princeton faculty) includes many new components, such as: representation of soil nitrogen deposition (CICS associate researchers Fabien Paulot and Benjamin Sulman), a coupled land-river nitrogen cycling model (CICS postdoctoral researcher Minjin Lee), a scheme for coupling fire emissions with atmospheric aerosols and chemistry (CICS postdoctoral researcher Daniel Ward), an urban climate model (CICS postdoctoral researcher Daniel Li), an improved
representation of plant respiration (Princeton associate researcher Paul Gauthier), and representation of land-surface heterogeneity (CICS postdoctoral researcher Nathaniel Chaney).

**Atmospheric model physics**
The representation of physical processes, such as cloud formation, remains a key challenge for the atmospheric component of earth system models. Numerous CICS researchers are contributing to advances in this area, including convective cloud modeling (CICS postdoctoral researcher Nadir Jeevanjee), representation of ice nucleation (Princeton faculty Pablo Debenedetti and Athanassios Panagiotopoulos). CICS postdoctoral researcher Levi Silvers has examined the impact of clouds on the simulated large-scale circulation and climate, and CICS postdoctoral researcher Alexandra Jones has conducted detailed comparison of different radiation scheme implementations.

**EARTH SYSTEM MODELING APPLICATIONS**
The sophisticated comprehensive earth system models developed through CICS/GFDL collaboration have been applied to a variety of problems of societal importance by CICS researchers.

**Biogeochemistry and Marine ecosystem applications**
CICS scientists including Jorge Sarmiento (Princeton faculty) and his group have played a central role over time in the development of ocean biogeochemistry models and their application to a wide range of problems such as the global carbon cycle and response of marine ecosystems to climate change. Recent work by CICS associate researcher Desiree Tommasi explored the application of seasonal to decadal climate predictions to marine resource management, and CICS researchers including Fernando Taboada, have explored their application to biogeochemical and ecosystem variables. (Princeton researcher) Nicolas Oostende and (Princeton faculty) Bess Ward have made improvements to the GFDL ESMs which allow the simulation of coastal hypoxia.

**Prediction and predictability**
GFDL models are being applied to predictions on time scales from subseasonal to decadal. Numerous CICS researchers have examined the predictive skill of these models, and the predictability of specific phenomena, including drought (Nathaniel Johnson), Arctic sea-ice (Mitch Bushuk), South American rainfall (Honghai Zhang), the Pacific Decadal Oscillation (Liping Zhang), and the Intra-American Seas region (Lakshmi Krishnamurthy).

**Air quality**
A societally important application of ESMs is the understanding and prediction of air quality, with implications for human health. CICS scientist Meiyun Lin has quantified the relative importance of local emissions, remote emissions, and climate in determining the surface-level ozone within the United States. CICS associate researcher Bing Pu has applied GFDL climate models to explore the impact of climate variability on air quality due to dust.

**Extreme weather**
Extreme weather events such as floods and tropical cyclones have a large societal impact, and understanding the changes in frequency and characteristics of these events under a changing climate is an important application of GFDL ESMs. (CICS postdoctoral researcher) Karin van der Wiel, in collaboration with James Smith (Princeton faculty), has examined precipitation extremes, including the Louisiana 2016 floods, which were made more likely by climate change. (Princeton faculty) Ning Lin, has focused on the statistical prediction of tropical cyclones in a changing climate.
3. PROJECT DESCRIPTION

3.1 INTRODUCTION AND GOALS

This proposal for a Cooperative Institute for Modeling of the Earth System (CIMES) would continue and extend the research and educational programs currently supported under the Princeton Cooperative Institute for Climate Science (CICS). CICS is the most recent incarnation of a highly successful five decade long collaborative relationship between Princeton University and the Geophysical Fluid Dynamics Laboratory (GFDL), to develop computer models of the earth system, to understand climate and the earth system on a wide range of temporal and spatial scales, and to educate the next generation of climate and earth system scientists. The three linchpins of the GFDL/Princeton relationship on which CICS was built and which we propose to continue through CIMES, are:

First, the outstanding graduate academic program in Atmospheric and Oceanic Sciences, which has trained many eminent scientists working today in climate and earth system science. The great majority of the AOS grad students have been advised by GFDL scientists appointed to the AOS program faculty. As of December 2017, the program has awarded a total of 113 Ph.D.s and hosted over 350 postdoctoral, research and visiting scientists. The excellence of the graduate and postdoctoral training program enabled by the GFDL/Princeton collaboration is seen in the current success of those former students and postdoctoral researchers, most of whom are now government researchers or faculty in prominent academic institutions. (See Appendix 2 - “Past Graduate Students and Researchers” for more information.) The continuing strength of the collaboration is evident in the joint authorship of publications: in 2017, 68% of GFDL publications had Princeton University co-authors. (See the CI Publication Output Table in Section 3.5 “Performance Measures”.

Second, the academic expertise of Princeton faculty and investigators. This has played an important role in the progress of GFDL science, beginning with developments in computational fluid dynamics pioneered by Princeton Professor George Mellor, and continuing through development of ocean biogeochemistry and carbon cycle model components by Professor Jorge Sarmiento and his group in the AOS Program, and development of the land biosphere models of Professor Stephen Pacala and his group in the Ecology and Environmental Biology Department. These continuing strengths in ocean and terrestrial biogeochemistry and ecosystems, are complemented by observational and laboratory expertise contributed by Professors Bess Ward, Daniel Sigman, and Francois Morel in the Geosciences Department.

Current Princeton University expertise also includes:

- Numerous specialists in environmental engineering in the Civil and Environmental Engineering and Mechanical and Aerospace Engineering Departments (Professors James Smith, Ning Lin, Elie Bou-Zeid, and Luc Deike), focusing on a variety of problems including hydrological extremes, tropical cyclones, atmospheric boundary layer, and ocean waves;
- Core expertise in ocean and ice-sheet model development, as well as development of software infrastructure for climate modeling, provided by researchers in the AOS program (Research Oceanographer Alistair Adcroft, Senior Research Oceanographer
Sonya Legg, Research Glaciologist Olga Sergienko, and Balaji, Head of the Modeling System Group);

- Science policy experts in the Woodrow Wilson School of Public Policy (Professors Michael Oppenheimer and Denise Mauzerall) and Princeton Environmental Institute (Geosciences Professor Gabriel Vecchi and Professor Emeritus Robert Socolow of Mechanical and Aerospace Engineering, who, together with Professor Pacala, leads the Carbon Mitigation Initiative, a university-industry research partnership focused on the science, engineering, and policy challenges of climate change).

These and other Princeton University researchers will continue to apply their world-leading expertise to enrich the research of GFDL, broadening the expertise available to contribute to GFDL model development and application.

**Third, the flexibility of the academic enterprise at Princeton University to respond to new initiatives and opportunities.** Research performed through CICS and the proposed CIMES collaboration between Princeton and GFDL will necessarily evolve through the next 5-10 years as research priorities of NOAA change, new initiatives and concerns arise, and available expertise changes as personnel and careers progress. A key strength of CICS has been its ability to develop in response to these changes, providing a flexibility to be receptive to and take advantage of new opportunities as they arise, including the ability to readily draw on expertise at other universities when needed. With much of CICS research performed by students and postdoctoral researchers early in their careers, CICS has been able to respond quickly to changing priorities, enabling GFDL access to new ideas and fresh talent. CICS has developed a strong set of processes, which we will carry forward in CIMES, that facilitate this flexibility, including annual admission of new graduate students and undergraduate interns, an annual call for postdoctoral fellows, timely hires of postdoctoral researchers in response to targeted funding streams, and an annual call for research proposals from Princeton faculty. Throughout the decision-making process for these appointments, the CICS leadership has been responsive to current GFDL needs and concerns, and would continue to be so in the reincarnation of CICS as CIMES.

**CIMES VISION, MISSION and GOALS**

**VISION:** In parallel with GFDL’s 2011 Strategic Science Plan, and in response to the Federal Funding Opportunity, and the history of the GFDL/Princeton relationship, the CIMES vision is to:

*Be a world leader in understanding and predicting the earth system, across time scales from days to decades, and from the local to global spatial scales, with particular focus on extreme events, integrating physical, chemical, and biological components.*

**MISSION:** The mission of CIMES is to contribute to achieving the vision principally by drawing on the three linchpins of the GFDL/Princeton relationship to

*focus the scientific talent of Princeton University at all levels from graduate students, through postdocs, and faculty, to address key questions related to climate science and earth system modeling, providing a bridge between NOAA-GFDL and Princeton University and the wider academic community.*
GOALS: The goals of CIMES, that is, the specific activities that CIMES will carry forward in order to make progress in accomplishing our vision together with GFDL, reflect the Program Priorities identified in the NOAA Federal Announcement of Opportunity, namely:

1. To develop the world leading earth system model, in collaboration with GFDL, by providing expertise in key processes, physical and biological components, and software development.
2. To apply this model to the problem of prediction across time and space scales, from high resolution simulations of extreme events, to prediction of climate phenomena from seasons to centuries.
3. To apply this model to understand impacts of a changing climate on societally-relevant problems, including marine ecosystems, weather extremes, droughts and air quality.
4. To train the next generation of leaders in earth system science, through the world-leading graduate Atmospheric and Oceanic Sciences program, and the AOS postdoctoral program.
5. To develop a more diverse workforce by broadening participation in earth system science training, through summer internships, visiting faculty exchange fellowships and increasing research collaborations with diverse institutions.

These CIMES research goals are closely aligned with NOAA goals, as detailed next:

GOAL 1: One of the Department of Commerce’s strategic objectives articulated in its 2018-2022 Strategic Plan is the reduction of extreme weather impacts through enhancing NOAA’s prediction capabilities through better data gathering and modeling technology. CIMES proposes to contribute to this enhanced modeling technology, working with GFDL to develop Earth System models for seasonal to centennial predictions and projections at regional to global scales. Such a model must include components for the atmosphere, ocean, sea-ice, ice-sheets, terrestrial surface, including both ocean and terrestrial biogeochemistry, and the fluxes of heat, water, momentum and chemical constituents between these components. An overarching goal of CIMES is the development of such a comprehensive earth system model, in collaboration with GFDL. This development requires a thorough understanding of the many different processes involved in the climate system, including information from observational campaigns and theoretical studies, and the complicated interactions between processes. CIMES researchers therefore include experts in different processes, as well as their interaction within the climate system as a whole.

GOAL 2: This goal on prediction aligns directly with the GFDL mission to advance scientific understanding of climate and its natural and anthropogenic variations and impacts; and to improve NOAA’s predictive capabilities, through the development and use of world-leading computer models of the earth system. Princeton faculty and researchers are involved in both the development and use of computer models of the earth system. This goal also aligns well with the NOAA mission to understand and predict changes in weather, climate, oceans and coasts. Specifically, CIMES research will focus on understanding and predicting changes in climate and oceans. This prediction goal is also aligned with NOAA’s weather-ready nation and climate adaptation and mitigation goals.

GOAL 3: CIMES third goal on impacts is closely aligned with NOAA’s mission to conserve and manage coastal and marine ecosystems and resources, and with several NOAA goals: weather-ready nation (through research on weather extremes) and healthy oceans (through ocean
biogeochemistry and ecosystems research).

GOAL 4: Achieving our scientific goals requires a strong scientific workforce, and to this end CIMES will continue its close relationship with the highly successful graduate program in Atmospheric and Oceanic Sciences. The program provides academic training leading to a Ph.D. degree, as well as the opportunity for students to conduct research in collaboration with NOAA scientists, therefore obtaining training in NOAA-relevant science. CIMES will continue to support the training of early career scientists in NOAA research areas through the AOS postdoctoral program, as well as encourage the collaboration between NOAA and established academic scientists through the AOS visiting scientist program.

GOAL 5: As the nation becomes more diverse, involvement in earth system science must be extended to all sectors of the population, both to maximize the talent of the workforce, and to ensure that diverse perspectives are included in examination of impacts on society. To this end CIMES will pursue several initiatives to broaden participation in earth system science, including summer internships, visiting faculty exchange fellowships, and K12 teacher training and outreach programs.

3.2 RESEARCH THEMES

In the following sections we outline a comprehensive program of research focused on modeling of the earth system. This program begins with the development of earth system models, numerical models which include the dynamical, physical, chemical and biological components of the atmosphere-ocean system and the coupling between them. We then discuss the use of these models for prediction across time and space scales, from weather to climate, from regional to global, through high-resolution simulation and predictability studies. Finally we propose applications of earth system models to examine problems of particular societal importance, including air quality, weather extremes and drought, and marine ecosystems.

3.2A EARTH SYSTEM MODELING

The development of improved models for studying the earth system is an ongoing major focus of the collaboration between Princeton and GFDL. Such models are continually improving to provide greater realism and credibility to simulations of the earth system by including more components of the earth system, by including better representation of physical, chemical and biological processes, and by increasing resolution. The major components of an ESM are:

1. An ocean general circulation model, including a dynamical core to represent the fundamental fluid dynamics, and parameterizations of sub-grid-scale processes, such as mesoscale and submesoscale dynamics, and mixing.
2. Models for cryospheric processes, including ice-sheets, sea-ice and icebergs.
3. An atmospheric general circulation model, including a dynamical core to represent the resolved fluid dynamics, a radiation scheme, and parameterizations of sub-grid-scale processes such as clouds, convection, and turbulent transport in the planetary boundary layer.
4. An atmospheric chemistry model for predicting important chemical tracers.
5. A land model for surface hydrology and terrestrial biogeochemical processes.
6. An ocean biogeochemistry model enabling the prediction of the carbon cycle.
For each of these components, improvement continues to be possible in creating faster and more accurate dynamical cores, more physically-based parameterizations, and including more active chemical tracers, e.g., the Nitrogen cycle. Here we describe improvements to the GFDL models proposed by Princeton researchers. A common theme of these improvements is the use of greater understanding of important climate processes, gained through a combination of observations, process modeling and theoretical analysis, to advance the global model representations.

3.2A.1 NUMERICAL MODELING OF THE PHYSICAL CLIMATE SYSTEM

MODELING OCEAN PHYSICS & DYNAMICS

Ocean dynamics and circulation modeling: MOM6 development
The latest incarnation of the GFDL Modular Ocean Model (MOM) is MOM6, used in the OM4 configuration (the ocean component of GFDL’s CM4, used for CMIP6), developed by a team led by Princeton researcher Alistair Adcroft. MOM6 differs from previous generations of MOM in the use of a new algorithm, the Arbitrary Lagrangian-Eulerian method (ALE), applied in the vertical to permit arbitrarily general coordinates. The ALE method enables MOM6 to use any vertical coordinate, including traditional geopotential (z-), isopycnal, and terrain-following coordinates, as well the hybrid coordinates (Bleck, 2002), and thus also allows us to easily develop new vertical coordinates to better represent certain processes.

MOM6 is being adopted by other national centers and universities, in addition to GFDL and Princeton. NOAA-EMC (Environmental Modeling Center) will use MOM6, with an OM4-based configuration, for the next operational ocean model code used in seasonal forecasting. National Corporation for Atmospheric Research (NCAR) will use MOM6 for the next generation of the Community Earth System Model (CESM), and are developing a new ⅔-degree resolution configuration. The US Navy is evaluating a pathway to merge MOM6 into their modeling systems. This rapid adoption of MOM6 is enabled by the numerical integrity of the model, GFDL’s commitment to the model, and the adoption of the “open development” paradigm for code management and collaboration.

Open development
Most scientific codes are considered open source: code is distributed and made freely available through periodic releases. Led by Alistair Adcroft, Princeton and GFDL scientists have instead developed MOM6 using a more collaborative “open development” paradigm, in which every single commit and bug is visible, in this case via the public code hosting site GitHub. All users have access to the latest code developments, and feel more engaged, and feedback is up to date. In addition to the source code, the open access paradigm applies to tools and configurations (input parameters and data) to enable reproducible science. A key ingredient to successful open development is the use of continuous integration (testing of commits as they are pushed to GitHub) in which Princeton researchers have invested a lot of effort. Adcroft will continue research into testing, and deployment of tests and services, via public portals such as GitHub. This is an important element of the MOM6 strategic plan.

Future plans for ocean model algorithm development, led by Alistair Adcroft, include the development of new hybrid coordinates optimized locally to follow neutral directions. Whereas existing hybrid coordinates tend to rely on a particular choice of potential density and are prone
to under-resolving some water masses, especially at high latitudes in halocline regions, our new proposed hybrid coordinate will remove the dependence on a particular potential density, rendering the coordinate globally appropriate and independent of climate. We will also explore merging the MITgcm non-hydrostatic algorithm with the ALE method of MOM6, a development needed for planned high-resolution regional applications.

**Regional implementations of MOM6**
A new collaboration with Rutgers faculty Enrique Curchitser has been developing a MOM6 regional-modeling capability. Conventional methods for open boundaries are being implemented first (such as the Flather and Orlanski boundary conditions). Initial regional configurations will cover both western and eastern boundary current domains for evaluation purposes. We will then develop new approaches to open boundaries that can take advantage of the MOM6 algorithm. A regional capability in MOM6 will allow high-resolution deployment of the model for ecological and fisheries applications and accelerate model development for high-resolution applications such as ocean-ice-shelf interactions.

**Ice-sheet/ocean interactions**
Interactions between the ice sheets and the surrounding oceans play an important role in the state and evolution of the ice sheets and the ocean. The current generation of ESMs do not account for the presence of Antarctic ice-shelf cavities, and as a result, misrepresent Antarctic Bottom Water formation. Together with GFDL scientists, Princeton researchers Adcroft and Sergienko have been developing MOM6 capabilities and configurations that include the ice-shelf cavities and account for thermodynamic interactions between ice shelves and sub-ice-shelf cavity circulations. These processes strongly depend on model resolution (e.g., Schodlok et al., 2016), and adequate representation of ice-ocean interaction processes requires an ocean model with at least $\frac{1}{8}$ degree resolution. Here, we propose to develop high-resolution configurations of MOM6, both global and regional, that explicitly resolve Antarctic ice-shelf cavities and large Greenland fjords and represent thermodynamics interactions between ice shelves, outlet glaciers and the ocean.

Earlier studies have demonstrated that ice-shelf melting/refreezing is strongly affected by the shape of an ice-shelf cavity (Goldberg et al., 2012, Sergienko 2013), and therefore, a two-way dynamic coupling between an ice-shelf and sub-ice-shelf cavity circulation is required. In order to capture these processes and represent ice/ocean interactions, we propose to develop a fully dynamically coupled ice-shelf/ocean/sea-ice configuration of MOM6 (see “Modeling the Cryosphere” section below for the ice-shelf model details). Development of such a configuration has many challenges (e.g., dynamic boundaries, sharp pressure gradients at the ice-shelf front, etc.). The MOM6 ability to use multiple vertical coordinates will be used to accommodate sharp transitions at the fronts of ice shelves and outlet glaciers. The movement of the grounding line will be represented using wetting/drying capabilities of MOM6.

**Ocean physics and parameterization of unresolved processes**
The time-scales of evolution in the ocean range from minutes and hours, for short spatial-scale processes such as Kelvin-Helmholtz overturns, to years and centuries, for basin scale phenomena such as global meridional overturning. Finite computational resources necessarily restrict the space and time-resolution of numerical models so that everything that is unresolved must be
parameterized as a sub-grid scale process. The computational resources available at GFDL are such that eddy-resolving simulations are still not affordable for routine climate simulation but can be used for exploratory shorter time-scale simulations. Here we describe plans to improve parameterization of key ocean sub-grid scale processes.

**Subgrid scale topography**

The rigid impermeable boundary of the ocean floor provides a leading order constraint on the ocean circulation. Ocean topography varies on a wide range of scales, from narrow and steep features such as fracture-zone canyons, to large scale obstacles such as continents. The introduction of finite volume methods for representing topography (Adcroft et al., 1997) allowed models to avoid quantization of topography in the vertical direction, greatly improving the representation of flow-interactions with topography in z-coordinate ocean models. However, not all important topographic features can be resolved on a finite-resolution lateral grid. Adcroft (2013) proposed a statistical approach to finite volume representation of topography that captures the leading order geometric effects of fine-scale topography by means of thin-walls and porous barriers. A barotropic demonstration recovers the tsunami arrival times of a fine-resolution model (1/120th degree) with a coarse model (1 degree) using the porous barrier concept. Adcroft plans to apply the porous barrier concept in a 3-dimensional circulation model. Since the details of water-mass formation and spreading are often connected to fine-scale topographic features (e.g., overflows through straits and canyons), this new representation of topography will greatly reduce the dependence of some circulation features on spatial resolution and better represent topographically-controlled exchange processes for important water masses.

**The air-sea interface and boundary layer turbulence**

Processes at the ocean-atmosphere interface have a profound effect on weather and climate (Garbe et al., 2014, de Leeuw 2011, Veron 2015). Breaking waves strongly affect the overall balances of momentum, mass and energy exchanges, heat and gas transfer. Breaking waves generate sea spray, transferring moisture and momentum to the atmosphere, and produce cloud condensation nuclei. On the ocean side, the wave field transfers momentum, energy and mass to the water column and leads to surface Stokes drift that controls Langmuir turbulence in the oceanic boundary layer. State of the art ocean-atmosphere flux parameterizations used in ocean and climate models, such as COARE 3.5 (Fairall et al., 2003, Edson et al., 2013), depend solely on wind speed, in disagreement with measurements of gas transfer in the ocean for gases key to the climate system such as O$_2$, CO$_2$, and dimethyl sulfide (DMS) (Garbe et al., 2014, Liang et al., 2017, Bell et al., 2017). Therefore, the role of waves and breaking waves needs to be incorporated in new parameterizations.

To solve this complex problem, Princeton Professor Luc Deike has investigated small-scale wave breaking processes, solving for turbulence, dissipation, drift, air bubble entrainment, bubble bursting and sea spray generation, using novel direct numerical simulations (DNS), based on adaptive mesh refinement techniques (Popinet 2009, Deike et al., 2015, 2016, 2018, Popinet 2018) (Figure 1). This single wave approach can then be scaled up to the open ocean, integrating the wave statistics from observational data or ocean models to obtain ocean-atmosphere fluxes (Deike et al., 2017). This will lead to novel parameterizations for gas transfer or sea spray usable directly through WAVEWATCHIII model inputs coupling the ocean and the atmosphere within...
OM4 and CM4. The proposed approach is general and can be applied to sea spray, momentum flux, and drag coefficient in the future.

