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

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Year 5: $18,054,074  
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1 Abstract

We propose to renew the Cooperative Institute for Modeling the Earth System (CIMES) to conduct research in support of NOAA’s mission and strategic goals as stated in NOAA’s FY22-26 Strategic Plan in areas related to Earth System Science. CIMES builds 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). This proposal is to renew the current CIMES grant, which ends June 30, 2023.

This proposal builds on the CIMES proposal submitted in 2018, and incorporates recommendations expressed in the NOAA Science Review of CIMES carried out May 17-18, 2022 (see Attachments 4.12). The Science Review rated CIMES as “outstanding”.

Vision. 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 local to global scales, 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 researchers, on whose skills and insights the future of climate science rests.

Themes. CIMES research will address the following three themes:

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.

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.

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.
**Mission.** 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 goals of a "Climate Ready Nation", "Equity" and 'Growth in an Information-Based Blue Economy’ as expressed in NOAA’s FY22-28 Strategic Plan. 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. CIMES is committed to, and has a proven track record of, promoting and training a strong and diverse cohort of scientists to become future leaders in the Nation’s efforts to develop solutions to pressing problems arising from weather and climate.

**Outstanding record of performance working with NOAA.** Princeton’s collaboration with NOAA/GFDL extends back more than 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 (many of them landmark studies), training of hundreds of postdoctoral researchers (in total more than 420 PostDoctoral researchers and scientists have been supported through the NOAA-Princeton University collaborative institutes), and more than 130 Princeton AOS PhDs have been awarded.

**Nationally and internationally 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. The calibre and reputation of the NOAA/GFDL—Princeton University collaboration is widely known in the natural sciences, with the 2021 Nobel Prize in Physics for former GFDL scientist and AOS faculty Syukuro Manabe certainly being a culmination point that also drew attention from the general public.

**Excellent educational program with a successful record of training earth scientists.** The Princeton AOS Program has awarded more than 130 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 more than 420 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 agreed to further increase its financial commitment to NOAA in line with the increase in the budget ceiling of this renewal proposal compared to the current proposal for FY19-23. That is, the total commitment of approximately $8M (see Attachments: Total Budget 4.6) over the 5-year Cooperative Agreement is roughly double the commitment to the FY18-23 CIMES proposal, and is the largest ever finan-
cial commitment in the 50+ years of collaboration between Princeton University and NOAA. The partnership with GFDL/NOAA is further underscored by a letter of strong support from Princeton University President Christopher L. Eisgruber (Attachments: Letter of Support President Eisgruber; section 4.1).
2 Results Overview CIMES 2018-2023

Project title: Cooperative Institute for Modeling the Earth System (CIMES)

NOAA Award: NA18OAR4320123
Total budget proposed 2018-2023: $43,156,204
Total budget effective (2018-2023): $41,963,722 (as of 2023/02/27)
Principal Investigator: Jorge L. Sarmiento (2018-2019)
Gabriel A. Vecchi (2019-2021)
Stephan A. Fuglister, 2021 - present.
Co-Principal Investigator: Sonya A. Legg

CIMES was evaluated by an external review committee in May 2022; below we highlight some key results for each theme from recent research funded through CIMES as also presented to the review committee. Further details are in Section 3.3. Comprehensive descriptions of all research activities are available in the CIMES annual reports provided at: https://www.princeton.edu/cimes/about-us/reviews-reports/

2.1 Earth System Modeling: Development and Analysis

A: GFDL Global Climate Models

CIMES researchers provided major contributions to the development of the recent suite of GFDL models created for the Climate Model Intercomparison Project 6 (CMIP6). A major achievement of the past year was the release and documentation of the new climate model suite, CM4.0, the fully coupled climate model developed for the Coupled Model Intercomparison Project CMIP6, described in Held et al. (2019), and OM4, the MOM6 ocean model configuration described in Adcroft et al. (2019). These physical models are combined with land and ocean biological models to form the GFDL Earth System Model version 4.1 (ESM4.1), documented in Dunne et al. (2020), combining carbon-chemistry with the physical climate models of CM4, and the atmospheric chemistry component of this model AM4.1, documented in Horowitz et al. (2020). CIMES researchers contributed to the ocean dynamical core, the modeling workflow, the land-surface component, the atmospheric dynamical core, the atmospheric chemistry component and the ocean biogeochemistry components of these models.

A total of 6 Cooperative Institute researchers contributed to the two multi-author publications describing the landmark models, CM4.0 and OM4, with distinctive contributions to ocean model algorithm development, stratospheric dynamics, cloud representation, and software development (Adcroft et al., 2019; Held et al., 2019). CM4.0 represents the state-of-the-art in climate modeling, with particularly good representation of the El Niño-Southern Oscillation and Madden-Julian Oscillation. OM4 uses a hybrid vertical coordinate which leads to a reduction in the model ocean drift, providing
a better model for long-term climate simulations.

CIMES researchers have also contributed to the “Seamless system for Prediction and EArth system Research” (SPEAR), GFDL’s next generation seasonal-to-decadal prediction system (Delworth et al., 2020; Lu et al., 2020), and the “System for High-resolution prediction on Earth to Local Domains” (SHiELD), GFDL’s new unified weather prediction system (Harris et al., 2020).

In addition to the team model development efforts described above, some recent advances in earth system model development led by early career CIMES researchers include: an improved representation of tropical forests in the GFDL land model (Cano Martinez et al., 2020); a parameterization of ocean submesoscale symmetric instability (Yankovsky et al., 2021); machine learning tools for improving and diagnosing ocean climate models (Sonnewald and Lguensat, 2021; Sonnewald et al., 2021); parameterization of tabular-iceberg decay (Huth et al., 2022); improving the land model