The ocean surface boundary layer (OSBL) is the mediator of heat, momentum, and gas exchange between the atmosphere and the ocean interior. Accurately simulating the evolution of the OSBL is critical for modeling processes with time-scales spanning from the diurnal cycle (e.g., days) to climate trends (e.g., centuries and longer). Led by Brandon Reichl, Princeton and GFDL researchers recently introduced a new energetic planetary boundary layer (ePBL) framework for OSBL turbulence parameterization in GFDL’s MOM6 ocean model, constructed for energetically-constrained vertical mixing robust across model resolution (Reichl and Hallberg, 2018). The next phase of ePBL development will ensure that energetic constraints for various processes that drive vertical mixing (e.g., the shear-turbulence parameterization of Jackson et al., 2008) are satisfied in an internally coherent manner, allowing ESMs to seamlessly transition across spatial scales.

As for air-sea fluxes, wave effects and Langmuir turbulence are critical for simulating the OSBL under both extreme weather events (Reichl et al., 2016a and 2016b) and climate (Fan and Griffies 2014; Li et al., 2016). Motivated by high-resolution Large Eddy Simulations, we have therefore modified the ePBL approach to consider the explicit impact of sea-state dependent Langmuir turbulence (Reichl et al., 2018). Led by Brandon Reichl, Princeton researchers will continue development toward a full atmosphere-wave-ocean-ice coupled system to incorporate wave effects within our ePBL vertical mixing framework of MOM6.

**Mesoscale eddies and sub-mesoscale turbulence**

Ocean mesoscale eddies are a leading order component in the vertical heat budget for the ocean interior (Griffies et al., 2015) and an important process in ocean heat (and carbon) uptake, as well as a major contributor to meridional heat transport. The conventional approach to mesoscale eddy parameterization of Gent and McWilliams (1990) is formulated to be a sink of available...
potential energy, but the appropriate effective eddy diffusivity remains an open area of research. In Jansen et al (2015b), Princeton researchers derived a model of eddy diffusivity, based on an explicit mesoscale eddy kinetic energy (MEKE) budget, which has been employed in OM4. A major remaining question concerns the vertical structure of lateral eddy fluxes. In addition, the diffusivity model primarily accounts for transient eddies but a large part of lateral eddy fluxes in the ocean is due to standing eddies. Future CIMES ocean parameterization activities, led by Alistair Adcroft, will be oriented around these questions, in particular accounting for the standing-eddy fluxes, a function of spatial resolution.

OM4 has a nominal horizontal resolution of ¼ degree, known as “eddy-permitting”, when the eddy processes are far from being well resolved and overall eddy activity can be weak. Princeton researchers (Jansen et al., 2015a) used the explicit energy budget of subgrid-scale eddies to return energy from subgrid scales to the resolved flow via backscatter, consistent with the inverse cascade. Alternative approaches which we plan to evaluate in eddy-permitting models include stochastic parameterizations, and the Bachman et al (2017) model using the QG Leith parameterization. Parameterizations must be resolution-dependent (scale aware) (Hallberg, 2013), so that mesoscale eddies are parameterized where they are not resolved, and energized where they are permitted but poorly resolved.

Submesoscale baroclinic processes occurring on much finer scales O(1km) than the mesoscale are known to be important in re-stratifying the OSBL. A widely used parameterization of mixed layer eddies (MLE) is that of Fox-Kemper et al (2008), based on a limited process study, which achieves an effectively vertical heat transfer by means of large-scale lateral transport. Led by Alistair Adcroft, we propose to improve MLE, accounting for heterogeneity of vertical convection (Ilicak et al., 2014). The MLE parameterization will be applied to subgrid components of the Ilicak scheme, achieving greater restratification efficiency without invoking as large an implied bolus circulation. This will combine three parameterization ideas (namely the near surface mixing schemes of Reichl and Hallberg, 2018, and Jackson et al, 2008, and Ilicak et al., 2014) into one consistent scheme. We will also explore parameterization of submesoscale instabilities associated with the bottom boundary layer adjacent to topography (Yankovsky and Legg, 2018).

Ocean mixing
Diapycnal mixing in the stratified ocean interior plays an important role in the ocean circulation, modifying density and stratification, determining where heat is diffused into the ocean interior, influencing heat and carbon storage, and steric sea-level rise. Most diapycnal mixing processes occur on very small scales, 10-100m, and therefore will need to be parameterized in global ocean models for the foreseeable future. The development of these parameterizations and understanding of their impact on global ocean circulation and climate will remain an important goal for CIMES research, led by Princeton researcher Sonya Legg.

During the past decade much attention has focused on the role of internal waves in driving diapycnal mixing. Princeton researchers, including Legg, participated in the Climate Process Team on Internal Wave Driven Mixing, focusing on parameterizing the diapycnal mixing driven by internal waves generated by tides, topographic lee-waves and wind-driven inertial waves (MacKinnon et al., 2017). A new tidal mixing parameterization (Polzin 2009; Melet et al.,
2013a) was implemented in GFDL models. Planned extensions of this parameterization will account for the physics controlling the variability in the fraction of internal tide energy dissipated locally (Nikurashin and Legg, 2011; Yi, Legg and Nazarian, 2017), and include subgrid-scale topography (Melet et al., 2013b; Lefauve et al., 2015). The parameterization will be extended to include trapped breaking waves in high latitude regions. We will continue to improve the tidal mixing parameterization to account for propagating internal tides, completing the implementation of a ray-tracing algorithm, and include the dissipation of internal tides at continental slope canyons (Nazarian and Legg, 2017a,b). A parameterization of topographic lee-wave driven mixing (Nikurashin and Ferrari, 2011) has been implemented in GFDL ocean models (Melet et al., 2014). The energy available for mixing depends on the mesoscale kinetic energy of the mesoscale eddies, and the distribution of that energy relative to topography. We propose to refine the connection between this lee-wave driven mixing scheme and the mesoscale eddy parameterization, such that the energetic transfers between the two are consistent. We propose further process simulations to fully understand the location of the lee-wave breaking, which may be either close to the topography or in critical layers.

Much of the mixing in the ocean interior is due to shear-driven mixing, when the vertical shear of the flow field is sufficient to overcome the stabilizing effect of stratification. For resolved shear (i.e. due to equatorial jets or bottom-intensified gravity currents) this mixing is achieved in GFDL models by the (Jackson et al., 2008) parameterization, recently recalibrated for the upper ocean (Reichl and Hallberg, 2018). Legg and Adcroft will explore modifications to this parameterization to account for mixing in straits and sills, where hydraulic effects accelerate the flow, when narrow topographic features are represented by the porous barrier algorithm.

MODELING THE CRYOSPHERE

The three cryospheric components of the GFDL ESM are the ice sheet model, the sea-ice model and the iceberg model. All these models have been actively developed by Princeton scientists, led by Olga Sergienko, in collaboration with GFDL scientists.

**GFDL Ice Sheet Model**

The present-day ice sheets, Greenland and Antarctica, lock ~63 m of sea-level equivalent in a form of glacial ice (Bamber et al., 2013, Fretwell et al., 2013). Even a small fraction of sea level change caused by ice-sheet mass loss can have strong impacts on densely populated low-elevation coastal areas. Princeton researcher Sergienko has been developing a thermomechanically coupled continental-scale ice-sheet model (ISM) based on a widely used approximation of the momentum balance which allows for a simultaneous representation of shear-dominated ice flow, characteristic of ice sheet interiors, and basal-sliding dominated ice flow, characteristic of ice streams, outlet glaciers and ice shelves (e.g., Schoof and Hindmarsh, 2010). The model uses parameters (e.g., basal sliding coefficients) optimized for the present-day ice-sheet flow, based on inverse modeling techniques and observations of the surface ice-sheet flow and surface and bed elevations.

Recent analysis (Fyke et al., 2018) has demonstrated that interactions between ice sheets and other components of the Earth system give rise to feedbacks (both positive and negative) that cannot be represented by stand-alone ice-sheet models. Therefore, we propose to develop a two-way coupled ice-sheet model component of the ESM in collaboration with GFDL scientists. A
fundamental difference between ice sheets and other components of the Earth system is the evolution of their vertical and horizontal extent, so that the ISM component has dynamic boundaries. Significant model-development efforts must therefore be devoted to accommodating the dynamic boundaries of the ISM component within the ESM framework.

Another significant difference between the ISM component and other ESM components is the horizontal spatial resolution required for adequate representation of a number of physical processes. For instance the dynamics of the grounding line (a transition between the grounded portion of an ice sheet and its floating ice tongues and ice shelves) needs significantly higher spatial resolution (on the order of 500 m or less) than the horizontal resolutions typical of other ESM components. Coupling model components with such differences in horizontal resolution remains a substantial challenge. One approach to this problem is the development of conservative downscaling/upscaling schemes that can accurately represent mass and energy fluxes to and from the ISM component to the other components. Another approach is to develop parameterizations of physical processes that can allow for coarse resolution of the ISM component.

Parameterizations for the GFDL Ice Sheet Model

We propose to focus on several poorly understood physical processes that have leading-order effects on the ice-sheet behavior and develop parameterizations suitable for continental-scale ice-sheet models and the ice-sheet model component of the ESM.

Basal conditions: Led by Sergienko, we propose to develop parameterizations for distributed and channelized subglacial flow regimes (Hewitt, 2013) and their effects on ice basal sliding. Different sliding laws and hydrology models will be applied for soft beds, like under the West Antarctic ice sheet (e.g., Tulaczyk et al., 2000, Schoof, 2006, de Fleurean et al., 2014, Damsgaard et al., 2017). These parameterizations will account for spatial and temporal variability of the ice-sheet basal sliding and will be tested and validated where observations of subglacial hydraulic systems exist (e.g., subglacial water pressure variability, basal reflectivity, etc.).

Grounding line dynamics: The transition between the grounded parts of an ice sheet and its floating parts – ice shelves and floating tongues – is called the grounding line. Ice flux through the grounding line determines the ice-sheet contribution to eustatic sea level. Hence, the grounding line dynamics control the extent of the grounded ice sheet and the rate of change in sea level caused by ice discharge. Continental-scale ice-sheet models cannot resolve the grounding line motion, which must be parameterized, using analytic relationships between the ice flux and ice thickness at the grounding line (e.g., Pollard and DeConto, 2009). Princeton scientists have developed such a relationship suitable for the majority of ice streams and outlet glaciers floating into confined ice shelves (Haseloff and Sergienko, 2018). Led by Sergienko, we propose to implement these parameterizations and to develop new time-dependent parameterizations of the grounding line dynamics.

Iceberg Model

Icebergs are an important pathway in the polar hydrologic cycle, responsible for transporting approximately half of the mass loss from Antarctica away from the continent (Rignot et al.,
Icebergs modify ocean stratification through melt water, and thus can affect ocean heat uptake, sea-ice formation and biological productivity. Princeton researchers were the first to include icebergs in a coupled climate model by means of a pointwise particle-iceberg model (Martin and Adcroft, 2010). Most iceberg mass is contained in large tabular icebergs, for which a point-wise representation becomes less defensible as ocean model resolution is refined. Stern et al., (2017) resolve this limitation by joining particles together with rigid bonds to form the larger structures of tabular icebergs, and successfully demonstrated this approach in a study of an idealized ice-shelf calving event (Figure 2). Princeton researchers led by Adcroft and Sergienko plan to use this capability to simulate the subsequent evolution of a recent large-scale calving event to better understand the consequences of these events for the Earth system.

**Sea Ice Model**

The current GFDL sea-ice model component – the Sea Ice Simulator, version 2 (SIS2) – is based on an approximation of sea ice as a continuum medium that obeys an elastic-viscous-plastic rheology (Hunke and Dukowicz, 1997), utilizes a multi-category ice-thickness distribution (Bitz et al., 2001), and employs a conservative thermodynamic formulation with four ice layers and two snow layers. This recently developed model has a number of new features which improve upon the earlier SIS1 model, including a Delta-Eddington radiation scheme, revised thermodynamic algorithms with near-exact conservation of enthalpy, salt, and mass, and a C-grid discretization which allows for improved representation of ice transport through narrow channels. Planned future developments to SIS2 include prognostic melt ponds (Flocco et al., 2012, Hunke et al., 2013), a ridging parameterization (Lipscomb et al., 2007), and mushy layer thermodynamics with a prognostic salinity variable (Turner et al., 2013).
The melt pond parameterization will allow Princeton researchers, in collaboration with University Corporation for Atmospheric Research (UCAR) scientist Mitch Bushuk, to study ice-albedo feedback processes, crucial to both the seasonal evolution of sea ice (Bushuk et al., 2017a) as well as decadal-to-centennial climate responses to greenhouse gas forcings (Winton 2006). We also plan to explore the influence of ridging parameterizations on the spatial distribution of Arctic sea ice thickness. Ridging parameterizations enable rapid creation of thick sea ice in zones of ice convergence, which may ameliorate the thin sea-ice bias of the CM4 model.

**Lagrangian Sea Ice Model**

An approach that treats ice flows as Lagrangian elements has been proposed as an alternative to conventional Eulerian sea-ice models like SIS/SIS2, but existing Lagrangian sea-ice models are too computationally expensive for climate integrations (e.g., Hopkins, 2004; Herman, 2016). Princeton researchers Adcroft, Damsgaard and Sergienko, in collaboration with GFDL scientists, have developed a new, more efficient, Lagrangian sea-ice model, capable of simulating realistic behavior of sea-ice floes. Stand-alone simulations of this new model can successfully reproduce jamming behavior of sea ice in narrow straits, important for sea-ice dynamics but poorly represented in continuum models (e.g., Rallabandi et al., 2017). We propose to implement a Lagrangian sea-ice model component in the GFDL ESM framework. This will improve sea-ice prediction by adequately resolving granular sea-ice rheology, including improved treatment of ice advection in the sea-ice marginal zone (e.g., Feltham, 2005), fracturing and shear zone formation and dilation (e.g., Tremblay and Mysak, 1997), and dynamic jamming (e.g., Kwok et al., 2010).

**Development of a unified framework for cryosphere simulations**

Icebergs and sea ice are discontinuous materials, and are obvious components of the cryosphere to treat with a Lagrangian formulation. Princeton researchers, led by Sergienko and Adcroft, propose to additionally include ice shelves and grounded ice in the Lagrangian framework, coupled in the GFDL ESM. This approach simplifies the treatment of rupture propagation and calving dynamics at the ice-shelf front (e.g., Åström et al., 2014, Stern et al., 2017), which is crucial for iceberg production and ice-shelf stability in a warming ocean (e.g., Hulbe et al., 2010, Fürst et al., 2016).

**MODELING THE ATMOSPHERE**

NOAA/GFDL’s atmospheric model development is centered around the Finite-Volume Cubed-Sphere Dynamical Core (FV3) (Lin 2004 and 2016). The recently developed nonhydrostatic version of FV3 is the basis of fvGFS, an innovative, variable-resolution, global-to-regional atmospheric model which will replace NOAA's current Global Forecasting System (GFS) model and form the basis for NOAA’s Next-Generation Global Prediction System (NGGPS), which aims to eventually provide global cloud-resolving model (GCRM) simulations for NOAA’s weather forecasting and climate research. The hydrostatic version of FV3 is currently the basis for GFDL’s CMIP6 model AM4 (Zhao et al 2018), running at 100 km resolution with parameterized convection. Progress in computational power allows for increased global and regional resolution, as well as for improved representations of physical and chemical processes. In tandem with increased resolution and complexity, however, many current parameterizations also need to be adjusted, and scale-aware process representations need to be developed. Of
particular importance is a coherent framework of physical and chemical process representations for model configurations tailored to address specific objectives, and support for techniques such as nesting and nudging to optimize use of computational resources.

**High resolution modeling of clouds and convection**

A major development in NOAA’s global modeling capabilities has been the advent of non-hydrostatic FV3. Princeton researchers, including Xi Chen and Linjong Zhou, have contributed to this by developing numerical algorithms (such as the Riemann solver technique, Chen et al., 2013) as well as developing the variable resolution or ‘nesting’ technique. The latter has significantly improved predictions of precipitation and temperature in the contiguous US, as well as hurricane intensity and structure (Zhou et al., 2017). Princeton researchers will continue to improve fvGFS's nesting algorithms and make them more computationally efficient, to allow for even higher nested resolutions, and will also contribute to GCRM development through contributions to DYAMOND (Satoh 2017), an inter-comparison of GCRMs evaluated against field data from the NARVAL campaign (Stevens et al., 2016).

In tandem with the dynamical core development, the moist processes of convection need to be adapted and improved. Ongoing Princeton research shows that with the new GFDL single-moment six-category cloud microphysics (Chen and Lin 2013), major improvement in predictions of convective scale precipitation and its diurnal cycle is achieved in the contiguous United States. Princeton researchers will continue development of this scheme, including development of a double-moment version of the scheme, as well as a comparison and/or reconciliation of this scheme with AM4's current Rotstaysn-Klein microphysics scheme.

Another tool for FV3 model development are cloud-resolving, doubly-periodic radiative-convective equilibrium (RCE) simulations which feature idealized, uniform surface boundary conditions. Princeton researchers, including Nadir Jeevanjee, have used cloud-resolving RCE to understand how convective vertical velocities vary with resolution and the hydrostatic approximation (Jeevanjee 2017a, see Figure 3), as well as how convective organization varies with dynamical damping parameters (Anber et al., 2018). Such understanding will be critical for understanding the fidelity of continental convection and organized, extreme storms as simulated by fvGFS and NGGPS. Further work will include substantial contributions from FV3 to RCEMIP (Wing et al., 2017a) to help develop RCE benchmarks, as well as using RCE as a testbed for evaluation of GFDL's various microphysics schemes.

Such limited-area, high resolution simulations can also bridge the gap between short-term explicit convection simulations and longer term parameterized convection simulations, by running limited-area, steady-state simulations of large-scale circulations using both O (1 km) resolution cloud-permitting and O (100 km) resolution parameterized convection configurations. Examples include the mock Walker cell configuration discussed in (Jeevanjee et al., 2017b), or the large-domain, self-aggregated simulations of (Silvers et al., 2016). These configurations present opportunities to benchmark a coarse-resolution, parameterized convection simulation against a higher-resolution, explicit convection version, simplifying the identification of errors in the convection scheme, since both simulations would have the same large-scale microphysics and planetary boundary layer (PBL) schemes.
For efficient and effective use of the various model configurations described above, the configurations must share the same code base. A coherent representation of physical and chemical processes across model configurations is required to seamlessly model the atmosphere from the Weather to seasonal and climatological time scale. In particular, CIMES research will address currently existing gaps between AM4 and fvGFS. Specifically, the AM4 code base currently does not contain the new GFDL microphysics scheme (which currently resides only in the fvGFS code base). Princeton researchers will implement the doubly-periodic configurations described above in the AM4 code base, as well as the GFDL microphysics scheme, to facilitate the work described above.

**Interactions between atmospheric composition and dynamics**

Changes in atmospheric composition, ranging from dust episodes to stratospheric ozone depletion, have pronounced impacts on atmospheric dynamics, through their impact on phase change of water and radiation, and need to be adequately accounted for in predictions and hindcasts on short to long timescales. Radiative transfer benchmark calculations will help to more accurately calculate these radiative forcings. Interactions between clouds and dynamics, and the role of clouds for regional precipitation biases are the focus of ongoing Princeton research (e.g., Popp and Silvers, 2017), and remain of great importance for the future development of ESMs. The representation of cloud microphysical processes of liquid, mixed-
phase and ice clouds will be improved. In collaboration with Princeton faculty (Debenedetti, Panagiotopoulos; e.g., Haji-Akbari and Debenedetti, 2015; 2017), ice nucleation is studied based on first principles with the objective to provide physically self-consistent, scale-aware parameterizations. Below, we outline three areas of particular importance: representation of dust, troposphere-stratosphere coupling, and modeling tropospheric chemistry for air quality analyses and predictions (Section 3.2C.1, “Air Quality Applications”, below).

Dust
A faithful representation of dust is critical for accurate global simulations across the weather-climate continuum: it is the most abundant aerosol by mass following sea salt, and absorbs and scatters both solar and terrestrial radiation, influencing large-scale seasonal phenomena such as the West African monsoon, Indian monsoon, and Atlantic tropical cyclones.

The absorbing and scattering properties of dust depend on both the chemical composition of dust as well as how it is mixed or coated with other aerosols. In most climate models, however, including GFDL’s CM3 (Donner et al., 2011), the radiative properties of dust are parameterized into a few key variables, such as refractive index, which furthermore do not vary with space and time. We propose to improve the fidelity of seasonal dust forcing in GFDL models by better quantifying the radiative parameters using observational mineralogy datasets, as well as allowing the refractive index to evolve in both space and time, and finally by considering the mixing of dust with other aerosols.

To capture the global radiative effects of dust on longer climate timescales, it is important to capture the strong interannual and decadal variations of African and Australian dust. This will require updating GFDL’s current dust emission scheme based on (Ginoux et al., 2001). We propose to add anthropogenic dust sources (estimated to account for 25% of global dust emission, (Ginoux et al., 2012), as well as better constraints on dust emission from dynamic vegetation models and observations, and adjust dust size distributions from observations.

Troposphere-Stratosphere coupling
The coupling between stratosphere and troposphere increases the persistence of variations in the troposphere (Baldwin et al., 2003). This longer memory from the stratosphere is expected to benefit forecast skill on seasonal to sub-seasonal timescales. Based on simulations with GFDL FLOR, Princeton researchers including faculty Stephan Fueglistaler have shown improved prediction skill resulting from stratospheric initialization (Jia et al., 2017). Increasing vertical resolution and a higher model top, as well as realistic yet computationally efficient representation of radiatively important constituents such as ozone will further improve the model’s troposphere-stratosphere coupling, skill particularly for seasonal forecasts.

Princeton researcher Pu Lin is developing a simplified scheme to represent stratospheric ozone variations. The performance of this scheme surpasses other similar ozone schemes employed in numerical weather prediction models (e.g., Cariolle and Déqué 1986, McLinden et al., 2000, McCormack et al., 2006). Preliminary results show that this scheme can reasonably simulate stratospheric ozone changes in response to forcings, and the scheme will be included in weather and seasonal forecast model configurations. Systematic evaluation of the impact on forecast skill, and analysis of the impact on future climate projections will be performed.
Orographic and non-orographic gravity waves play an important role in troposphere stratosphere interaction dynamics. The current non-orographic gravity wave drag scheme is based on Alexander and Dunkerton (1999), assuming a constant wave source at a fixed level. We will implement new gravity wave schemes that calculate gravity wave sources from simulated convection, and schemes that can represent the stochastic nature of the wave source. Progress in the development of the dynamical core may allow the development of a new orographic gravity wave scheme, superseding the current scheme (Garner, 2005).

**Tropospheric chemistry modeling**

The atmospheric chemistry component of the GFDL model includes a detailed representation of the gas and aerosol processes that contribute to air pollution. The GFDL dynamical core enables long simulations (10+ years) of atmospheric composition at high resolution, offering unique insights into the influence of meteorology and chemistry on atmospheric composition (Lin et al., 2014; Lin et al., 2017; Paulot et al., 2017b; Schnell et al., 2018), and the impact of air pollution on dynamics (Bollasina et al., 2011; Westerveld, 2017).

The rapid changes in the speciation and spatial distribution of anthropogenic emissions amidst climate variability present unique opportunities to evaluate the fidelity of the GFDL model under a range of meteorological and chemical conditions. Using 40 years of observations and GFDL model simulations with full chemistry, (Lin et al., 2014) demonstrated the importance of decadal climate variability in modulating the response of tropospheric ozone to rising Asian emissions as measured at Mauna Loa Observatory. (Li et al., 2018) showed that a revised treatment of biogenic oxidation in the GFDL gas-phase mechanism enables capture of decadal changes in organic nitrogen in the US. (Paulot et al., 2017a) showed the increase of the in-cloud oxidation rate of SO2 can help explain the observed weak sensitivity of winter SO4 to declining SO2 emissions.

The following model developments proposed by Princeton researchers, including Fabien Paulot and Meiyun Lin, aim to expand the range of processes that are represented in the GFDL model, to broaden the range of conditions that can be accurately simulated.

a) Organic aerosols are often the largest component of PM2.5 by mass, but their formation remains challenging to capture in global models. We will focus on the representation of secondary organic aerosols (SOA) for which precursors and formation pathways have been elucidated (IEPOX, glyoxal), enabling improved understanding of changes in SOA production due to natural and anthropogenic emissions (Marais, 2017).

b) Halogens. Currently the GFDL model does not represent the chemistry of tropospheric halogens, which play an important role primarily in remote regions. We will focus on implementing a detailed representation of bromine chemistry, following (Schmidt et al., 2016), improving representation of methane sinks and better characterizing natural variability in the atmospheric oxidative capacity (Naik et al., 2013).

c) Coupling with land. Currently there is little interaction between atmospheric chemistry and other components of the GFDL ESM. For instance, calculations of atmospheric deposition and natural emissions, two fundamental drivers of atmospheric composition, rely on static land-use
and vegetation maps, inconsistent with the land model. Work is ongoing to use the land model to represent fire and biogenic emissions as well as dry deposition, enabling better representation of the modification of atmospheric composition by changes in surface properties. (See Section 3.2C.1, “Air Quality Applications”.)

3.2A.2 INCORPORATING BIOGEOCHEMICAL AND ECOLOGICAL PROCESSES INTO MODELS

TERRESTRIAL BIOGEOCHEMICAL AND ECOLOGICAL PROCESSES

Modeling land and vegetation processes is critical for simulating and predicting the impact of environmental change on biogeochemical cycles and human habitats; the land surface still represents the highest source of uncertainty in Earth System Models (Friedlingstein et al., 2006). Forests and croplands are major players in the hydrological cycle that modulates atmospheric cooling (Shevliakova et al., 2013, Mueller et al., 2016, Bonan 2008). Increasing CO$_2$ concentrations will lead to reductions of plant evapotranspiration due to downregulation of plant stomatal opening, which may increase tree mortality (Anderegg et al., 2015), with consequences for hydrological and biogeochemical cycles, as well as atmospheric warming (Shevliakova et al., 2013). Modeling the non-linear soil-vegetation-atmosphere continuum and its interaction with the hydrological and biogeochemical cycles is therefore a high priority.

The decades-long collaboration between Princeton researchers and GFDL has resulted in a new generation of land model, LM4, integrating the most advanced representation of vegetation dynamics, biogeochemical cycles, and the hydrological cycle (see Figure 4). Continuing this collaboration is critical to maintain NOAA’s leadership in land surface and biogeochemical cycle modeling. Given Princeton’s strength in vegetation-hydrological cycle modeling (led by Professor Steve Pacala) and the recent Princeton faculty appointment of ecohydrology expert, Amilcare Porporato, the next advancement of the land model aims to improve representation of soil-land ecosystem hydrological cycles and their dynamic feedback to the atmosphere.

Princeton faculty Steve Pacala and Amilcare Porporato have significantly contributed to modeling plant regulation of the hydrological cycle (Pacala et al., 2005, Weng et al., 2015, Wolf et al., 2016, Calabrese et al., 2017, Hartzell et al., 2017, Porporato et al., 2015, Band et al., 2014). Remote sensing data and ecosystem measurements of drought-driven changes in water balance within and between ecosystems have led to new discoveries in plant stomatal behavior (Wolf et al., 2016, Brodribb 2017). Vegetation response to drought is currently absent from most ESMs but is being implemented in GFDL LM4 by the Princeton-GFDL collaboration.

**Next generation vegetation model, LM4**

Representing the inherent complexity of land ecosystems is still an urgent challenge for ESMs. LM4 integrates an ecosystem demography (ED) model (Moorcroft et al., 2001) and an analytically tractable model of forest dynamics, the perfect plasticity approximation (PPA), (Weng et al., 2015, Weng et al., 2017). Applied globally, LM4 allows for a better representation of ecosystem dynamics at global and regional scales by modeling succession, diversity and competition between and within species. These vegetation and ecosystem dynamics make GFDL-LM4 unique and allow for the reduction of uncertainties associated with land response to environmental variations and climate extremes e.g., drought.
Most recently, the collaboration between Princeton scientists and the GFDL land model group led to the development of a new plant hydraulic model (Wolf et al., 2016) that increases the predictability of stomatal behavior and improves its representation during drought (Anderegg et al., 2017). Figure 4 describes the different component of the plant hydraulic model and its interaction with vapor pressure deficit (VPD), soil moisture, irradiance and temperature. The integration of the new hydraulic model in LM4 will allow better representation of ecosystem response to drought.

Modeling the hydrological cycle and the soil-vegetation-atmosphere continuum is key for predicting current and future impacts of environmental change on vegetation, its feedback to the atmosphere and the possible impact on human life. We therefore propose to advance the structure and parameterization of the land model by implementing improvements described below.

**Implementing CAM photosynthesis in LM4**

The framework of LM4 is designed to facilitate the implementation of specific plant species with mechanistic trait parameterization facilitating the evaluation of carbon, nutrients and water cycles at regional to local scales. The current number of plant functional types is restricted to C3 and C4 grass, tropical trees, deciduous and needleleaf temperate trees, but LM4 has the potential to include as many species or representative groups of species as current computing capacity could support. This unprecedented possibility remains constrained by the available modelisation...
of each plant type, namely: C3 and C4. However, in water limited climates and areas, plant species that utilize Crassulacean Acid Metabolism (CAM) often have a competitive advantage over other photosynthetic plant types. CAM is the most evolved photosynthetic pathway, capable of assimilating carbon at the highest rate per unit water as compared to C3 (e.g., rice) and C4 (e.g., maize) plants. CAM species thrive in arid and semi-arid regions, which make up 47% of land area globally (Lal 2004) and 40% of the United States (UNSO/UNDP 1997) and show a strong tolerance to high temperatures (Borland et al., 2009). Consequently, for an accurate understanding of plant competition and dynamics, CAM photosynthesis should be modeled consistently with C3 and C4 photosynthesis.

While C3 and C4 plants dynamics are consistently represented in widely used models, the first CAM plant dynamics model (Bartlett et al., 2014) has recently been formulated. A relatively simple model of CAM photosynthesis has allowed for CAM plant dynamics to be coupled to light, temperature, humidity, and rooting depth, as well as to soil moisture, which connects the plant process to the overall water cycle (Bartlett et al., 2014, Hartzell et al., 2015). We propose to make use of this work to implement a CAM specific photosynthetic parameterization in LM4, in addition to the already existent C3 and C4, model competitive advantages, and predict relative distributions of the three photosynthetic types globally and in particular in water limited regions. This will facilitate analysis of the food-water-energy tradeoffs involved in food and biofuel production in arid regions of the world (Porporato et al., 2015).

Modeling land use and croplands
In recent years, many advancements have been made to our understanding of land use and its contribution to anthropogenic CO2 emissions. Since 1850, one third of anthropogenic CO2 emissions resulted from land use. Humans have also modified the hydrological cycle and in the past 40 years, irrigated areas have increased by ~70% (Gleick 2003). With rising population and temperature, critical challenges in agriculture and irrigation infrastructures may affect human capacity to sustain higher food demand. Temperature and CO2 could affect plant productivity in different ways. By accelerating metabolism, temperature and CO2 should increase plant productivity. On the other hand, CO2 reduces stomatal aperture, and evapotranspiration and drought may reduce enhancement in productivity (Gray et al., 2016). The direct impact of increasing CO2 on evapotranspiration (Mueller et al., 2016, Anderegg et al., 2015, Shevliakova et al., 2013) could intensify atmospheric warming. We propose to develop specific parameterizations for major crops within LM4 that will allow us to assess the sensitivity of these ecosystems to climate change. Incorporating information on date of sowing, nutrient applications and harvesting will help model carbon, nitrogen and water biogeochemical cycles from soil to atmosphere at regional and global scales.

Implementing plant capacitance in LM4
In addition to photosynthetic mechanisms for coping with water limitation already implemented in LM4, plants also have a water storage capacitance for effectively managing water uptake, not represented in most land surface models. In dryland areas, this water storage may buffer against droughts; conversely, in humid areas, this storage may allow for more efficient water uptake (Porporato et al., 2015, Bartlett et al., 2014, Goldstein et al., 1998). Plant water storage also helps to reduce diurnal and seasonal variability in plant water stress, increasing carbon assimilation by up to 50% under certain hydrologic conditions (Hartzell et al., 2017). Moreover, plant water
storage determines if a plant has a safe or efficient water uptake strategy (i.e., drought tolerant or drought avoidant, Hartzell et al., 2017), determining how the ecohydrology of a landscape responds to changing climate. We propose to incorporate a simplified model of plant water storage in LM4, allowing more accurate depictions of vegetation dynamics, including competition, productivity, and mortality under water stress (Porporato et al., 2004) and increasing the predictability of ecosystem response to drought.

**Dependence of soil carbon and nutrient cycles on water availability**
Recent developments in the field of soil biogeochemistry have highlighted the critical importance of incorporating interactions among microbial decomposers, organic materials, and mineral particles in order to accurately model soil biogeochemical cycles, and in particular their responses to changes in climate and water availability (Schmidt et al., 2011, Wieder et al., 2013, Sulman et al., 2014). Recent work by Princeton researchers has incorporated cutting-edge representation of these processes into GFDL’s LM4 and related ecosystem-scale modeling studies focused on soil carbon cycling (Sulman et al., 2014), coupled carbon-nitrogen cycles (Sulman et al., 2017) and the role of microbial responses in drying-wetting cycles (Salazar et al., 2018). Ongoing work by Princeton researchers coupling plant and soil carbon and nutrients cycles and integrating the role of symbiotic relationships between plants and microorganisms is critical to establish the links between soil water content and ecosystem productivity.

Better mechanistic representation of soil biogeochemical cycling will improve simulations of hydrological feedbacks to the atmosphere and soil, and vegetation responses to drought. Microbial processes fundamentally alter soil carbon cycle responses to drought and wetting cycles (Salazar et al., 2018) and incorporating these processes into LM4 will improve ecosystem simulations. We propose to improve simulations of how ecological and climatic changes affect transfers of nitrogen from soils to lakes and rivers by coupling soil carbon-nitrogen cycle simulations including critical impacts of microbial and mineral soil processes, improving our ability to model runoff. We also plan to use the existing mechanistic soil C and N cycling framework to integrate fire impacts on soils and ecosystem-scale C and N cycling into the model, improving simulations of fire impacts at both short and long time scales. This work will include fire effects on nutrient availability (Pellegrini et al., 2018) as well as simulating inputs of fire-affected organic matter (char) into soil. The advanced mechanistic soil model already implemented in GFDL LM4 will also facilitate improved simulations of peatland and permafrost ecosystems sensitive to changes in hydrology.

**Ecological and phenological parameterizations of tropical tree mortality**
Tropical ecosystems play a fundamental role in the global biogeochemical and hydrological cycles (Huntingford et al., 2013, Korner et al., 2009, Santiago 2015). Recent expansion of field and ecosystem-scale CO₂ exchange measurements has established the ecological and physiological connections between tree mortality and soil nutrient availability under drought. Two recent drought events in the Amazonian Forest in 2005 and 2010 showed a delay in tree mortality. During severe drought, the tree water column is likely to be damaged and if it persists, hydraulic failure leads to severe xylem damage. The carbon cost associated with the reconstruction of damaged xylem imposes additional competitive pressure on tree species and can lead to lethal starvation, ultimately leading to tree death long after the end of the drought.
We propose to investigate and model the connection between tree drought mortality and soil nutrient availability, as recent empirical evidence indicates soil phosphorus is the strongest predictor of tropical tree drought mortality at both seedling and adult phases (L. Comita and G. Vargas personal communications). Princeton faculty Lars Hedin and Steve Pacala have studied the connection between water availability, drought, symbiotic nitrogen fixation, and plant phosphorus acquisition strategies. In addition, current Princeton research on the connection between vegetation dynamics and the nitrogen and phosphorus cycles indicates that ecosystem disturbances (such as land-use, fires, and hurricanes) and biomass recovery patterns can drive vegetation nutrient limitation via plant growth nutrient demand. We propose to extend this research by mechanistically modeling plant strategies to connect vegetation dynamics, nutrient cycling, and the hydrological cycle. These improvements to LM4 will allow better prediction of droughts, biogeochemical cycles, and vegetation in the future Earth System.

**Linking land Model and the open Ocean**

Human services, agriculture and fisheries rely on freshwaters, such as rivers, lakes, and reservoirs. Rivers play a critical role in marine resources by delivering vast amounts of nutrients from land to the oceans. Excessive nutrients from land cause hypoxia and algal blooms in many coastal waters with serious consequences for marine ecosystems. Most global land models, however, focus on terrestrial ecosystems and ignore freshwater nutrient dynamics, such as freshwater emissions, river routing and exports to the oceans, hindering their ability to understand causes and consequences of freshwater nutrient pollution and track the fate of nutrients from land to oceans.

Princeton-GFDL LM3-TAN (Lee et al., 2014) is one of a few global land models that includes river routing and biogeochemistry and has been further extended to include lake biogeochemistry (Lee et al., 2017). This model captures coupled terrestrial C-N dynamics that critically affect the state of N storage in vegetation and soils, and thus, in principle, is more appropriate to simulate hydrological N leaching from soils to rivers, lakes, and the oceans. While most land models are constrained with global terrestrial N budgets which include substantial uncertainty, LM3-TAN can be constrained based on relatively abundant measurements of regional N exports from rivers. Incorporation of this freshwater biogeochemistry into LM4 would provide long-term dynamic river N inputs to ocean models, which currently rely on prescribed N inputs largely based on empirical approaches. We propose to apply long-term dynamic river N inputs to GFDL ocean model Carbon, Ocean Biogeochemistry and Lower Trophics (COBALT) (Stock et al., 2014), which would allow assessment of terrestrial and freshwater impacts on coastal ecosystems and marine resources. Ultimately, this freshwater biogeochemistry model will be extended to include other nutrient cycles (e.g., phosphorus) and serve to connect land and ocean biogeochemical components of GFDL’s next generation ESMs.

**Anthropogenic impacts on the water cycle over land**

Until recently, land models have primarily focused on natural systems with minimal regard for managed systems which in many regions now constitute a significant component of the observed landscape. Within ESMs, this lack of managed systems translates into a poor accounting of the role of human activity with regards to urban systems, water abstraction, reservoir, irrigation, industry, among others. Recent efforts within hydrologic models provide a promising path forward to address this strong limitation in land models (e.g., Wada et al., 2014).
Recognizing the role of anthropogenic activities on the water cycle, recent efforts have begun to include many of these missing processes within LM4. For example, (Li et al., 2016) added an advanced yet computationally efficient urban canopy parameterization into LM4, illustrating the large difference that a robust characterization of the urban processes can have on the partitioning of energy from local to global extents. Furthermore, there is ongoing work to include water management within LM4, finalizing the inclusion of irrigation through water abstraction from rivers, reservoirs, and groundwater. The addition of these processes will provide an important step to include and understand the role of human activity over land in coupled and uncoupled water, energy, and biogeochemical cycles.

High-resolution land modeling and impacts on weather, seasonal, and global predictions
As ESMs move towards higher spatial resolutions, there is a recurring need to more adequately characterize and parameterize the underlying observed spatial patterns that influence the processes over land (e.g., topography). Many common assumptions that suffice at large spatial scales (e.g., above 100 km) are no longer appropriate at much finer spatial scales (e.g., lack of communication of groundwater between grid cells). Recent efforts have focused on addressing this issue within LM4 by harnessing the existing petabytes of environmental data to more adequately characterize the observed heterogeneity of the physical environment; this has led to an effective spatial resolution between 100 and 1000 meters within the updated modeling framework (Chaney et al., 2017). Numerous future activities emerge from this new high-resolution framework within the land model. First, a more complete characterization of the observed land heterogeneity leads to an improved coupling of the water, energy, and carbon cycles and improved short-term, medium-term, and long-term predictions. Second, this work adds the ability to provide field-scale (~100 meter) predictions while maintaining the computational advantages of macroscale models; this provides numerous advantages to the land model including: 1) locally relevant predictions more readily accessed and used by stakeholders and 2) a more formal approach towards validating and evaluating modeling efforts using in-situ to field-scale measurements. Finally, these efforts provide a seamless approach towards working with novel grid structures such as the stretched grid used to provide high resolution land information over areas of special interest.

OCEAN BIOGEOCHEMICAL PROCESSES

The ocean has absorbed between one quarter and one third of anthropogenic carbon emissions, making understanding of current and future ocean uptake a primary goal for earth system models. Oceanic carbon uptake occurs through two pathways: the physical and chemical processes of dissolution and transport of dissolved inorganic carbon referred to as the solubility pump, and the formation and downward transport of organic matter and CaCO₃ by biological processes referred to as the biological pump. Both are potentially affected by feedbacks in ocean biogeochemical processes. Accurate representation of these processes is a significant goal of coupled ESMs. In addition to understanding current and future carbon uptake, ESMs are our main tool for predicting future changes to water properties, such as pH, oxygen content, calcium carbonate saturation state, and nutrient availability, that serve as indicators for and determinants of the health of ocean ecosystems, and enable us to assess the potential impact of such changes on ocean ecosystems and services.
Carbon chemistry and the physical solubility pump were added to ESMs as part of early collaborations between GFDL and Princeton scientists in Jorge Sarmiento’s group. Ocean chemistry is relatively well understood, so the primary source of uncertainty in future projections of the solubility pump is due to uncertainty in model predictions of the physical processes determining the air-sea gas exchange rate, the solubility (T and S), and circulation and mixing in ESMs, our plans for which have already been discussed in previous sections (except for gas exchange, see below). The current focus of biogeochemical model development and evaluation is on the remaining large source of uncertainty, namely, the representation of biological processes and the impact of climate change on biogeochemical tracer distributions.

GFDL/Princeton research on the representation of climate-relevant biogeochemical processes has been accomplished by Princeton researchers (primarily Eric Galbraith) and GFDL researchers (primarily John Dunne and Charlie Stock, both of whom were Princeton postdocs before joining GFDL) using a hierarchy of biogeochemical models of varying complexity. The state of the art models currently in use are the Tracers of Ocean Phytoplankton with Allometric Zooplankton (TOPAZ) intermediate complexity model (30 prognostic tracers) (Dunne et al., 2010, 2013) and the more complex COBALT model, which resolves cycles of macro and micronutrients, free living bacteria, and multiple size classes and predator-prey relationships of phytoplankton and zooplankton (33 state variables) (Stock et al., 2014). This representation of detail comes at a computational cost. To parameterize the important biogeochemical complexity with minimal expense, Princeton and GFDL developed the Biogeochemistry with Light Iron Nutrients and Gases (BLING) with only six explicit tracers (Galbraith et al., 2010) and its more streamlined version, miniBLING (Galbraith et al., 2015), which keeps only three tracers. Together, this suite of biogeochemical models has been embedded in different resolution physical models to represent the biogeochemical processes important to climate over a range of time and space scales.

Planning for future model development between Princeton and GFDL centers around several broad lines of effort; the first we discuss is improved observations of biogeochemical tracer distribution for model validation.

**Improved biogeochemical tracer distributions for model validation**

Modeling current and future changes to the carbon cycle and determinants of ocean health requires accurate representation of the mean state and variability of tracers throughout the ocean. Data evaluations of model output are central to determining how well current parameterizations capture key features of ocean biogeochemical processes. In this respect, the longtime community leadership contributions of Princeton researcher and CICS contributor, Robert Key, have been crucial to carrying out the Global Ocean Data Analysis Project (GLODAP) for carbon, an internally consistent and quality-controlled database of carbon relevant tracers from oceanographic research cruises (Key et al., 2015). The GLODAP data have been used extensively for model validation in CICS.

CICS scientists from both Princeton and GFDL have also been involved in exciting new developments in our ability to measure ocean biogeochemical tracers with unprecedented spatial resolution and frequency using robotic floats. A first large-scale prototype of this approach is currently being tested in the Southern Ocean as part of the Southern Ocean Carbon and Climate
Observations and Modeling (SOCCOM) project. While this project is funded principally by National Science Foundation (NSF), it has significant in-kind support from NOAA and NASA, including major input to the scientific justification based on research by CICS, including by Jorge Sarmiento (Director of SOCCOM) and his group. This research has shown that the Southern Ocean is of particular importance to the climate system due to its absorption of 40-50% of the total oceanic uptake of anthropogenic carbon (Gruber et al., 2009; Frölicher et al., 2015) and its supply of nutrients that fuel much of the productivity north of 30°S (Sarmiento et al., 2004). The challenge to scientists is that it is also a region of persistent model biases in mixing and nutrient supply to the upper ocean (e.g., Figure 5), and it has had very few observations over most of the region. This is now rapidly changing, thanks to the 200 robotic SOCCOM floats that are to be spread throughout the Southern Ocean, and CICS is at the forefront of those who are already using these data to test and improve models.

The GLODAP dataset spans almost 5 decades, providing a view of the mean state of ocean biogeochemical parameters and the long-term rate of change that can be used to evaluate the carbon cycle in climate models. Time tracers such as radiocarbon and chlorofluorocarbons provide a reference for mixing and ventilation rates. SOCCOM floats offer the first year-round and under-ice observations of biogeochemical data in the Southern Ocean, which are challenging prior conclusions of oxygen and carbon air-sea exchange (Bushinsky et al., 2017, Gray et al., 2018). Determining whether these differences are due to an incomplete view of the mean state due to seasonal biases in measurements, long-term changes, or greater interannual variability than was previously understood is a matter of open investigation. Comparisons of CM 2.6, GFDL’s 1/10 degree ocean model, and lower resolution GFDL models to SOCCOM data indicate wide disagreement in the amplitude and phase of the seasonal cycle in carbon fluxes. The development and interpretation of a biogeochemical float network that parallels and enhances the Argo network of temperature and salinity measurements will require a coupled approach of model and observational studies. Princeton researchers involved with SOCCOM have been working towards the expansion of a biogeochemical Argo network based on the successful Southern Ocean effort. Assimilating of such data into models such as ensemble coupled-climate data assimilation (ECDA) and Southern Ocean State Estimate (SOSE) provide one means of understanding changes in the ocean, feeding back into the refinement of prognostic models and predictions of future carbon uptake. Improving the seasonal representation of biogeochemical cycles in models and understanding the resolution required to capture the important processes is one of the goals of current and near-term efforts.

Response of biogeochemistry to multiple scales of change in data and models
Developing the ability to accurately capture natural biogeochemical variability on seasonal to interannual and decadal scales will require high resolution data of the type that GLODAP and SOCCOM provide, combined with model intercomparisons that allow the determination of required model resolutions and parameterizations to represent these features. Understanding and modeling variability is also essential for separating the anthropogenic forcings and predicting when future signals will emerge in carbon parameters (Carter et al., 2016) as well as other indicators of ocean health.
While physical ocean prediction systems routinely assimilate observations and produce seasonal to decadal forecasts, ocean biogeochemical prediction systems are less mature. Challenges include insufficient biogeochemical observations, uncertainties from physical and biogeochemical processes in ESMs, and properties of biogeochemical variables that challenge data assimilation approaches (e.g., non-Gaussian, complex patterns of cross-correlation). A particular impediment that CICS scientists are working to overcome, is high biogeochemical sensitivity to transient momentum imbalances that arise during physical data assimilation. A pragmatic strategy now under development integrates COBALT with the ECDA system used for GFDL’s seasonal to decadal global climate predictions. Ocean and atmosphere data constraints in the assimilation system are optimally modified to reduce biogeochemical biases while retaining the information of observed physical states (Park et al., 2018). In tests, initializing the model with output from the ECDA system coupled with COBALT, seasonal to multi-annual prediction skills of nutrient anomalies, oxygen, phytoplankton and zooplankton show higher and
longer-term predictability than sea surface temperature. Assessment of biogeochemical predictions against satellite datasets shows a gap between potential predictability and achieved prediction skill, which will be the focus of further investigation.

Oceanic observations of CO$_2$ coupled with similar atmospheric measurements provide constraints on air-sea CO$_2$ fluxes, but little information about the biogeochemical and physical processes driving them. These uncertainties have far reaching implications for our understanding of the carbon cycle and its representation in climate models. Climate models, including GFDL-EMS2M and GFDL-ESM2G, used to predict future climate-carbon cycle feedbacks, are being validated in an effort led by Princeton faculty Laure Resplandy using novel approaches and observational constraints, such as atmospheric potential oxygen, which combines records of atmosphere CO$_2$ and O$_2$/N$_2$ content (Nevison et al., 2016, Eddebbar et al., 2017, Resplandy et al., 2016).

Modeling of biogeochemical tracers related to ocean health has been an area of ongoing collaboration between researchers at Princeton and GFDL. Particular focus in the past has been on changes in pH and the associated impact on marine calcifiers (Orr et al., 2005). Changes in oxygen are also predicted to have significant impacts on future ocean productivity, especially in coastal areas and fisheries (Breitburg et al., 2018). Expected changes in ocean circulation and stratification will impact the exchange of deep, cold waters replete in inorganic carbon and deficient in oxygen; recent studies suggest changes in ventilation significantly impact ocean oxygen content. However, there is still significant uncertainty in the air-sea exchange parameterization of oxygen, which as a low solubility gas is impacted by bubble injection during high wind speeds to a far greater extent than very soluble gases such as carbon dioxide. Princeton researchers have embedded recent air-sea gas parameterizations that explicitly resolve the bubble processes into the last generation GFDL ocean model MOM5, with resulting impacts on air-sea exchange and ocean oxygen content in areas of deep water formation. Future work is aimed at determining whether bubble injection is an important process to include in future coupled ESMs, and include parameterizations of breaking waves on air-sea exchange (Deike et al., 2016) (see “Modeling Ocean Physics and Dynamics in section 3.2A.1 above”).

On-going work by Princeton researcher Resplandy to understand submesoscale-mesoscale dynamics on the biological pump and carbon export using modeling and in-situ observations. It will also build on prior work by Princeton researchers who evaluated TOPAZ using satellite measurements of ocean color and in situ O$_2$/Ar measurements (Jonsson et al., 2015).

**Modeling phytoplankton functional groups and their trophic interactions**

Data validation of model results has yielded significant understanding on how well tracers are represented in ESMs and where parameterizations of biogeochemistry can be improved. For example, GFDL’s ESM2M embedded with COBALT can simulate global (seasonal and latitudinal) patterns of phytoplankton biomass enabling prediction of carbon cycling, ocean primary production and fisheries yield, but fails to represent the full range of chlorophyll concentrations observed in the ocean and detected by satellites. This is especially important in coastal regions, where small-scale features contribute disproportionately to phytoplankton biomass and fisheries. Additionally, the subarctic Atlantic spring phytoplankton bloom in ESM2M-COBALT occurs too early and bloom magnitude is too low (Stock et al., 2014).
Sensitivity analyses during COBALT development indicate that both these problems may be due to the trade-offs in the representation of the phytoplankton functional groups and their trophic interactions. In the case of chlorophyll distributions in the coastal regions, recent work by Princeton researchers Van Oostende and Ward showed that introduction of a new phytoplankton functional type was required (Van Oostende et al., in review), with attributes associated with chain forming diatoms, the basis of some of the world’s most productive food webs, including upwelling regions and the subarctic Atlantic.

Future development work led by Princeton faculty Bess Ward will go beyond simple allometric and stoichiometric principles in modeling phytoplankton functional types, focusing on the key traits of important groups and incorporating model relationships to represent them. For example, current models recognize the greater need for iron to support nitrogen fixing phytoplankton, but the special relationship between silica and diatoms is not considered. The aim of the new phytoplankton parameterization is to simultaneously capture the deep Chl maximum in the subtropics and the correct timing and magnitude of the spring bloom in the subarctic ocean. This approach is based on results from Princeton researchers in collaboration with C. Stock (GFDL) and R. Dussin (Rutgers University) which, for the first time, successfully simulated the Chl concentration gradient of >2 orders of magnitude from oligotrophic to highly productive coastal upwelling along the western North American coast (Van Oostende et al., in review), and supported and guided by field observations, theoretical concepts and results from coastal upwelling mesocosm simulation experiments (Raimbault et al., 1988; Chavez 1989; Thingstad 1998; Irigoien et al., 2004; Van Oostende et al., 2015, 2017). Accurate parameterization of phytoplankton size structure and physiology is critical for addressing model biases in magnitude and distributions of phytoplankton biomass and productivity, and therefore for accurate simulation and prediction of the biological pump, carbon sequestration and fisheries.

3.2A.3 THE PRINCETON HIERARCHICAL EARTH SYSTEM MODELING INITIATIVE (PHESM)

As described above, Princeton contributions to GFDL model development involve a range of model resolution and complexity, and idealized and process models as well as full Earth system models. In addition, CIMES and AOS will be training a new generation of modelers among Princeton students and post-doctoral researchers. The basis for this training is the model hierarchy (the subject of a World Climate Research Programme and Princeton University sponsored Model Hierarchies Workshop in 2016, Jeevanjee et al, 2017b), where understanding the behavior of complex models requires simpler ones, whose ideas are then drawn into the comprehensive models when mature. CIMES plans to formalize this process in the Princeton Hierarchical Earth System Modeling Initiative, headed by Princeton faculty member Fueglistaler. All the GFDL models are built upon a single infrastructure, the Flexible Modeling System (Balaji, 2012). We propose to build and maintain a repository of all the publicly available GFDL model configurations as a CIMES adjunct to GFDL, in cooperation with the Princeton Institute of Computational Science and Engineering (PICSciE), who may contribute software engineering support, as well as a computational platform based on Princeton faculty contributions to the PICSciE computational cluster. CIMES-supported engineers will maintain an “open development” platform that allows a wider community to configure and run these models, as well as submit modifications. Activities to be undertaken under the PHESM Initiative include the following:
- Maintenance and update of a code repository of publicly available GFDL models and configurations.
- Maintenance of a continuous integration and automated testing framework that allows ingesting submitted code from collaborators when they meet the required test criteria of physical accuracy and computational performance. See discussion of ‘Open development’ in “Modeling Ocean Physics and Dynamics.”
- Development and maintenance of a pedagogical interface to allow students to configure, run, and analyze models, so that the model hierarchy may be more easily integrated in coursework.

3.2B SEAMLESS PREDICTION ACROSS TIME AND SPACE SCALES

The ESMs described in the previous research theme are increasingly being applied to prediction, in support of scientifically-based decision-making. Such predictions occur on a variety of spatial and temporal scales, dependent on the problem of interest. In order to make the best use of resources, increasingly the same code base is being applied to different prediction problems at different resolutions. Many of the model advances described in the previous research theme allow the same model to be applied to prediction at different scales, by incorporating scale-aware physically-based parameterizations, a choice of model formulation with the appropriate physics for the scale of interest (e.g., nonhydrostatic v. hydrostatic), and varying degrees of comprehensiveness and complexity. Here we describe two different aspects of prediction across time and space scales, the very high resolution modeling necessary to resolve extreme weather phenomena, and the predictability of different weather and climate phenomena.

3.2B.1 HIGH RESOLUTION MODELING AND EXTREMES

VISION FOR HIGH-RESOLUTION (HR) MODELING SUBTHEME

Here we summarize CIMES-HR, the CIMES contribution to high-resolution modeling at NOAA-GFDL, focusing on the development of model components that accurately represent physical processes as model resolution is increased beyond the current norm of 25-100 km, and the computational and data issues associated with the development of high-resolution coupled models. The unique strengths of the NOAA-GFDL modeling system include the FV3 atmospheric dynamical core; the MOM6 ocean model; and the Flexible Modeling System (FMS) infrastructure underlying those, to which Princeton scientists have made substantial technical and scientific contributions. The vision for CIMES-HR can be summarized as follows:

- Collaborate with NOAA-GFDL on the scientific development of high-resolution model components for atmosphere, ocean, land surface, sea ice, and ice sheets, with the goal of improving the prediction of extreme events such as tropical cyclones and droughts, seamlessly across timescales from weather to climate (minutes to millennia);
- Substantially contribute to the technical development of high-resolution coupled models, including advancing models, data archival, and analysis on next-generation computing platforms;
- Make novel contributions complementary to NOAA/GFDL’s efforts in advancing transition to operations. These will include supporting an open development environment,
exploration of cloud technologies for computing and data analysis, and research into machine-learning approaches to accelerating model development.

SCIENTIFIC AND TECHNICAL CONTEXT

Both earth system modeling and computing technology are at a critical stage in their evolution. While many global aspects of the climate system are largely well understood, accurate prediction on the scales of societal interest remains a complex problem. Clouds in particular remain a particular challenge (Bony et al, 2015), with large-scale radiative effects, driven by dynamics of cloud formation at scales $O(10 \text{ m-1 km})$ (Schneider et al, 2017a), well below the resolution of global climate simulations today, with microphysical processes occurring at still finer scales of $O(m-cm)$. A key dynamical issue is that there is no intrinsic length scale at which convective processes can be considered resolved: the 3D atmospheric turbulence regime extends down to the Kolmogorov length scale of molecular dissipation (Nastrom and Gage, 1985). Deep convective systems in the atmosphere that are largely responsible of the distribution of moisture, energy and entropy in the vertical, appear to take place on scales of $O(1 \text{ km})$, while deep convection also appears to self-organize on larger scales of $O(1000 \text{ km})$ (Holloway et al, 2017; Wing et al, 2017b). Neither the process of convective initiation or convective aggregation is simulated at all with the state of the art for global climate models today, which typically run at $O(100 \text{ km})$ in resolution and parameterize convection using closure assumptions along the lines of quasi-equilibrium between the resolved and unresolved scales (e.g Arakawa and Schubert, 1974 and its many descendants). These resolutions also cover the range often called the “gray zone” where the hydrostatic assumption ceases to hold, and a non-hydrostatic and compressible form of the primitive equations must be used for explicit solution of vertical motions (Jejevanjee, 2017a). Current global model resolutions are in the gray zone, marking the difficult transition from hydrostatic to non-hydrostatic flows, and from parameterized to resolved deep convection.

Similar considerations obtain in ocean dynamics as well, where mixing processes well below the threshold of simulation resolution cascade back to the large-scale in ways that cannot be easily parameterized (Fox-Kemper et al, 2014). There is increasing recognition that the ocean plays a role at weather scales so operational systems are moving to fully coupled predictions (Hewitt et al., 2017). For climate scales, it is widely understood that the mesoscale eddy field is a critical ocean process to resolve. As resolution is refined from eddy-permitting to eddy-resolving, boundary currents are better resolved and boundary separation becomes more realistic (Marzocchi et al., 2015; Chassignet and Xu, 2017). At seasonal scales there is evidence of regional coupling between the atmosphere and ocean (Small et al., 2008; Kelly et al., 2010). At weather scales there is speculation that sub-mesoscales in the ocean could couple with the atmospheric planetary boundary, but in most ocean models only the restratification process by mixed-layer eddies is parameterized (Fox-Kemper et al., 2008). Understanding how sub-mesoscale processes interact with the atmosphere requires very high-resolution coupled models.

Turning to computational technology, we find ourselves at a critical juncture in its evolution as well. We have experienced several generations of exponential increase in computing power, encapsulated in “Moore’s Law” – the observation by Gordon Moore that transistor density on silicon – roughly equivalent to computing power – doubles every 18 months and driven by the physical phenomenon of “Dennard Scaling” (Dennard et al, 1974), which notes that power
density per unit area on a chip remains constant as circuitry is miniaturized, ensuring total power consumption remains constant as transistor density increases. Now miniaturization has reached a point where power requirements prohibit further increases in transistor density, and silicon technology no longer obeys Dennard scaling. Further increases in computational capacity come from adding more transistors without increasing density. From the point of view of algorithms, this means that arithmetic will not get faster, but we can perform more of it in parallel. Attempts to migrate climate and weather codes to the new generation of massively parallel chips are described in (Balaji, 2015). Responses to the Dennard scaling crisis include the suggestion to take advantage of the inherent chaotic nature of the climate system (Palmer, 2017) by use of inherently stochastic parameterizations, using low-precision arithmetic (Palmer, 2014) or even stochastic hardware (Duben et al., 2014).

A further transition is now upon us, known by the buzzwords “artificial intelligence” or “machine learning” (ML). Underlying technologies such as deep convolutional neural networks (NNs) or “deep learning,” have made possible dazzling advances such as facial recognition and self-driving cars. The basic premise is that given a sufficiently large and representative training dataset, NNs can be trained to produce a compact representation resulting in a fast and approximate emulator of the underlying process. As the approach is sufficiently powerful in such a wide range of circumstances of great popular significance, computing hardware is increasingly driven by ML as an application (See Google’s TPU for an example of such a new chip). While there are a few examples of the use of ML in our field (e.g., Faghmous and Kumar, 2014; Krasnopolsky et al., 2013), the approach remains in its infancy. CIMES-HR embraces high-risk high-reward research, continuing to take advantage of the forefront of computing technologies to advance Earth system science and modeling, by leveraging the computing industry’s turn toward ML.

THE CIMES-HR PROGRAM

We propose a research and development program to be undertaken at CIMES in high-resolution modeling, focusing on the development of model components suitable for high-resolution model simulations, and the development of coupled models, including novel approaches to model calibration or “tuning”. In addition, the CIMES-HR program includes a number of technical contributions to coupled model computational infrastructure. For the purposes of CIMES-HR, high resolution is defined as cloud-system-resolving and cloud-resolving in the atmosphere, and mesoscale-eddy-permitting and -resolving in the ocean, with comparable resolutions in the sea-ice and land-surface components.

Atmospheric model development for high-resolution simulations

NOAA/GFDL’s atmospheric model dynamical core FV3 is currently the basis of both low resolution climate models, e.g., GFDL’s CMIP6 model AM4 (Zhao et al. 2018), and cloud-resolving models at finer resolutions, but for shorter times (see “Modeling the Atmosphere” in section 3.2A.1 for more details). As a rule of thumb, a climate model must run at around 5 simulated years per day (SYPD) for useful science; a weather forecast model at about 0.5 SYPD. FV3 has demonstrated the ability to meet the climate requirement at around 10 km resolution, and the weather requirement at around 3 km, which is marginally a global cloud-resolving model on around 100,000 computational cores. A fundamental goal of CIMES-HR in collaboration with
GFDDL is the development of modeling systems that target unified weather-to-climate predictions, including coupled global forecast models with sufficient resolution to simulate both high-impact, extreme weather and regional phenomena such as drought, tropical cyclones, atmospheric rivers, severe floods and mesoscale convective systems, as well as large-scale climate variations, on timescales from subseasonal to multidecadal. These models will make use of both scale-aware parameterizations and the regionally enhanced resolution provided by FV3’s nesting capabilities. See “Modeling the Atmosphere” in section 3.2A.1 for further details of atmospheric model development necessary for high-resolution modeling including associated scientific benchmarking. In addition, CIMES will undertake research into using machine-learning to develop reduced-dimensionality representations of cloud processes based on these high-resolution studies, as outlined in the Machine Learning section below.

**Ocean model development for high-resolution simulations**

Current Ocean model development across the weather-climate spectrum at GFDDL is centered on the latest version of the Modular Ocean Model, MOM6, described in “Modeling Ocean Physics and Dynamics”. Resolutions in use currently at GFDDL range from 0.25° in CM4 and 0.5° in ESM4. Along the seamless prediction spectrum, where it has been shown (e.g Murakami et al, 2015) that ocean resolution may be sacrificed without losing skill; MOM6 is run at 1°. CIMES-HR contributions to the future development of MOM6 will focus on very high resolution models. Key developments necessary for very high resolution ocean modeling include non-hydrostatic capabilities and scale-aware parameterizations, as well as regional nesting capabilities. (see section “Modeling Ocean Physics and Dynamics” in section 3.2A.1 above for details of these developments). CIMES-HR will continue in the tradition of using MOM6 for process studies in controlled settings, and using those to develop parameterizations to be used at coarser resolutions for climate studies and prediction models. Led by Princeton researchers Adcroft and Legg, we will construct models on a hierarchy of resolutions from 1/8° to 1/64° and use the process studies to build representations of sub-grid physics suitable for use at the resolution GFDDL typically runs. The parameterization creation process will include machine-learning approaches as described below.

Mesoscale eddies are key controls of ecosystem dynamics and essential to assess impacts on ecosystem services (fisheries, conservation of emblematic species, carbon sequestration etc.). Led by Princeton faculty Resplandy, we will construct a hierarchy of nested high-resolution ocean models coupled to biogeochemical and ecosystem modules. This work will build upon the ongoing developments of regional and open boundary capabilities in MOM6 performed by GFDDL and Princeton researchers, allowing representation of eddy-driven dynamics in strategic regions, such as Western Boundary Currents and Eastern Boundary upwelling systems (see subtheme on Ecosystem impacts of climate change), while incorporating the influence of global changes and variability.

**Coupled model development**

A key ingredient of Princeton contributions to NOAA/GFDDL modeling has been the highly efficient coupling infrastructure introduced by Princeton researcher Balaji in collaboration with GFDDL developers. The coupling infrastructure is based on the exchange grid (Balaji et al 2006), which enables different model components to be discretized on their chosen grids (for example, FV3 uses a cubed-sphere grid, and MOM6 uses a tripolar grid) and still maintain high accuracy
and strict conservation of exchanged quantities. For example, studies of sea level rise (see “Modeling the Cryosphere” in section 3.2A.1 above) require exchanges of water between atmosphere, land, ocean and cryosphere to be simulated accurately with exact conservation over $10^9$ timesteps (Balaji, 2015). The exchange grid in FMS has enabled the building of several generations of models of increasing resolution and complexity without sacrificing performance. Preliminary results from the CPMIP project comparing computational performance across CMIP6 models shows that FMS-based models appear to outperform most other models of equivalent resolution and complexity (Balaji et al, 2016). Another key feature of the FMS coupler, enabling efficient parallel ensembles (Zhang et al 2005), is particularly relevant to the study and prediction of extreme events using ensemble methods (see “Data Assimilation Research and Implementation” in 3.2B.2 “Predictability” and section 3.2C.2 “Extreme Weather Events and Drought”). This feature is used extensively in data assimilation methods using Kalman filters and the detection and attribution of extreme events.

Future research directions in CIMES will continue to explore and extend the FMS coupler on future computational platforms. A particular research focus is to make sure that the coupling cost as measured in Balaji et al (2016) remains a modest fraction of total computational cost as we move toward coupling cloud-resolving atmosphere and eddy-resolving ocean models in a single coupled system.

**Machine learning research**

As noted above, the computing industry is moving very substantially toward machine-learning as a key application, and GFDL will need to rapidly evaluate how to take advantage of this. CIMES proposes to become the hub of this research, led by Balaji. There are two potential directions for CIMES-HR to take advantage of ML techniques:

A first approach is the use of very high-resolution model output to train a low-dimensional representation of the same physics. An approach outlined in Schneider et al (2017b) for instance focuses on large-eddy simulations (LES) data from boundary layer convection to train representations of shallow clouds in General Circulation Model (GCMs). The approach is rather general, and one could attempt to follow this approach for deep convection (Wing et al, 2017a), or for mesoscale or sub-mesoscale ocean eddies (Fox-Kemper et al, 2014; Zanna et al, 2017).

A second approach is the development of fast approximate models. The great attraction of the use of fast approximate models in climate modeling is in our approaches to the treatment of uncertainty. We have previously made reference to the use of ensembles to deal with chaotic uncertainty. A further difficulty in simulating the Earth system is the vast complexity of the system, and the many processes that have poor observational constraints. This parametric uncertainty has been treated by different approaches. Collectively referred to as “tuning”, these methods generally impose global constraints (such as top-of-atmosphere radiative balance, or global mean surface temperature) on the value of particular process parameters, a process described in detail in Hourdin et al (2016) and Schmidt et al (2017). The difficulty remains in the enormous cost of tuning using “full” models, which means that only a portion of the uncertainty space is ever explored (Golaz et al, 2013). Other approaches to parametric uncertainty include a pure “brute force” approach to exploring parameter space (Knight et al, 2007), the use of statistical techniques to constrain the space of uncertainty (Williamson et al, 2013), and the
deriving of compact “metamodels” (Neelin et al, 2010) describing the system response to parameter variation. Examples from the past literature cited above include the “gustiness parameter” of sub-gridscale velocity fluctuations used in Neelin et al (2010) and the “autoconversion threshold” at which non-precipitation cloud droplets become precipitating hydrometeors, as used in Golaz et al (2013).

**Computational platform**
CIMES will need an independent computational platform in addition to the resources available from NOAA HPC resources. We propose two initiatives to complement existing and future NOAA resources:

1. PICSciE maintains and runs a substantial computational resource for the benefit of the University’s computational research community, allowing scientists to pool their resources to create a cluster greater than the sum of its parts, on which scientists receive allocations proportional to their contribution. Princeton faculty members Resplandy and Vecchi already contribute to PICSciE resources. We propose to expand CIMES participation in this unique resource. PICSciE invests in a diverse suite of cutting-edge hardware in partnership with vendors, on a faster timescale than NOAA acquisition cycles. GFDL will benefit from a CIMES foothold in the PICSciE computing environment, by having its models tested and measured on novel hardware using standard metrics of computational performance (Balaji et al, 2016). PICSciE training in advanced computation, including a graduate certification in computational science, will be available to students recruited through CIMES.

2. Investments in cloud computing. Princeton researcher Balaji has a recent award from Google allowing us to explore the Google Cloud Platform as a computational resource. This initial award of free cloud credits will allow CIMES to explore and compare the possibilities of cloud computing as an adjunct to dedicated supercomputing.

**Data archival and analysis**
CIMES proposes a data archival and analysis package to allow greater community involvement in the analysis of CIMES-generated output from GFDL models. A transformational new approach to data analysis has emerged in recent years, called containers. Popular examples include Docker and Kubernetes. A container is a lightweight and self-contained complete software stack for a particular application. As it contains its own operating system and all the software dependencies for the application, it can be deployed anywhere with little effort. Princeton researchers Balaji and Nikonov have begun an initial foray into container technology under a Department of Energy (DOE) award for the Distributed Resources for the Earth System Grid Advanced Management (DREAM) project. Under this approach, we will be exploring installing the Earth System Grid Federation (ESGF) data node, which is used for public archival and distribution of large-scale climate model output (e.g., from the CMIP5 and CMIP6 projects) as a Docker “image”.

With additional resources from CIMES, we propose to expand use of Docker to enable scientists to develop their own climate analytic products and deploy them quickly close to a data archive. As data volumes grow, it will become increasingly difficult to download data for analysis. This
will fulfill the long-standing promise of “bringing the analysis to the data” rather than downloading data for analysis.

In addition to the Google award for cloud computing, Princeton researcher Balaji has a separate award from Google for storing climate data on Google Cloud Services. Under this initial award, we propose to archive a modest amount of test data from GFDL’s CMIP5 data holdings on Google’s cloud. Using the ESGF Docker technology outlined above, we propose to make that data available for research and analysis. Should the pilot project be successful, Google has expressed an interest in expanding the amount of data they will make available in this fashion, using Google’s “Public Datasets” program.

3.2B.2 PREDICTABILITY

The next generation earth system modeling tools that have been and will be developed at NOAA/GFDL present a rich opportunity for collaborative research aimed at understanding of the underlying predictability of the earth system, on timescales from hours to decades, and building systems that realize this predictive potential. Predictability on these timescales can arise from both the dynamical evolution of the earth system from its initial state (“initial value problem”) and from changes in factors external to the system in question (“boundary value problem”). Here we describe research into predictability, data assimilation and realizing prediction skill that CIMES proposes to undertake over the coming years, in close collaboration with scientists at NOAA/GFDL.

UNDERSTANDING MECHANISMS, SOURCES, AND LIMITS OF PREDICTABILITY

Understanding the underlying sources of predictability of phenomena, how these sources depend on model representation and underlying state of the earth system, and the inherent limits to predictability are essential to developing skillful predictions. Led by Princeton faculty Gabriel Vecchi, Laure Resplandy, Stephan Fueglistaler, James Smith, Elie Bou-Zeid, Michael Oppenheimer and Amilcare Porporato, and Princeton researchers Liping Zhang, Hiro Murakami, Kun Gao and Xi Chen, CIMES proposes to investigate these sources and limits, across the full range of timescales, from hours to decades, with particular focus on regional water and extreme events such as tropical cyclones.

To push weather forecast skill closer to its intrinsic limit, it is critical to understand error growth dynamics. High-resolution convection-permitting global simulations which are now being performed at GFDL, supplemented with regional nested higher resolution runs, provide an unprecedented opportunity for examining weather forecast error growth through the interactions among multi-scale atmospheric processes, and quantifying weather predictability. The proposed research at CIMES includes:

● Develop novel diagnostic techniques for quantifying the sources of the numerical weather prediction errors and understand the error growth characteristics.
● Explore the practical and intrinsic aspects of atmospheric predictability particularly for extreme weather systems (e.g., severe continental convection and tropical cyclones).
● Understand the dependence, and mechanisms behind the dependence, of the predictability of weather events on the underlying state of the earth system (e.g., weather predictability dependence on El Niño-Southern Oscillation or the state of Atlantic multi-decadal variability).

CIMES proposes to build on recent advances by GFDL scientists in collaboration with Princeton University researchers to promote unified weather-to-climate prediction, providing new opportunities to enhance our understanding of climate predictability on timescales ranging from hours to decades. In particular, GFDL’s latest global dynamical forecast systems can accurately simulate high-impact weather and subseasonal climate phenomena, including major hurricanes, the Madden-Julian Oscillation, atmospheric rivers, and atmospheric teleconnection patterns.

CIMES proposes to develop model experiments and analyses that probe these questions of weather, subseasonal-to-seasonal (S2S), seasonal-to-decadal (S2D) and longer term predictability in a unified framework. The suite of GFDL dynamical forecast models provide an opportunity to develop a mechanistic understanding through a hierarchy of models of different resolution. For example, “nudging” experiments that target potential predictability sources, such as tropical sea surface temperatures, stratospheric initial conditions, and soil moisture anomalies, have shed new light on the mechanisms of subseasonal-to-seasonal predictability.

Through analysis of observations, model simulations and targeted model experiments, CIMES will continue work to better understand the mechanisms behind the intrinsic modes of variability that provide the basis of weekly to decadal predictions, such as the Madden-Julian Oscillation, ENSO, the Pacific and Atlantic Meridional Modes, Atlantic and Pacific modes of decadal variability (e.g., Yang et al., 2013; Xiang et al., 2015.a; Choi et al., 2015; Zhang and Delworth 2015, 2016). The connection of those modes to regional phenomena and extremes (e.g., Vecchi et al., 2014; Xiang et al., 2015.b; Murakami et al., 2015, 2016.b; Zhang et al., 2017.a,.b,.c; Gao et al., 2017) will provide a basis for extracting regional and extreme event information from S2S predictions.

Recent dramatic changes and variations in Arctic sea ice have created a burgeoning research interest in seasonal-to-interannual prediction and predictability of Arctic sea ice. CIMES will explore the potential for pan-Arctic and regional sea ice prediction on 1-2 year lead times, longer than current operational seasonal predictions (Bushuk et al., 2017a-b, 2018). To close this prediction skill gap, CIMES proposes to investigate the role of the ocean, atmosphere, and sea ice state in driving sea ice variability in the Arctic and Antarctic. CIMES also will perform idealized perfect model predictability experiments to quantify the limits of sea ice predictability and how these limits are expected to change under a changing climate, incorporating implications of sea-ice model improvements described in “Modeling the Cryosphere” in section 3.2A.1 above for predictability.

Predictability on timescales of months to decades can arise from modes of intrinsic variability, changes in radiative forcing (e.g., from aerosols, greenhouse gases and solar forcing), and changes to land surface and vegetation (e.g., Yang et al., 2013, 2018; Jia et al., 2015, 2016; Delworth et al 2015). Through analysis of large ensembles, initialized predictions and targeted predictability experiments with GFDL models, CIMES will work to understand the relative roles and interactions between internal variations of the earth system and changes to atmospheric
composition and land surface in providing predictability, with a particular focus on regional hydrology and extreme events. Particular focus will be understanding the controls on tropical cyclones (e.g., Vecchi et al., 2014, Xiang et al., 2015b; Murakami et al., 2015, Gao et al., 2017), precipitation extremes (e.g., van der Wiel et al., 2016), drought (e.g., Delworth et al., 2015, Seager and Vecchi 2010), and other extremes across the range of timescales from days to decades.

To enhance understanding of predictability and prediction skill on seasonal to decadal timescales, CIMES proposes to perform simulations with a hierarchy of models, including targeted experiments, large ensembles and initialized predictions, and use analyses of these simulations and observations to: isolate key physical processes vital to seasonal to decadal predictability of large-scale changes to the earth system; understand mechanisms connecting large-scale changes to the earth system, and regional water and extremes; isolate the influence of radiative forcing agents and land-use changes in modulating modes of internal variability and changing the probability of extreme events; explore the mechanisms behind past and recent extremes in the earth system, such as droughts and tropical cyclone activity; understand the mechanisms behind extreme events over the past century and millennium; understand the role of stratospheric variations on predictability of the ocean and surface climate.

DATA ASSIMILATION RESEARCH AND IMPLEMENTATION

Advancement in data assimilation systems has been and will continue to be a primary source of improved weather forecast accuracy. Led by Princeton faculty Gabriel Vecchi and Stephan Fueglistaler, with Princeton researchers Liping Zhang, Hiro Murakami, Kun Gao and Xi Chen, CIMES proposes to conduct research on data assimilation to support the development of NOAA’s NGGPS and advance weather prediction accuracy, particularly for extreme events, by:

- Developing and improving advanced data assimilation methods (4D-Variational and Hybrid Ensemble Variational methods) for weather prediction at global and regional scales.
- Improving use of aircraft reconnaissance observations, satellite radiance and wind observations for tropical cyclone prediction, and radar wind and reflectivity observations for severe storm predictions.

Subseasonal-to-Seasonal and Seasonal-to-Decadal forecasts are made by integrating ESMs forward from a set of initial conditions based on the observed state of the climate system at the initial time, requiring a method for optimally combining observations and model states across various model elements (e.g., ocean, atmosphere, land and sea ice) at a given time through data assimilation (DA). GFDL has pioneered the ensemble coupled data assimilation (ECDA) system (Zhang et al., 2007, Chang et al., 2013), successfully used for experimental decadal prediction (Yang et al., 2013, Vecchi et al. 2013), and operational seasonal prediction in the North American Multi-model Ensemble for seasonal prediction (Vecchi et al., 2014). The ECDA system, combining state-of-the-art DA methodology and GFDL’s climate models, provides an effective starting point for GFDL and Princeton scientists to advance data assimilation research and implementation.
CIMES proposes to work closely with GFDL to develop new ensemble coupled data assimilation systems for GFDL’s new models, and to explore novel techniques required to build high-resolution ensemble coupled data assimilation systems for seasonal to multi-decade integration with high-resolution ESMs. CIMES proposes to work with NOAA/GFDL to explore different initialization methods for multiple-timescale applications, and understand the impact of different observing system elements on state-estimation and prediction skill (e.g., Xue et al., 2017; Chang et al., 2018).

To enhance predictions of regional sea ice, CIMES proposes to advance sea ice data assimilation techniques for both sea-ice concentration and sea ice thickness (SIT), a key source of predictability for summer sea ice predictions (Bushuk et al., 2017a). New assimilation techniques will take advantage of the recent proliferation of satellite-based SIT observations from CryoSat-2, SMOS, and the forthcoming Ice, Cloud, and Land Elevation Satellite (ICESAT-2), which present an opportunity for accurate initialization of SIT for unified prediction applications. Developing sea-ice data-assimilation techniques will provide better initial conditions for predictions of sea ice, as well as more accurate reanalyses for investigation of the variations of the Arctic and Antarctic.

REALIZING AND REFINING PREDICTION SKILL

Recent advances in GFDL’s dynamical forecast model development have opened new frontiers in weather and subseasonal prediction. As the resolution of GFDL’s dynamical forecast models has improved, simulations of previously unresolved high-impact weather phenomena such as hurricanes have emerged in coupled global forecasts for the first time. In addition, GFDL’s latest models have demonstrated substantial skill in simulating large-scale, sub-seasonally varying phenomena such as the Madden/Julian Oscillation (MJO), necessary for the development of unified prediction systems.

However, there will always exist scales, processes and phenomena of interest to NOAA and the Nation that will fall outside the ability of a given generation of ESMs. For example, even at 25km or 12.5km resolution one cannot explicitly represent the details of many coastlines, nor certain atmospheric phenomena such as tornadoes, nor the detailed interactions between weather and the urban landscape. Furthermore, even with the growing sophistication of next generation ESMs, there are detailed processes important to disease vectors, agriculture, energy and fisheries that will not be explicitly represented. Finally, refinement of the output of ESMs can often yield predictions with better calibrated probability distributions than a finite ensemble of model simulations. CIMES proposes to leverage the broad talent across Princeton University to work with GFDL to build methods to enhance the quality and value of prediction tools.

In order to broaden the societal utility of earth system predictions, and help build tools to understand the interplay between the earth system and society, CIMES proposes to work with GFDL to develop prediction methodologies with targets beyond the physical state of the ocean and atmosphere, such as unified predictions targeted at fisheries (e.g., Tommasi et al., 2017.a-c, including future collaboration with Prof. Vecchi in the Dept. of Geosciences) and disease (e.g., Muñoz et al., 2017, in collaboration with Princeton faculty Grenfell, Metcalf, Porporato, and Vecchi), and in applying prediction methodologies to urban settings (in collaboration with, for
example, Profs. Bou-Zeid and Smith). These efforts will use both GFDL’s latest ESMs, as well as statistical and dynamical methods to extend the scope of predictions.

Despite the expected advances in prediction skill resulting from the development of a unified high-resolution model detailed in Section 3.2B.1, “High resolution modeling and extremes,” predicting extreme events at small regional scales using dynamical models remains challenging while of paramount societal importance. Some of the limitations of dynamical prediction can be alleviated using so-called “hybrid predictions” or “statistical-dynamical predictions” in which a statistical model is constructed using an empirical relationship between observations and large-scale variables predicted by the dynamical model. We propose to construct hybrid models to improve prediction skill from dynamical models for the better prediction of extreme events.

Recently Princeton scientists have succeeded in building hybrid models for predicting tropical cyclone activity at seasonal to decadal time scales in which prediction skill is significantly higher than the dynamical model prediction (Vecchi et al., 2011, 2013; Villarini and Vecchi 2013; Murakami et al., 2016a; Zhang et al., 2017.a). CIMES proposes to explore the potential of hybrid models to improve prediction skill, with a particular focus on improving the quality of information on regional events and extremes. One approach that was used in Vecchi et al., (2011, 2013) for tropical cyclones was to build statistical models of Atlantic TC frequency based on the output of high-resolution atmospheric models run across a broad range of states; advantages of this approach were that the statistical model was robust to a broad range of possible outcomes, and its underlying potential predictability was well defined. CIMES will target the development of hybrid statistical-dynamical models for major hurricane landfall, rainfall and storm surge. Additional targets include landfalling extratropically transitioned storms (e.g., Liu et al., 2017) and their impacts, due to the severe threat highlighted by Hurricanes Irene (2011) and Sandy (2012). CIMES proposes to extend the concept behind these methodologies to other regional and extreme events, such as atmospheric rivers and snowfall extremes; recent and planned advances in high resolution modeling open the potential to target the statistics of severe convective storms and tornadic activity with hybrid methodologies on timescales of weeks to decades. Enhancement of prediction skill for rainfall through statistical post processing (e.g., Salvi et al., 2017.a-.b) and through novel methods of combining multiple models (e.g., Villarini et al., 2016, Zhang et al., 2017.d) will also be explored. These efforts would involve Princeton faculty Smith, Lin, Oppenheimer, and Vecchi among others.

3.2C EARTH SYSTEM SCIENCE: ANALYSIS AND APPLICATIONS

The earth system models developed in collaboration with GFDL will be applied to understanding a wide variety of societally-relevant climate problems. These include the impacts of climate change and natural climate variability on sea-level (an application of the ocean and cryospheric components of the modeling system), and the attribution of climate change to natural and anthropogenic forcing (an application of the predictability methodologies described in the section 3.2B.2, “Predictability”). Here we focus on a small subset of the possible range of earth system model applications, by way of example; air quality, extreme weather events and drought, and ecosystem impacts of climate change.
3.2C.1 AIR QUALITY APPLICATIONS

CLIMATE PENALTY ON AIR QUALITY VIA ECOSYSTEM-ATMOSPHERE INTERACTIONS

In populated northern mid-latitude regions, climate change and variability influence air quality by altering the frequency, severity, and duration of heat waves, air stagnation events, precipitation, and other meteorology conducive to pollutant accumulation. Some regions may be particularly sensitive to large feedbacks from natural ozone (O₃) and aerosol sources, such as wildfires, dust, and biogenic precursors, and from changes in chemical and deposition sinks. For example, regional air quality in the southeast US and southern Europe may be particularly sensitive to climate variability and change due to vegetative feedbacks. Under climate change, the western US is projected to be increasingly susceptible to drought conditions, wildfire outbreaks, dust, and resulting particulate matter (PM). We propose to advance knowledge of the effects of ecosystem-atmosphere interactions on extreme O₃ and PM pollution through application of GFDL ESMs.

How does surface O₃ respond to changing land use, drought, and dry deposition?

Tropospheric O₃ is a potent greenhouse gas, deleterious to human and plant health, and central to atmospheric chemistry controlling the removal of air pollutants and reactive greenhouse gases. Removal by dry deposition to the Earth’s surface is an important control on near-surface O₃ concentrations. Understanding the factors controlling O₃ dry deposition velocity (V_{d,O₃}) has implications for interpreting observed surface O₃ trends, especially over areas where land-atmosphere interactions are known to play a role in regional climate. In southern Europe, for example, the lack of precipitation and the associated depletion of soil moisture result in reduced evaporative cooling and thereby amplify the summer hot extremes (Hirschi et al., 2011). Under drought stress, plants close their stomata to conserve water, consequently limiting O₃ uptake by vegetation [Gerost et al., 2009b; Emberson et al., 2013]. Recent measurements have demonstrated considerable interannual variability in V_{d,O₃} and the role of stomatal versus non-stomatal deposition pathways (Mikkelsen et al., 2004; Rannik et al., 2012; Clifton et al., 2017). However, simulating such land-biosphere-atmosphere interactions in air quality models is challenging [Fowler et al., 2009; Rydsaa et al., 2016; Kavassalis and Murphy, 2017; Lin et al., 2017]. The influence of changes in O₃ dry deposition, expected to evolve with climate and land use, is often overlooked in air quality projections.

Princeton scientists are implementing a new parametrization scheme for calculating tracer dry deposition velocities in the GFDL dynamic vegetation land models (LM3/LM4) coupled to the GFDL atmospheric chemistry-climate models (AM3/AM4) (Shevliakova et al., 2009; Donner et al., 2011; Milly et al., 2014; Zhao et al., 2018). Stomatal conductance is determined mechanistically, depending on light, soil moisture, temperature, vapor pressure deficit, and leaf-surface CO₂ concentrations. This scheme presents a major improvement upon the Wesley scheme widely used in other chemistry-climate models. Ongoing work led by Princeton researcher Meiyun Lin demonstrates the importance of including varying V_{d,O₃} with drought in the GFDL LM4/AM4 model with full chemistry for simulating the observed high surface O₃ events above 80 ppb during the 2003 European heat wave (Lin et al., 2018; Figure 6). Without
considering the influence of drought, the model underestimates these severe O₃ pollution events that exacerbate negative health effects of heat.

Leveraging the improved land and atmospheric modeling capabilities at GFDL, Princeton researcher Meiyun Lin proposes to systematically investigate the influence of changes in O₃ dry deposition on surface O₃ extremes and trends over the past half century and under future climate scenarios. Using available observations, a process-oriented analysis will be conducted to evaluate the simulated seasonal and interannual variability of Vₐₒ₃, including their sensitivity to changes in the land-model formulations from GFDL LM3.0 (CMIP5) to LM4.0 (CMIP6 CM4) to LM4.1 (CMIP6 ESM4). The impact of changes in O₃ deposition on observed surface O₃ trends at polluted regions over the past half century, and the evolution of O₃ deposition with changes in the frequency, severity, and duration of drought, CO₂ level, and land cover under CMIP5 and CMIP6 future climate scenarios will be assessed.

Figure 6. Drought reduced O₃ deposition sink to vegetation, worsening O₃ air pollution during the 2003 European heat wave. (Top) Standardized Precipitation Evaporation Index (SPEI) and anomalies in Vₐₒ₃ for August 2003 relative to 1990-2010 as simulated by GFDL-LM4; (Bottom) Probability distribution of surface O₃ concentrations as observed (black) and simulated by GFDL-AM4 nudged to NCEP winds without (blue) and with considering decreased Vₐₒ₃ due to drought (red). Median (m), 90th percentile (q90) and standard deviation (s) are shown. Credit: Lin et al. [2018].
Impact of increasing climate variability on wildfires, air quality and public health.
The incidence of large wildfires in the US is increasing in recent decades with more land area burned and a longer wildfire season (Collins, 2014; Abatzoglou and Williams, 2016). The smoke from these fires increases fine PM with diameter smaller than 2.5 mm (PM2.5), which are known to have adverse effects on public health. Increasing incidence of severe fires has been partially attributed to increasing variability in climate with periods of moisture followed by drought and higher temperatures. Wildfire risk depends on a variety of factors including temperature, humidity, soil moisture, and the presence and condition of trees, shrubs and grasses, all of which are influenced by short-term climate variability and longer-term climate change. The impacts of fires include their effect on air quality as well as property damage. Planning for future fire incidence would benefit from improved predictions of fire incidence and extent.

Led by Princeton faculty Denise Mauzerall and researcher Meiyun Lin, we propose to employ the GFDL ESM model to predict future fire incidence, the associated emissions that affect short-lived air pollutant and CO₂ emissions, and the impacts of resulting changes in air quality on public health. This will build upon earlier work by Mauzerall examining the effect of recent fires in California on air quality and health using observed PM2.5 concentrations, regional air quality models, and acute concentration-response relationships from the epidemiological literature for PM2.5, and by Lin investigating the influence of wildfires on O₃ air quality (Lin et al., 2017).

Variability and sources of dust under present and future climate
Fine dust contributes about 40-50% of total PM2.5 mass over the southwestern US in spring and about 20-30% over the southwestern to central US in summer (Hand et al., 2017). Climate models project a drying of these dust-prone regions in the late 21st century (e.g., Cook et al., 2015). Observation-based studies led by Princeton researcher Bing Pu found significant increasing trends of fine dust over southwestern and central U.S. in the past twenty years (e.g., Pu and Ginoux 2017a), and enhanced dust activities during recent severe droughts over California and the Great Plains (Pu and Ginoux 2017b). To understand whether current increasing trends of fine dust will persist into the future and how dust concentration will change in response to climate extremes and variability requires further investigations utilizing climate models to advance our understanding of the emission and transport processes of dust. With proposed updates in the model (section “Modeling the Atmosphere”), we will be able to better quantify the relative contribution of natural climate variability and anthropogenic land use to dust concentration variations and identify key controlling factors of dust variability to better predict dust-induced air quality changes.

NITROGEN AND AIR QUALITY
Human activities have almost doubled the production of reactive nitrogen in the Earth System, mostly through the production of fertilizer but also through the burning of fossil fuel. The increase of fixed nitrogen has environmental implications ranging from air quality, to ecosystem damage, and perturbations to climate and carbon cycling (Gruber and Galloway, 2008).

Previous work by Princeton researchers has focused on the direct impact of changes in reactive nitrogen on air pollution. For instance, (Li et al., 2018) showed that the decrease of nitrogen oxide emissions in the US has led to an increase in the relative contribution of organic nitrogen to NOy, with important implications for future ozone changes. (Paulot et al., 2017) found that
high ammonia emissions have contributed to the observed weak response of sulfate aerosol to SO$_2$ emission controls in winter and spring by increasing the in-cloud oxidation of SO$_2$. (Paulot et al., 2018) also found that nitrate, has contributed to changes in aerosol optical depth and aerosol forcing over China and India in the last 15 years. Accurate representation of the impact of nitrogen on atmospheric composition and air quality is complicated by persistent uncertainties in the representation of its surface sources and sinks. For instance, the influx of nitrogen to the atmosphere is prescribed using global emission inventories in the GFDL model, as in most global models. This approach is well suited for some anthropogenic sources, such as fossil fuel combustion, but does not account for the physical and biological processes that modulate other sources of nitrogen such as soil NO$_x$ (Hudman et al., 2010) or marine and agricultural sources of NH$_3$ (Paulot et al., 2015, Bash et al., 2013, Riddick et al., 2016). Efforts to better capture these processes and integrate the representation of nitrogen in the atmosphere with that in the ocean and land are ongoing, and will help better characterize the impact of anthropogenic perturbations to the nitrogen cycle from air quality to climate. We propose to focus on the following questions:

- Impact of reactive nitrogen on PM2.5. How will changes in environmental conditions affect nitrogen emissions? Can detrimental impacts on air quality associated with future changes in nitrogen emissions be alleviated through changes in agricultural practices (e.g., fertilizer application timing)?
- Nitrogen deposition. What is the contribution of nitrogen deposition to coastal and lake eutrophication? How will nitrogen deposition be altered by changes in magnitude and speciation of anthropogenic emissions?
- Nitrogen in marine systems. How has the marine source of NH$_3$, one of the largest natural source of reactive nitrogen to the atmosphere, been altered by increases in atmospheric NH$_3$ and nitrogen deposition, acidification, and global warming? Do marine NH$_3$ emissions track ocean productivity and if so can long-term records of NH$_4$ deposition in Antarctica provide constraints on Southern Ocean productivity?

SEASONAL PREDICTION OF EXTREME O$_3$ AND PM POLLUTION

In populated regions, air pollution results from the combination of high emissions and unfavorable weather that are conducive to pollutant accumulation. To the extent that regional meteorology is predictable on sub-seasonal to seasonal time scales, the relationships between air pollution meteorology and air quality can be used to assess the seasonal risk of air pollution extremes. Princeton researcher Meiyun Lin proposes to advance knowledge of the dynamical causes of extreme O$_3$ and PM pollution, seeking to gauge seasonal predictability of air quality.

While regional emission controls have led to improvements in U.S. air quality, pollution can spike during large-scale heat waves and drought (Lin et al., 2017). Observations show large-scale enhancements of summer O$_3$ pollution in the eastern U.S. in 1999 and 2011 under La Niña conditions, in contrast to 1997 and 2009 under El Niño conditions. La Niña-related drought conditions may also increase the incidence of dust and wildfires, and resulting PM. The links between known modes of climate variability and the accumulation of pollutants over the eastern US can be exploited to develop seasonal predictions of air quality. In contrast to the eastern US, where local emissions dominate pollution events during summer, O$_3$ air quality in the high-elevation western US is susceptible to background influences from
stratospheric intrusions, intercontinental pollution, and other natural sources (Lin et al., 2012a; Lin et al., 2012b). More frequent deep stratospheric intrusions reach western US surface air during spring following strong La Niña conditions (Lin et al., 2015a; Lin et al., 2015b). The high-resolution GFDL seasonal prediction system has been shown to provide skillful predictions of extratropical storm tracks with 0-9 month lead times (Yang et al., 2015), particularly the ENSO-related patterns, and thus is a tool well-suited to exploit seasonal predictability of high surface O₃ events from stratospheric intrusions.

Meiyun Lin and her collaborators propose a systematic investigation of the linkage of year-to-year variations of extreme O₃ and PM pollution at mid-latitude populated regions to modes of climate variability (e.g., ENSO, NAO and AMO), leveraging the GFDL Seamless System for Prediction and EArth System Research (SPEAR), which builds upon the GFDL AM4/LM4 chemistry-climate-land surface model assisted by local grid refinements (~25x25 km²) over a region of specific interest (Harris et al., 2016).

3.2C.2 EXTREME WEATHER EVENTS AND DROUGHT

There are broad areas of research interactions involving GFDL and Princeton University faculty in the area of extreme weather and drought. Hydrology is central to major problems areas involving extreme weather and drought and is a core area of strength in Princeton, complementing research programs at GFDL. Research programs in the hydrologic sciences include theory, modeling and experimentation, and are led by Eric Wood, Mike Celia, Elie Bou-Zeid, Amilcare Porporato, Mark Zondlo, and Jim Smith.

Princeton has also developed broad expertise in extreme weather associated with tropical cyclones. In order to improve modeling and prediction capabilities for tropical cyclones and their resulting impacts to society, collaborative research at Princeton will advance understanding of the mechanisms controlling tropical cyclone characteristics (including their frequency, track, intensity, extra-tropical transition) and hazards (wind, surge, and rainfall flooding) on timescales from days to decades through observational analysis and targeted experiments using high-resolution atmospheric-ocean-coupled models and hydrodynamic and hydrological models. Established research programs led by Gabe Vecchi, Ning Lin, Jim Smith and Michael Oppenheimer address key areas of tropical cyclone modeling and hazards.

Tropical cyclone mechanisms have been examined most thoroughly for storms over open ocean, but hazards center on storm properties as they approach and move over land. An important challenge for tropical cyclone science is developing a more robust understanding of their properties in the coastal environment and over land. In addition to track and intensity, evolution of storm structure is a key element of coupled hazards from wind, rain-induced flood and storm surge. Storm properties at the land-water boundary are tied to land-atmosphere interactions; improved capabilities for modeling surface fluxes and atmospheric boundary layer processes are critical for improving assessments of tropical cyclone hazards. Improving modeling capabilities for tropical cyclones that undergo extratropical transition (like Hurricane Sandy) is also a key element of improving hazards characterizations for tropical cyclones, especially for the densely populated east coast of the US. Furthermore, large uncertainties remain in assessing changes in tropical cyclone frequency, tracks, intensity, and induced hazards in a warming climate. Superimposed on these uncertainties are the effects of sea level rise, which will affect the
impacts of storm surge on coastal regions. Changes in tropical cyclone intensity have major impacts on wind, surge and rainfall-induced flood hazards. Continued advances in model resolution are central to reducing uncertainties in hazards in a warming climate.

Land-atmosphere interactions are central to many of the extreme weather and drought problems that will be addressed. Elie Bou-Zeid, Amilcare Porporato, Marcus Hultmark, Lex Smits, Steve Pacala and Jim Smith lead research programs in this area and their research interests will contribute both to assessing weather extremes and improving modeling capabilities. Land surface modeling and atmospheric boundary layer (ABL) modeling efforts will play an important role in development of capabilities for better assessing hazards from extreme weather and drought. ABL research at Princeton includes fundamental theoretical treatments of the ABL, development of computational tools for studying the ABL and experimental programs for studying ABL structure, which can play an important role in improving parameterizations for ABL processes in ESMs. Drought and extreme weather predictions will also rely on the strong program in ecohydrology, described in “Terrestrial Biogeochemical and Ecological Processes” in section 3.2A.1 above.

Research efforts in remote sensing and in situ measurement of atmospheric processes at Princeton have contributed to climate assessment capabilities. Atmospheric measurement research has focused on development of sensor systems for monitoring atmospheric aerosol and trace gases important for climate change. There are a broad range of areas in which experimental, modeling and remote sensing efforts provide opportunities for collaboration. Remote sensing and atmospheric measurement research has been led by Mark Zondlo and Eric Wood.

In addition to tropical cyclones, research on extreme rainfall and flooding will focus on warm season convection. The most extreme floods in the US, and many other parts of the world, are tied to organized thunderstorm systems. Both numerical weather prediction models and climate models have serious shortcomings in their ability to predict key features of extreme rainfall from warm season convective systems. As with tropical cyclones, resolution is a central issue for improving model representations of flood-producing rainfall from organized convection, especially in complex terrain, including mountainous regions, coastal regions and urban areas. Advances in assessing extreme rainfall hazards will also require improvements in modeling of land-atmosphere interactions, especially in providing more accurate representation of the diurnal cycle of surface temperature and air temperature and humidity in the lower atmosphere. Microphysical routines used for numerical weather prediction and climate models have large impacts on prediction of rainfall extremes and there are notable shortcomings of these models for heavy rainfall from organized thunderstorm systems. Advances in modeling extreme rainfall will contribute to NOAA’s climate mission in developing precipitation frequency and Probable Maximum Precipitation procedures. Research groups that address these problems are led by Jim Smith, Elie Bou-Zeid and Amilcare Porporato.

Advances in climate modeling are required to address water resources management applications in the US. Drought in the arid/semi-arid regions of the US are a particularly important challenge. Changing availability of water resources in the southwestern US (especially the Colorado River basin) holds the potential for imposing radical changes to southern California and the major...
cities of the Southwest. Improved assessments of water resources are needed at time scales ranging from seasonal to decadal. We will take advantage of improved coupled models, including enhanced land-atmosphere interactions described in “Terrestrial Biogeochemical and Ecological processes” in section 3.2A.1 above, to improve seasonal and interannual forecasting and to assess decadal changes in water availability and drought. Eric Wood, Amilcare Porporato, and Gabe Vecchi led research efforts that have contributed to advances in these areas.

High-impact weather in urban environments is a particular area of strength at Princeton. Hurricanes have some of their most profound impacts on coastal cities, both from storm surge and rainfall-induced flooding. More generally, drought and flood in urban regions are special challenges for climate assessments. In addition, to water resources applications, climate modeling in urban areas will also address hazards associated with heat waves. Urban climate research at Princeton includes efforts led by Elie Bou Zeid, Forrest Meggers, Ning Lin, Jim Smith, Michael Oppenheimer, Gabriel Vecchi and Guy Nordenson.

3.2C.3 IMPACT OF CLIMATE VARIABILITY AND CLIMATE CHANGE ON MARINE ECOSYSTEMS

The assessment of the impact of climate variability on marine ecosystems using ESMs is a key aspect of research at CIMES. This activity embraces interrelated efforts ranging from the direct assessment of model outputs to the development of pilot studies targeting major socioeconomic and environmental issues. The research proposed here continues to combine empirical, theoretical and applied research. Well established activities like the assessment and application of century scale projections of climate change will be complemented with the incorporation of novel ecosystem diagnostics and the development of new ecosystem modules. CIMES will also pursue the application of S2S2D in real world management scenarios, fostering the use of ESMs to support NOAA’s commitment to promote sustainable management strategies that lead to healthy and productive marine ecosystems.

CENTURY SCALE PROJECTIONS AND SIMULATIONS

The development of centennial simulations of past and future climate conditions at a range of scales developed in this proposal and as part of GFDL’s contribution to CMIP6 provides an invaluable opportunity for the continued analysis and development of climate impacts on marine ecosystems. Historical simulations allow past climate fluctuations to be related to contemporary patterns and trends, while centennial scale projections of future conditions allow the assessment of climate impacts on ecosystem goods and services, and the consequences of alternative management scenarios.

Princeton and GFDL researchers have led the development of a framework for the application of Intergovernmental Panel on Climate Change (IPCC)-like ESM models to the assessment of climate change impacts on living marine resources (Stock et al., 2011). They are also contributing to the development of ESM applications targeting the conservation of charismatic species (Saba et al., 2012) and habitats (Dorman et al., 2015; Kleypas et al., 2016), range shifts (Pinsky et al., 2013; Grieve et al., 2016), and the future evolution of fisheries (Cheung et al., 2013), within the context of Princeton faculty Sarmiento’s long involvement in the Nereus program (www.nereusprogram.org). Our approach relies on the development of mechanistic
models featuring the relationships between environmental stressors and ecological responses (e.g., Mislan et al., 2017), tied to a balanced representation of ecological interactions from seasonal to interannual scales (e.g., Kearney et al., 2013; Asch 2015).

Previous research has focused mainly on the identification of physiological constraints on organism performance associated with changes in temperature, oxygen availability and ocean acidification, leading to increased awareness of the importance of interactions among multiple stressors and ecological processes. Princeton Prof Sarmiento and Rutgers Prof Curchister have also developed robust protocols for the incorporation of ESM uncertainties in ecosystem assessments (Hollowed et al., 2012; Cheung et al., 2016). The proposed research at CIMES will target the interaction among multiple stressors and multiple ecosystem processes. The mechanistic, integrative approach championed here provides an ideal framework for the development of these applications. The proposed research will focus on three specific goals:

● Assessment of projected impacts on highly valued species and habitats. Princeton researchers will assess the impact of varying resolution ESMs on the simulation of physiological and dispersal constraints on species range shifts, taking advantage of previous experience on several model systems (coral reefs; leatherback turtles, Scombrids and marine mammals). The buffering role of climate refugia habitats in the sea like upwelling regions will also be assessed.
● Propagation of changes in the productivity and phenology of pelagic food webs to upper trophic levels. This research will extend the current “match-mismatch” paradigm to include interactions with other physiological stressors affecting organism performance, especially the vulnerable planktonic larval stages of many marine invertebrates and fishes.
● Incorporation of socio-ecological interactions in assessments of climate impacts. This task will provide a retrospective assessment of observed ecological impacts, including the historical variability and collapse of marine fisheries. Princeton researchers will combine climatic simulations with ecological models including economic drivers of fisheries demand and profit, guiding the development of socio-ecological scenarios for fisheries exploitation (Österblom et al., 2013).

NOVEL OBSERVATION SYSTEMS AND ECOSYSTEM DIAGNOSTICS

The lack of adequate observations is the single most limiting factor to understanding the functioning of marine ecosystems and thus to the development of reliable ESMs. Researchers at Princeton University have pioneered the incorporation of novel technologies in Earth System science. Emerging technologies convey a dramatic increase in resolution with respect to previously available records and reveal new aspects of the functioning of marine ecosystems.

Bringing isotope spectrometry and molecular methods to Earth System science
Princeton Prof. Sigman and Prof. Ward lead the development of methods to measure primary production and nitrogen cycling based on the isotopic fraction of oxygen and nitrogen (Zhang et al., 2015). These techniques allow us not only to study contemporary oceanic conditions, but also to reconstruct palaeoclimatological records providing information about the long-term evolution of the climate system, enabling the assessment of the elusive coupling between nitrogen fixation and remineralization, and contributing to our understanding of iron limitation in the sea on a range of time scales (Rafter et al., 2017; Martínez-Garcia et al., 2014). Researchers at the Ward
Lab are also pioneering the application of functional genomic data to the analysis of ecological succession in the sea (Ward & Van Oostende 2016). Molecular marker data is starting to reveal emergent associations between functional diversity and nutrient cycling, ecosystem production and export (e.g., Guidi et al., 2016). Similar approaches reveal the importance of ecological succession and ecosystem model complexity in eastern boundary upwelling systems (Van Oostende et al., 2015).

The flexibility of the CIMES program and the experience of Princeton researchers allow the exploration of other emerging technologies like geostationary ocean color sensors (IOCCG 2012), which provide a dramatic increase in the coverage of satellite chlorophyll retrievals, and hyperspectral ocean color sensors, which provide the capability of exploring changes in the composition of phytoplankton assemblages and to study of harmful algal blooms (IOCCG 2014).

**ECOSYSTEM MODEL DEVELOPMENT**

The collaboration between Princeton and GFDL researchers has been critical for the development of the ecosystem component of the pelagic food web models currently employed in GFDL ESMs (i.e. TOPAZ, Dunne et al., 2010, and COBALT, Stock et al., 2014). Princeton researchers will contribute to the refinement and development of these ecosystem modules, focusing on two main aspects: (i) the development and implementation of new theoretical frameworks to model plankton dynamics and (ii) the explicit modeling of the flow of planktonic production towards upper trophic levels, including fisheries. The overall objective is to improve the predictive skill of plankton productivity and export in ESMs, paralleled by a steady progression towards a more realistic description of the pelagic food web that extends the scope of applications embraced by ESMs.

**Phytoplankton stoichiometry and virus dynamics**

The development of new theoretical frameworks by Princeton Prof. Levin and GFDL researchers seeks a fully mechanistic representation of cell growth based on allometric constraints and algorithmic parameterizations that capture the observed diversity of nutrient allocation strategies and chemical composition across phytoplankton functional types (Bonachela et al., 2017). CIMES researchers will continue developing and testing these frameworks in EMSs with the inclusion of a dynamic representation of changes in plankton stoichiometry, and the exploration of applications targeting the management of harmful algal blooms and the inclusion of mixotrophic strategies in GFDL models.

Related efforts targeting an improved representation of top-down regulation of phytoplankton dynamics involves the modelling of non-trophic phytoplankton mortality associated with marine viruses (Bonachela and Levin 2014; Weitz et al., 2015). Viral lysis enhances nutrient recycling and limits material flows to upper trophic levels. Princeton researchers will contribute to improving the parameterization of viral lysis in ESMs and to assess the implications of this process in major biogeochemical cycles.

**Upper trophic levels and fisheries**

Through the Nereus program (www.nereusprogram.com), Princeton Prof. Sarmiento and researchers from NOAA GFDL and the Marine Fisheries Service have collaborated extensively to explore the multiple dimensions of the management of marine fisheries in a changing ocean.
This research has revealed the benefits that ESMs data and simulations convey in fisheries management (Stock et al., 2011; Hollowed et al., 2012; Cheung et al., 2016). The current generation of GFDL ESMs capture prevailing bottom-up effects on the bulk production of upper trophic levels, but do not account for varying transfer efficiencies associated with changes in the internal dynamics of marine food webs (Stock et al., 2017).

A major objective of ongoing and future efforts at CIMES is to contribute to the development of a so-called ‘end-to-end’ ESM module for pelagic and coastal ecosystems – i.e. a mechanistic model linking ocean biogeochemistry and plankton dynamics with upper trophic levels (Kearney et al., 2013; Fiechter et al., 2015). This model will be structured by size and stage to explicitly incorporate allometric, ecological and behavioral constraints, and it will implement dispersal limitation during recruitment and connectivity constraints associated with fish foraging behavior. The model will consider distinct functional predatory guilds to capture the diverse role that marine fishes play in pelagic and benthic food webs, and the different economic value associated to fish species with different life history strategies. Both aspects are essential to capture transitions and regime shifts involving changes in the composition of fish assemblages that convey important socioeconomic impacts.

The joint CIMES-GFDL model will contribute to the Fish and Marine Ecosystem Model Intercomparison Project (FishMIP, Tittensor et al., under review) of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP). Although this primary research plan targets marine fisheries, the sustained collaboration between Princeton and GFDL has also set the basis for the exploration of ESM applications involving other upper trophic levels, including the trophic role and impact of jellyfishes (Kearney et al., 2015; Henschke et al., 2017) and the conservation of charismatic species (Kearney et al., 2013) (Figure 7).

Figure 7. Example output of an end-to-end ecosystem model coupling a biogeochemical and a pelagic food web model, from plankton to upper trophic levels and fisheries. The graph shows pathways between sockeye salmon prey and all predators. Light blue edges indicate all links associated with primary production, grazing, and predation; purple edges are those leading to sockeye salmon from their prey groups; dark blue indicates all other predation links leading from those prey groups. Kearney, et al., 2015
ASSESSMENT OF HIGH-RESOLUTION MODEL SIMULATIONS

The development of unprecedented high-resolution Earth System numerical simulations (see section 3.2B.1., “High Resolution Modeling and Extremes”) offers an invaluable opportunity for the assessment of long standing hypothesis about the importance of mesoscale and submesoscale features in nutrient renewal and ecosystem connectivity in the marine realm (Lévy et al., 2014). Princeton Professor Resplandy and CIMES associates at Rutgers like Professor Curchister lead the development and assessment of high resolution models from regional to global scale applications (Resplandy et al., 2011; Van Oostende et al., under review). Research on this activity will focus on the role of mesoscale and submesoscale features on nutrient fluxes and ecosystem processes in four challenging systems:

- eastern boundary upwelling ecosystems like the California current (Fiechter et al., 2014),
- western boundary currents like Gulf Stream (Kang & Curchister 2013, Zhang et al., 2017)
- coastal shelves and its interaction with large scale circulation like the Mid-Atlantic Bight (Saba et al., 2016), and
- regions with a complex coastal morphology like the Bering Sea (Danielson et al., 2012) and the Coral Triangle (Castruccio et al., 2013; Kleypas et al., 2016).

Coastal upwelling systems are amongst the most productive marine ecosystems. They sustain ~5% of global marine primary production and 20% of global fish catch, while extending over an area of ~1% of the global ocean (Chavez and Messié, 2009). GFDL global climate models, including CM4, present systematic sea surface warm biases up to 5°C in these coastal boundary systems (Wang et al., 2014; Dunne et al., 2015; Richter, 2015). These biases in coastal temperature and circulation are likely to undermine future projections of primary production, coastal warming and regional sea level rise (Saba et al., 2016). One of the most likely sources of these warm biases is the absence of eddies that carry cold coastal waters offshore because of the coarse ocean model resolution (Resplandy et al., 2011).

High-resolution modeling also provides an opportunity to explore the impact of mesoscale structures on nutrient fluxes and transport in other systems, such as the Gulf Stream region (Kang and Curchister 2013). The large scale forcing of coastal transport and mixing suggest important impacts on ecosystem dynamics and structure in the Indonesian Throughflow region (Castruccio et al., 2013), and makes the US east shelf especially vulnerable to undergoing ocean warming (Saba et al., 2016). The implementation of regional nesting capabilities in the ocean model MOM6 and the development of dedicated regional studies in selected systems will provide the opportunity to examine the role of ocean eddies and evaluate their impact on CMIP6 projections and model biases. Eddy detection algorithms (Kang and Curchister 2013; Zhang et al., 2017) and Lagrangian approaches (van Sebille et al., 2018) developed at CIMES will be used to assess the contribution of alternative transport mechanisms in these systems.

APPLICATIONS OF SUBSEASONAL TO SEASONAL TO DECADAL (S2S2D) FORECASTS

Princeton Prof. Vecchi and GFDL scientists are leading the application of S2S2D forecast products to improve the management and conservation of living marine resources and coastal ecosystems (Stock et al., 2015). This approach represents a breakthrough in the emerging field of...
ecological forecasting (see review by Tommasi et al., 2017a), where currently available approaches mostly rely on short-term projections that ignore potential changes in environmental conditions. The involvement of GFDL in CMIP6 Decadal Climate Prediction Project (DCPP) offers an invaluable opportunity for the continued development of novel applications (Section 3.2B.2, “Predictability”).

Work developed in close collaboration with GFDL scientists has already demonstrated the potential advantage of incorporating seasonal forecasts of sea surface temperature from GFDL Global Climate Model forecast system FLOR into the management of commercially exploited fish species (Tommasi et al., 2017b). Underway efforts also include the assessment of subseasonal predictability of surface water conditions in the major estuarine systems of continental US, an application that builds upon hybrid approaches combining habitat modeling and empirical statistical downscaling of dynamic ESM projections (Muhling et al., 2017a,b). Future work will also involve a retrospective assessment of the utility of decadal forecasts of sea surface temperature in fisheries management by focusing on;

- the ability to anticipate fisheries collapse in major US fish stocks (e.g., Pershing et al., 2015) and,
- the optimal spatial set up of fishing fleets confronting climate induced changes in the distribution of fished stocks and altered navigation costs (Pinsky et al., 2013).

The underway development by Princeton and GFDL scientists of a fully integrated biogeochemical forecasting system will expand the range of potential applications (see “Ocean Biogeochemical Processes”). The hypothesis underlying this development states that internal ecosystem dynamics can enhance the predictability of biogeochemical variables over pure physical processes (Séférian et al., 2014). Planned work includes assessment of the potential predictability of coastal hypoxia and ocean acidification, as well as changes in primary production, plankton size structure and phenology. Applications will target;

- the impact of changes in upwelling on aquaculture and fisheries along the Northeast Pacific coast, with attention to hypoxia and hypercapnia (Grantham et al 2004; Feely et al., 2008),
- a multiple stressor coral bleaching prediction system incorporating changes in temperature, oxygen and ocean acidification (Harborne et al., 2017); and
- subseasonal forecasting of conditions favoring the development of coastal harmful algal blooms and hypoxia along US coastal shelves.

These applications will rely on physiologically motivated environmental niche models and take advantage of available frameworks for climate downscaling at GFDL. They will also assess the benefits of using biogeochemical forecasts over purely physical variables.

3.2C.4 INFECTIOUS DISEASE AND CLIMATE CHANGE

Human health is a major societal concern for which the potential contribution of Earth System science remains relatively unexploited. Researchers at the Metcalf Lab and at the Grenfell Lab in Princeton lead the development of theoretical and empirical modeling approaches to the study of infectious diseases, targeting the identification of links between the emergence, spread and effectiveness of vaccination programs and changes in climatic conditions (Metcalf et al., 2017).
Princeton researchers will target two related efforts: the application of S2S2D forecasts to the prediction of infectious disease dynamics and the retrospective analysis of the historical data for the identification and assessment of robust mechanistic links between climate and disease.

A diversity of infectious pathogens, ranging from influenza to malaria, show clear seasonal fluctuations in incidence, providing a uniquely repeatable probe for evaluating the association between climate drivers and health outcomes. Yet leveraging this repeatable process is complicated by the diversity of ways by which health outcomes can be affected seasonally. For infectious diseases, the effects of seasonal fluctuations can range from direct effects of climatic conditions on pathogen transmission, indirect effects as a result of seasonal human biology or behavior, and finally seasonal concentration or disruption (e.g., floods or cyclones) of health system functioning (Metcalf et al 2017). Building on increasingly detailed re-analyses of climate dynamics combined with infectious disease data opens the way providing short-term (subseasonal to decadal) projections. Collaboration between GFDL scientists and Princeton researchers will be critical to identifying the relevant scales and variables (e.g., ground level humidity is a key variable for many pathogens, Shaman & Kohn 2009) and transferring this knowledge to improved projections using ESM forecasts.

A major impediment for the characterization of mechanistic links between climate variability and the impact of infectious diseases is the lack of long time series of climate observations (Bjørnstad and Grenfell 2001). Since pathogen transmission is generally unobserved, and pathogen dynamics are inherently non-linear, mapping from changes in climate drivers to pathogen incidence outcomes is non-trivial. ESM century scale projections of climate provide an opportunity to reverse engineer the role of key drivers. By simulating infectious disease dynamics on top of ensemble climate simulations, using biologically grounded mathematical framings for transmission, we can identify the scale of data (temporally and spatially) required to identify phenomena of particular interest, evaluating, for example, the footprint of sub-annual climatic features such as the Madden-Julian Oscillation on infectious disease burden. This will open the way to evaluating existing incidence data in light of climate drivers.

3.2C.5 ASSESSING POPULATION INSECURITY ASSOCIATED WITH DROUGHT AND CLIMATE CHANGE

The effect of climate variability and drought on food productivity is a major concern under future climate change predictions. Predicting the impact of climate change on global food security is critical to predict and prevent civil unrest as it recently occurred in the Middle-East (Werrel and Femia 2013). Food insecurity and grain price inflation have been causing suffering and violence for centuries (Bellemare 2015, Carleton and Hsiang 2016). Civil unrests in Syria in 2011 resulted from the most severe drought in the country’s history and climate models have predicted increased drought for the Middle-East and the rest of the world. Increased in drought is likely to amplify food insecurity, creating greater political instability and rising violence. Predicting future drought events, their intensity and duration is then critical to advise future political strategies regarding food prices regulations and global effort to mitigate the impact of drought and climate change.

We propose to use ESM4 to (1) assess the risk of future drought in the US and across the World under multiple future climate scenarios and (2) predict the duration of any given drought event
and (3) anticipate the impact of future drought on crop yield and food security. The proposed research at CIMES will develop a range of machine learning tools using current available data on climate, food production and civil violence. These tools will be available to NOAA to instruct policymakers on the potential risks of food insecurity and political instability.

3.3 EDUCATION

This section describes NOAA related graduate and post-graduate educational activities at Princeton University that have developed out of its longstanding relationship with GFDL and that we propose to continue under CIMES. The far-reaching impact of this program in training many of the most eminent scientists working today in climate and earth system science, and in contributing to GFDL research, has already been documented in Section 3.1 “Introduction and Goals”. The primary home for most of these educational activities is the Atmospheric and Oceanic Sciences (AOS) program. AOS is an autonomous PhD awarding program within the Department of Geosciences. It was originally established as the Geophysical Fluid Dynamics Program in 1968 when GFDL moved to the Princeton campus. The name was changed to AOS in 1988 to reflect the evolution in scope of the graduate training. The faculty is comprised of a small number of Princeton University professors, and about 10 GFDL federal scientists, who receive a University appointment as lecturers, teaching and advising in the graduate program. Further details of the graduate and post-graduate programs are given in the following two subsections, followed by a third section describing other ongoing and proposed education and outreach activities.

3.3A AOS GRADUATE PROGRAM

*Academic program:* Graduate students in the AOS Program receive a broad education in atmospheric, oceanic and climate-related science, through 4 semesters of course work, culminating in a written qualifying exam at the conclusion of the 4th semester, after which they become full time researchers under supervision of AOS faculty members. Ph.D. research in AOS is advised interchangeably by GFDL scientists and/or Princeton University faculty in the Program. All students have full access to both Princeton University facilities and GFDL resources. In addition to those GFDL scientists serving as AOS faculty, other GFDL federal scientists can be appointed to AOS student thesis committees when appropriate. The AOS program is housed in Sayre Hall on the Forrestal Campus, adjacent to GFDL, and students may have offices either in Sayre Hall or GFDL, ensuring close proximity to their GFDL advisor and/or committee members.

Graduate students frequently make use of GFDL models to study a particular aspect of the climate system, or focus on a particular process and its representation in GFDL models. Students attend weekly seminars at GFDL, and those students advised by GFDL scientists are an integral part of their scientific research group, participating in group meetings and workshops. Students have access to all the wide range of resources available to all grad students at Princeton, such as the McGraw Center for Teaching and Learning, which has training programs that can lead all the way to a Teaching Certificate. Instruction in scientific writing is available through the Princeton University Writing Center.

*Admission:* The selection of AOS graduate students is carried out by the full AOS faculty, including GFDL federal scientists, during the annual graduate admissions process coordinated
through the Princeton University Graduate School. Students are selected for their academic excellence and research abilities as well as their interest in AOS and GFDL-related research. The AOS program is making a concerted effort to increase the diversity of students participating in earth system science. For several years, the AOS program students have been about 50% female.

Following the Princeton University Best Practices for Diversity (https://www.princeton.edu/reports/2013/diversity/report/PU-report-best-practices-graduate-students.pdf) several new initiatives for increasing recruitment from historically underrepresented minorities have been established (i.e., Visiting Faculty Exchange Fellowships and student summer internships, described in 3.3C “CIMES Education and Outreach”). The AOS program graduate student admissions process is undergoing reform to decrease reliance on some traditional measures shown to be biased toward particular over-represented groups. The AOS program continues to work closely with the Princeton University Graduate School Office of Diversity and Inclusion to explore further means of increasing access and inclusion in earth system science for under-represented groups.

Financial Support: All AOS students are fully funded by Princeton University fellowships during their first year, and thereafter are supported by a combination of Cooperative Institute research funds, competitive research fellowships such as the NSF-GRF, graduate research assistantships funded by research grants to individual faculty, and teaching assistantships. Further details are given in the Business Plan, Section 3.4.

3.3B THE AOS POSTDOCTORAL AND VISITING SCIENTIST PROGRAM

Overview: As is currently the case with CICS, the majority of CIMES research will be carried out by early career scientists with Postdoctoral Researcher or (for those more than 3 years post PhD) Associate Research Scholar appointments in the Atmospheric and Oceanic Sciences program working in close collaboration with GFDL scientists and Princeton senior researchers. Since the inception of AOS, early career scientists have worked in all areas of GFDL-relevant science, from fundamental atmosphere and ocean dynamics, cloud physics, hydrology, to marine ecosystems, and terrestrial biosphere responses to changing climate. Many important and lasting contributions to GFDL earth system models have been made by AOS postdocs and associate research scholars. In addition to its central role in accomplishing our research goals, our program provides outstanding training to early career scientists in areas relevant to NOAA’s and GFDL’s present and future needs (See Appendix 2 – “Past Graduate Students and Researchers” documentation, indicating that 57% of our currently active alumni are in faculty positions, with most of the rest in research).

The AOS postdoctoral and visiting scientist program is making a concerted effort to increase diversity and broaden participation from under-represented groups. Over the past 10 years, 28% of AOS postdoctoral and associate research scholar appointments have been female. This represents a 50% increase over the prior decade, and we anticipate this trend to continue to increase in the future. Female AOS postdocs and associate research scholars are eligible to participate in the Princeton Women in Geosciences (PWiGs) mentoring programs. Following the Princeton University Best Practices for Diversity (https://www.princeton.edu/reports/2013/diversity/report/PU-report-best-practices-post-doc.pdf), the AOS postdoctoral and visiting scientist program is instituting practices intended to increase applications from under-represented groups, including targeted advertising of opportunities and
increasing links with faculty at minority serving institutions through the Visiting Faculty Exchange Fellowships (see below).

**Appointment process:** There are currently three routes for postdoctoral and associate research scholar appointments. The first is an annual widely-advertised open competition which invites applicants to submit a short proposal for research based at GFDL, under the supervision of a GFDL host. A “visiting scientist” committee composed of AOS faculty and the heads of GFDL research groups reviews these applications, and makes a recommendation based on the research record and potential of the application, as well as the alignment of the proposed research with GFDL and NOAA goals. The number of postdoctoral appointments made through this process fluctuates annually in response to availability of NOAA funding and changing research needs, but is typically 2-4 per year.

The second route operates in response to NOAA-funded opportunities targeting a specific area of research. The number of postdoctoral and associate research scholar appointments funded by the Cooperative Institute, and the areas in which the early career researchers work, is able to adjust rapidly in response to NOAA and GFDL research priorities, allowing the Cooperative Institute to swiftly ramp up efforts in a particular research area as needs require. AOS postdoctoral and associate research scholars may also be fully or partly funded by other sources, such as NASA, ONR, NSF, or grants from the private sector, while working in collaboration with GFDL scientists, providing a further benefit to GFDL and NOAA science. In the case of the second route, the position advertisement specifies the desired expertise, and the GFDL scientist responsible for the project carries out the initial review of applications, followed by review by the full visiting scientist committee. For this type of appointment, the number of hires varies greatly according to the availability of funding, typically 4-6 per year.

In addition to the AOS postdoctoral appointments described above, a third (indirect) route for postdoc appointments supported by NOAA would be through the Cooperative Institute using Task III funds to encourage Princeton University faculty to become more directly involved in NOAA relevant research. This is as part of a competitive proposal process that is discussed further in the “Business Plan”, Section 3.4.

Short term visiting appointments of more senior scientists and faculty members based at other institutions are also made through AOS, primarily to facilitate collaboration with GFDL and the visitor’s home institution. Applications, including a research proposal, are again reviewed by the visiting scientist committee. CI funds are provided for travel expenses and occasionally summer salary. These short-term visits provide an important mechanism for increasing the network of collaborators in academia contributing to GFDL and NOAA science.

**Other procedures:** All AOS early career appointments are made in AOS after review by the Dean of the Faculty, following normal University practices. Appointments are initially for one year, with a renewal for a second year following satisfactory progress (reviewed annually by the visiting scientist committee). Occasionally appointments can be extended for a third year, subject to continuing funding from the relevant project. Cooperative Institute-funded appointments are usually only extended beyond the third year for those with associate research scholar appointments and who are playing a crucial role in GFDL science such that their expertise is needed longer-term.
All AOS postdoctoral researchers and associate research scholars work either in Sayre Hall (AOS), or across the street in GFDL, where they form an integral part of the research group of their GFDL advisor. Since CI-funded AOS early career scientists are either working on a specific NOAA-funded project or on a research project that has been reviewed and approved by the visiting scientist committee composed partially of GFDL scientists, their research is naturally closely tied to GFDL and NOAA goals.

AOS postdoctoral researchers and associate research scholars have full access to all Princeton University facilities, including Princeton Career Services, the McGraw Center for Teaching and Learning, and the Princeton Writing Program, and receive employment benefits such as health insurance and paid vacation. The Princeton Postdoctoral Council sponsors social and professional development activities for postdocs.

### 3.3C CIMES EDUCATION AND OUTREACH

In addition to the education of graduate students and postdoctoral researchers supported by research funds, CIMES proposes other education and outreach activities supported through dedicated funds from the Task 1B component of the budget. These activities described below have the goals of disseminating earth system research to a broader audience, increasing scientific literacy related to climate, and broadening participation in climate science.

**Cooperative Institute Research Internships**

Several 8-10 week summer research internships will be awarded annually, based on an open competitive application, to undergraduate or graduate students interested in gaining research experience at GFDL, working with a GFDL mentor. Initiated in 2016, the goal of this program is to broaden participation in climate and earth system science studies by recruiting students from primarily undergraduate institutions and minority serving institutions. No prior experience in climate-related science is required. In addition to gaining experience in climate and earth system science research, under the supervision of a GFDL mentor, students can attend workshops on Python programming, applying to graduate school, as well as GFDL seminars and journal clubs. At the end of the 8-10 week internship, students present the results of their research to the GFDL community, and write a short progress report. In the first two rounds of internships thus far, a total of 16 students have participated, 40% of whom were underrepresented minorities. We expect to offer 6 internships in 2018, and anticipate continuing at this level, contingent upon continued Task 1b funding.

**Cooperative Institute Visiting Faculty Exchange Fellowships (a new initiative in 2017)**

In order to encourage connections between GFDL and a wide range of academic institutions, particularly those serving communities that have historically been underrepresented in climate science, several faculty exchange fellowships will be awarded annually, following an open competitive application process. Current faculty at US academic institutions, particularly minority serving institutions, will be eligible for travel grants to cover visits of one week to three months at GFDL. The goal of these exchange fellowships will be to generate new collaborations between GFDL/CIMES and diverse US academic institutions, thereby broadening participation in climate science. The number of fellowships will be flexible, depending on the level of funding available each year.
Summer Institute on Weather and Climate
This week-long summer institute for teachers of grades 3-8, officially titled “Questioning Underlies Effective Science Teaching” (QUEST), is hosted by the Princeton University Program in Teacher Preparation. Led by Steve Carson, a middle school teacher and former researcher at the GFDL, and Danielle Schmitt, the academic laboratory manager at the Princeton University Department of Geosciences, QUEST is designed to enhance teachers’ knowledge of Climate and the Ocean, through laboratory experiments and experiences aligned with the Next Generation Science Standards (NGSS) of the New Jersey state education curriculum. Teachers from New Jersey schools (usually 12-14 participants/year) will revise lessons to align with the NGSS, as well as discuss pedagogy and underlying science with colleagues and the institute faculty. QUEST provides a forum for communicating topical climate science to K-12 educators, thereby increasing environmental literacy. This program has operated on a biannual basis since 2008, under CICS, and we plan to continue the institutes at the same frequency under CIMES funding.

New Jersey Ocean Fun Days
CICS has participated in this annual weekend outreach event, organized by the New Jersey Sea grant at the Jersey shore, since 2014, and CIMES will continue this engagement. Table-top experiments, demonstrated by Princeton researchers and students, illustrate topics in ocean and climate science, such as iceberg melting, ocean acidification, and oceanic density currents, to event attendees, largely composed of New Jersey families.

Young Women’s Science Conference
This annual one-day conference is organized by the Princeton University Plasma Physics Laboratory for girls in grades 7-10. The goal of the event is to encourage girls to pursue interests in STEM. Since 2014, CICS and AOS students and postdocs have participated by organizing hands-on experiments to illustrate climate-related topics, such as iceberg melting and ocean acidification. CIMES will continue this engagement. In 2016, there was a record number of participants - 575 seventh through tenth grade girls from New Jersey, Pennsylvania, and Maryland.

Additional K-12 outreach activities
Several CICS researchers and students undertake additional K-12 outreach activities, including talks and laboratory demonstrations to schools and community groups, for which the CICS loans demonstration materials. These individual outreach activities will continue to be encouraged and supported through CIMES, and researchers and students are encouraged to document these activities in their annual CI reports.

Additional workshops and symposia
To better communicate GFDL/Cooperative Institute science to a wide range of interested parties, individual workshops and symposia will be funded by CIMES on a case-by-case basis. A previous workshop supported by CICS focused on the application of seasonal to decadal climate predictions for marine resource management. This workshop brought climate scientists from Princeton University, GFDL and elsewhere together with fisheries scientists and resource managers, to assess the utility of present climate predictions for marine resource management and develop new and innovative applications of these predictions. Future workshops will be funded depending on available funds, and following a short internal review process.
3.4 BUSINESS PLAN

The basic elements of our proposed business plan as laid out in the org chart below are based on our current experience with CICS, and our understanding of the NOAA Interim CI Handbook.

**Cooperative Institute for Modeling Earth Systems (CIMES)**

**AOS Program:** Building on the past five decades of shared experience between GFDL and Princeton University, we propose that CIMES continue to be managed within the AOS Program, with ties to the Department of Geosciences (AOS is an autonomous program within the GEO Department) and the Princeton Environmental Institute (PEI), which shares many of the same interests. AOS was founded five decades ago as part of the collaboration between Princeton and GFDL, and has served its function extraordinarily well as judged by the success of our graduates, and past reviews of CICS.

Jorge Sarmiento (Director) is a professor of geosciences at Princeton with joint appointments in the Department of Geosciences (GEO) and AOS. He has over 35 years of experience in carbon and climate-related research, participating in the scientific planning and execution of many of the large-scale multi-institutional and international oceanographic biogeochemical and tracer programs of the last two decades. He was Director of Princeton's Atmospheric and Oceanic Sciences Program from 1980 to 1990 and again from 2006 to 2016, and is Director of the current Cooperative Institute for Climate Science.

Gabriel Vecchi (Deputy Director) is a professor of geosciences and PEI and is currently Director of PEI’s Climate and Energy Challenge. He was formerly the head of the Climate Variations and Predictability Group at GFDL.

Sonya Legg (Associate Director) is Associate Director of the current Cooperative Institute for Climate Science and a Senior Research Oceanographer in the AOS program and lecturer in geosciences. Her research focus is on ocean turbulence and mixing.
Management and Staff: Responsibility for management of CIMES lies with the Director (Jorge Sarmiento), the Deputy Director (Gabriel Vecchi) and the Associate Director (Sonya Legg), who are listed as the Principal Investigators for this proposal. (Sarmiento is the Principal Investigator and Vecchi and Legg are Co-Principal Investigators)

The current support staff for administrative and fiscal oversight for CICS comprises ~1 full time equivalent (FTE), not including additional support staff provided by Princeton University. In addition, our current Cooperative Institute includes approximately fifty researchers, faculty, students and postdocs housed in the GFDL building, Sayre Hall, and on the main Princeton University Campus, about three miles away. We anticipate similar numbers for CIMES.

Executive Board: We propose that the CIMES leadership be advised by a single Executive Board that encompasses both the management and budgetary responsibilities described in the Interim CI Handbook, and the scientific research management responsibilities of the Council of Fellows described in the same handbook.

The overall responsibility of the CIMES Executive Board would be to ensure that high quality research is being conducted, consistent with the goals of both NOAA and Princeton University, and to address any budgetary or management issues that may arise. Specific examples of Executive Board responsibilities would include providing concept development, program strategy, annual research plans, peer review, resource allocation, research and technology coordination, overarching goal of regional and disciplinary integration, communication of NOAA policies, priorities, coordination of opportunities and performance matters; review and comment on the annual progress reports prepared by staff.

Proposed CIMES Executive Board Membership: The individuals currently serving on the CICS Board would mostly be the same for the CIMES board. CICS has received outstanding reviews for its board function under the current structure. In addition to the CIMES Directors, membership of the CIMES Executive Board would consist of the Director of the AOS Program, Director of GFDL, two additional GFDL scientists with appointments as AOS faculty, and two additional Princeton University faculty. A proposed initial membership for the CIMES Executive Board would be:

Jorge L. Sarmiento – Director of CIMES, Professor of Geosciences
Gabriel A. Vecchi – Deputy Director of CIMES, Professor of Geosciences and Princeton Environmental Institute
Sonya A. Legg – Associate Director of CIMES, Senior Research Oceanographer in Atmospheric and Oceanic Sciences Program, Lecturer in Geosciences
Thomas Delworth – GFDL Physical Scientist, Lecturer in Geosciences
Stephan Fueglistaler – Director of the Atmospheric and Oceanic Sciences Program, Associate Professor of Geosciences
Isaac Held – GFDL Senior Research Scientist, Lecturer with rank of Professor in Geosciences
Michael Oppenheimer – Professor of Geosciences and Public and International Affairs, WWS
Stephen W. Pacala – Professor of Ecology and Evolutionary Biology
Venkatachalam (Ram) Ramaswamy – Director of GFDL and Senior Research Scientist

(NOTE: the GFDL members are examples only, as communication between us on this proposal is embargoed until a decision on funding is made.)
**Funding Tasks Explanations**

*Tasks*: Cooperative Institutes typically break down their functions and budgets into the following three types of ‘tasks’ and related organizational structures:

Task I. *Administrative, Education and Outreach Activities* will be carried out by the AOS Program.

NOAA funding for Task IA will support 1.5 months of the Director, Deputy Director and Associate Director, as well as a part-time administrative assistant and travel to attend the annual CI meetings at NOAA Headquarters. Task IB will support summer interns, faculty exchange program and related expenses such as travel and supplies. Additionally it will support QUEST, a summer educational outreach program. Princeton’s cost sharing will cover an additional 1.5 months’ salary for the Associate Director; as well 6 months support for administrative and/or financial staff, travel to the annual CI administrator’s meeting and $20k/year for scientific conferences, meetings, symposiums. (See budget narrative attachment for details.)

Task II: *Cooperative Research Projects and Educational Activities* usually involve on-going direct collaborations with NOAA/GFDL scientists and are carried out in the GFDL building. This will continue to be accomplished largely through the AOS Program of Princeton University.

One of the most important, and thus far, successful tasks of the cooperative institute has been the post-doctoral, research and visiting scientist program. As described earlier in the proposal, research projects are undertaken both by postdoctoral scientists and by research scientists in long-term positions. Projects involving research scientists are typically developed in both formal and informal discussions with GFDL scientists. Most major research projects are intertwined with GFDL projects (for example, the development of the next-generation ocean model), and there is two-way consultation and collaboration on a daily basis, as well as the more strategic and formal discussions.

Appointments are made in the AOS Program on the recommendation of the Visiting Scientist Selection Committee, which includes both Princeton University and GFDL scientists as members. The committee is currently chaired by Sonya Legg and Leo Donner (GFDL Physical Scientist and AOS Faculty member).

Students advised by GFDL scientists are usually funded by Cooperative Institute Task II research funds, although some students advised by Princeton University professors receive funding from Cooperative Institute Task III, following a competitive proposal review process. A strong connection between student Cooperative Institute-funded research and GFDL and NOAA goals is ensured by research guidance from GFDL advisors and/or committee members.

Graduate students are formally admitted to the AOS Program by the Graduate School at Princeton University, based on a recommendation by the faculty of the AOS Program, which includes, approximately 10 employees of GFDL/NOAA, thus ensuring that the NOAA vision is fully represented. Without exaggeration, we believe that the partnership between Princeton University and NOAA has been one of the most, if not the most, successful collaborations of this nature in the country.
Task III: Principal Investigator led research projects fall within the themes of CIMES, usually involving some collaboration with NOAA/GFDL scientists, and are instigated by the Princeton researchers. These projects generally occur within Princeton’s departments, centers, institutes and programs, and may also include subcontracts to research groups at other institutions as-needed. Task III is the main route for involvement of Princeton faculty in GFDL-relevant science. Funding is primarily through an annual call for proposals, with a review and evaluation process carefully designed to avoid conflicts of interest, promote engagement of a wide group of Princeton faculty in CI research, and involve GFDL scientists to ensure alignment of funded research with GFDL goals. For further details, see the Proposal Selection and Submission section below.

**Strategic Planning and Project Coordination**

Strategic planning would be undertaken by CIMES Executive Board, ensuring that the long term goals of both the University and GFDL are met. Cooperation in this regard between GFDL and the University has been excellent in the past and we expect that to continue.

Because of the complexity of Earth System Modeling, coordination among and between projects will be essential, and of necessity this involves coordination with GFDL scientists. Model development and applications would be coordinated via Model Development Teams, which are teams comprised of both government and University scientists and that coordinate the development of a model component or model as a whole. Team leaders would be chosen without regard to organizational affiliation, and the position implies no formal supervisory status. The teams typically meet on a weekly or bi-weekly basis. The physical proximity of GFDL to University scientists is a vital component of the collaboration.

**Proposal Selection and Submission**

CIMES anticipates receiving a certain amount of funding for Task III: Individual Research Activities from NOAA/GFDL, as has been the case with CICS. These are research activities led by non-NOAA scientists; however, they are evaluated in part, on their relevance to NOAA’s and GFDL’s strategic goals, and collaboration with NOAA/GFDL scientists is strongly encouraged. These proposals can include subcontracts to other academic institutions as well as meetings and/or conferences. Princeton’s cost-sharing will support an additional two researchers under Task III.

CIMES will have two types of these Task III PI-driven proposals that may be funded.

The first type of proposal would be requests from Princeton University faculty and researchers. Proposals are reviewed by GFDL scientists, and funding decisions are made by the CIMES Executive Committee in consultation with the GFDL director.

The second type of proposal would be requests from other academic institutions for CIMES funding. If such a proposal is awarded by CIMES, a subcontract from Princeton University is made to that institution by Princeton’s Office of Research and Project Administration (ORPA). Princeton has had long standing experience in fostering partnerships through their current Cooperative Institute. Previous funding, for example, has been provided to Enrique Curchitser at Rutgers University, who is a renowned expert on the development of coupled Earth System Models and on their application to the study of ocean circulation and climate at multiple scales.
Task III proposals are solicited every year, and those submitted, from both internal (Princeton PIs) and external (other institutions’ PIs), are reviewed by GFDL scientists who are experts in the field of each project that is being proposed.

These reviews are ranked using the following criteria:

1. Contribution of research to NOAA's and, specifically, GFDL's mission;
2. Quality of the proposed research, including the likelihood that the research will result in publication of scientific results in refereed journals;
3. Likelihood that postdocs and graduate students supported by this research will be successful in obtaining a research, faculty, public policy, or other positions in this field upon completion of their stay at Princeton University.

These reviews and proposals are then evaluated by the CI Executive Committee, currently comprised of five Princeton faculty and three GFDL scientists, and funding is allocated. As with Task II funding, this procedure ensures that the interests of both GFDL and the University are met.

Task II CIMES funding, which is the largest task in the proposal, would be used to support GFDL/CIMES research and education, including graduate students, postdoctoral associates, research scholars, and visiting scientists. An annual advertisement for scientists would be broadly placed to attract highly qualified scientists to join the CI. The Visiting Scientist Selection Committee, consisting of about 12 GFDL scientists and 4 Princeton scientists, then considers the applications. The criteria used to judge an application include both the quality of the applicant and the relevance of the proposed research to the overall research program at CIMES and GFDL. This procedure ensures that the interests and requirements of both the University and GFDL are properly taken into account. Some candidates will be invited to visit and interview. Graduate students appointed to CIMES would usually have been accepted to the Program in Atmospheric and Oceanic Sciences, but on occasion, Applied Math, Geosciences, and Engineering graduate students have been and likely will be accepted to perform research with CIMES and/or GFDL scientists.

As a Princeton University program, CIMES would rely on all the processes, procedures, offices and personnel provided by Princeton to do business. Each department currently having similar goals and research interest with our current Cooperative Institute (i.e., Atmospheric and Oceanic Sciences, Princeton Environmental Institute, Ecology and Evolutionary Biology, Geosciences, Woodrow Wilson School, Chemical and Biological Engineering and Civil and Environmental Engineering) have an Administrator and support staff that assists each individual Principal Investigator in the preparation of proposals according to the specific requirements of each agency. These departmental representatives have been and will continue to be educated in the details particular to a CI proposal via e-mail, training classes, administrative meetings, and personal communications.

**Fiscal Management and Accountability**

Within the University as a whole, compliance with all government regulations is achieved by the combined efforts of the department administrators, Princeton’s Office of Research and Project
Administration, the Treasurer’s Office of Sponsored Research Accounting, and the individual Principal Investigators. Princeton’s internal control process is designed to ensure that we have a system of accountability for and oversight of operations at the University.

Some of the responsibilities of the Office of Sponsored Research Accounting, which resides in the Treasurer’s Office, are:

- Managing the Institution’s compliance with federal regulations, such as the Office of Management and Budget (OMB) Uniform Guidance.
- Coordinating all Department of Health and Human Services (DHHS) audit activity, including requests for information and audit responses.
- Assuring that all Institution cost policies are clear and complete with respect to federal regulations covering allowability.
- Determining whether actual costs and/or activities are allowable and recommending appropriate policies and practices.

**Human Resource Management**

Hiring of professional (Master’s and PhD-level) staff to work on sponsored research projects is administered by the Office of the Dean of the Faculty (DoF) at Princeton University. University policy requires that all advertisements for new academic staff be approved by the DoF before posting. The approved text of the position announcement must be posted in an appropriate venue (e.g., professional society publication and/or website) for one month before an official offer can be made. When a candidate has been identified, his/her CV, a suggested salary, and the advertisement are submitted to the DoF for approval before an offer of employment is made. Once the offer has been approved, the offer letter to the applicant is prepared and then sent to DoF for final approval.

Supervision of CIMES supported scientists performing research under Task III is the responsibility of the CI funded Principal Investigator. In the case of Task II scientists, the responsibility of supervision will be performed by an appropriate Princeton University researcher and/or faculty. In cases where CIMES scientists receive technical guidance from GFDL scientists, the Princeton University supervisor will regularly communicate with the GFDL mentor and CI employee to maintain productive working relationships. The CI Administrator shall approve all vacation, travel and sick time of CI scientists and will notify the GFDL technical host of any change of staffing to ensure work coverage.

Princeton University anticipates that GFDL will provide scientific direction and technical guidance for any collaborative sponsored research project, including an annual assessment of progress accomplished on said projects.

The performance and salary of every CI scientist is reviewed on an annual basis. The AOS manager submits performance evaluations (written by the AOS Director and CI Directors), as well as salary recommendations for approval by the DoF. This review process is performed each spring for staff with ongoing appointments, and several months before the scheduled end date for staff with term appointments. Promotion files may also be submitted for review at this time.
Promotions and salary increases for the upper ranks of independent researchers are reviewed by the Princeton University’s Committee on Appointments and Advancements for the Professional Researchers and Professional Specialists for advice. Continued employment in professional research and specialist staff positions is contingent on performance and the availability of funding. Except in the case of termination for cause (which is unusual and authorized only under extreme circumstances), the length of the notice period required for termination depends upon rank and length of service at the University.

CIMES supported personnel will have an office in the host lab, GFDL, or in Princeton University’s Sayre Hall, where the AOS Program has its offices. Having GFDL in close proximity allows us to stimulate and support collaborative research. All CIMES employees will be supervised by a Princeton University researcher and/or faculty. It is expected and understood that for any collaborative project, scientific and technical guidance may be provided by GFDL scientists.

**Communication**

In addition to frequent weekly seminars held at both GFDL and Princeton University, CIMES and GFDL will conduct formal and informal meetings throughout the year. An example of a formal meeting would be the Visiting Scientist Selection Committee Meeting, which considers candidates for Post-Doctoral, Research and Visiting Scientist positions in the AOS Program. Examples of informal meetings are meetings between GFDL management and the CIMES Directors and administrator to discuss general scientific direction and funding levels for existing and upcoming projects and other day-to-day business matters. The Visiting Scientist Selection Committee meetings would normally be held at GFDL and informal meetings could occur at either GFDL or Princeton University’s Sayre Hall, which is located across the street from GFDL. Additionally, meetings will be held as necessary between GFDL and ORPA on a wide range of business matters, including issues related to the building lease, maintenance, grounds, etc. Over the nearly fifty years of Princeton’s current partnership with NOAA/GFDL, the parties have found that this arrangement has the right balance between structure and flexibility to efficiently and effectively advance the relationship between the mission objectives of NOAA, CI and the rest of Princeton University.

**3.5 PERFORMANCE MEASURES**

Our success will be judged by three general criteria: (1) the contribution of ongoing CIMES research to NOAA’s and, specifically, GFDL’s mission; (2) the quality of the scientific output, measured in part by the publication of scientific results in leading refereed journals; and (3) the success of CIMES researchers and graduate students in obtaining research, faculty, public policy, or other positions in this field or related ones upon completion of their stay at Princeton University.

**1. Scientific Products and the NOAA Mission**

CIMES and GFDL scientists, working together, will produce numerical models of the Earth system and its various components. These models are the 'products' of GFDL and CIMES, and will be used nationally and internationally to understand and predict climate and climate variability, and will be included in various scientific assessments. The use and success of these
models, as described in the publications and reports mentioned below, is thus a measure of the performance of CIMES.

2. Scientific Publications
An important measure of research performance is scientific articles published in peer-reviewed literature, as well as books and book chapters and research reports and conference proceedings. In the past few years a large number of scientific publications has appeared from our current CI scientists co-authored with NOAA scientists, and the extent to which this will continue will be a measure of the success of CI scientists in collaborating with their NOAA counterparts, and a measure of the strength of the cooperation.

As shown in the table below, the number of publications for both our current CI and GFDL continues to increase. The Princeton participation in co-authoring these publications remains above 50%.

### CI Publication Output

<table>
<thead>
<tr>
<th>Year</th>
<th>CICS (Progress Report Year)</th>
<th>GFDL (Calendar Year)</th>
<th>GFDL (w/Princeton co-authors)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>28</td>
<td>99</td>
<td>41(41%)</td>
</tr>
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<td>22</td>
<td>103</td>
<td>48(47%)</td>
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<td>2012</td>
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<tr>
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</tr>
<tr>
<td>2016</td>
<td>83</td>
<td>186</td>
<td>101(54%)</td>
</tr>
<tr>
<td>2017</td>
<td>88</td>
<td>205</td>
<td>139(68%)</td>
</tr>
</tbody>
</table>

3. Success of post-docs and graduate students
The AOS Program maintains records of the subsequent employment and career development of graduate students, researchers and visiting scientists who have come through the program. (See Appendix 2 – “Past Graduate Students and Researchers,” for detail on past performance of these programs supported through the CI.)

4. Other ways in which the CI will be evaluated are:

**Performance Reporting**
CIMES will provide annual progress reports to NOAA, as required by all cooperative institutes. CIMES scientists will also provide progress reports on proposal-driven awards as required by NOAA.

**Employee Performance**
CIMES scientists, as Princeton University employees, will be evaluated annually as part of the standard Princeton University merit review process.
**Diversity**

As stated by the University’s President, Christopher L. Eisgruber, “Diversity and inclusion are central to Princeton's educational mission and its desire to serve society. Members of the University community have a deep commitment to being inclusive because they know that: diverse environments are more stimulating, fairness is a core value at Princeton, and our students should live and learn in an environment reflective of society.”

Additionally, the AOS program is making a concerted effort to increase the diversity of researchers and students participating in earth system science. For several years, the AOS program students have been about 50% female, while the national average for geosciences, atmospheric, and ocean sciences is 41%. Following the Princeton University Best Practices for Diversity (https://www.princeton.edu/reports/2013/diversity/report/PU-report-best-practices-graduate-students.pdf), several new initiatives for increasing recruitment from historically underrepresented minorities have been established at Princeton. Our current CI has also established a Visiting Faculty Exchange Fellowships and Summer Student Research Internships, described in Section 3.3C “CIMES Education and Outreach”, which are directed at recruiting underrepresented candidates. We have advertised these opportunities in the Institute for Broadening Participation’s Pathways to Science, Advancing Chicanos/Hispansics & Native American in Science Career Center (SACNAS), American Indian Science and Engineering Society (AISES), and the National Society of Black Physicists (NSBP) and National Society of Black Engineers (NSBE) in addition to our usual advertisement venues.

3.6 DATA MANAGEMENT PLAN

**Data collected and generated from the research**

CIMES will follow an open access policy and publication strategy: all of the source code and all of the datasets will be open access and governed by the Data Quality Act. Peer-reviewed science is the guarantee of data quality. Data that are deemed to be of sufficient scientific quality will be published. Where appropriate, we will follow the CMIP guidelines and standards so that data can be published to an Earth System Grid Federation (ESGF) node and assigned DOIs when the data are deemed to have passed their standards of data quality and documentation.

**Data formats**

No confidential or proprietary data are being produced. Specific data formats are derived from the analysis codes to be used and include:
- binary, GRIB2, NetCDF, ESRI Arc coverages and shapefiles.
- Python, Matlab, and R codes
- Excel, Word and PowerPoint files

Software to be used includes Ferret, Python, Matlab, and R. For any software or inventions (we do not anticipate to be seeking any patents) from this research we will follow the National Oceanic and Atmospheric Administration’s guidelines for data sharing. In particular, all software will be released in open source repositories, following the CIMES open development methods and procedures outlined in “Modeling Ocean Physics and Dynamics” and “The Princeton Hierarchical Earth System Modeling Initiative “ in Section 3.2A.1 of the proposal.
Data dissemination and sharing

We will follow the guidelines of the National Oceanic and Atmospheric Administration in implementing a data sharing policy that conforms to published guidelines. In particular, we will publish the results in well recognized scientific journals in a timely fashion. This work will be co-authored by those researchers (e.g., postdoctoral researchers, PI, and Co-PIs) who have conducted the research. The appropriate version of the publication and associated supplementary information (e.g., data) will be deposited and shared via Princeton Open Access Repository and Princeton DataSpace, which are two open access repositories for sharing and archiving the scholarly output from Princeton University.

For the data that will be used in this project that are freely available from the internet, the team will not make arrangements for them to be made available from their servers. On the other hand, the outputs that will be generated will be preserved on the Princeton data servers and made available to interested users. Small datasets will be available online, and larger ones will require consultation to determine the best delivery method. Costs associated with servicing data requests will be nominal and based on actual cost.

Data Storage and Preservation

Our short-term data storage plan is to store data from climate model experiments generated using Princeton University computers on servers owned by the CIMES Co-PIs at Princeton University. The present storage at Princeton University comprises an IBM General Parallel File System (GPFS – installed 4/2013) and provides 4.1 PB of usable storage which can be accessed by all major central HPC resources with an aggregate performance of 16 GB/s. This system is expected to be upgraded during 2018 to provide ~6 PB of usable storage. CIMES proposes to contribute its fair share to expand the size of this archive, as noted in the proposal. This hardware will ensure that there is enough space to store the required data (reanalysis data, data from global climate models) as well as the outputs generated by the project. The server will be backed up monthly on to an external drive, which will be stored offsite.

For long term storage and preservation, the data associated with publication and shareable will be submitted and uploaded to the Princeton DataSpace repository. The authors will submit metadata in Dublin Core format along with the data to facilitate its reuse. Other data that are collected or generated from the investigation will be stored for a period of at least three years following the publications of results.

The FMS Runtime Environment (FRE) workflow, developed by CICS researchers Balaji and Nikonov in collaboration with GFDL, also contains complete provenance information for exact reproduction of prior simulation and analysis. One of the principal goals of FRE is disaster recovery (DR). CIMES will attempt to store complete provenance of all their runs for DR, where FRE can in principle completely reconstruct missing data, if the hardware and software stacks continue to be available.

Finally, we note that the CIMES Data Analysis and Archival Plan contains plans to encode software using contemporary container technologies, and are pursuing partnerships with cloud vendors (e.g., Google). As part of the data management strategy, we are also looking to long-term storage and access with analytic capabilities on the commercial cloud.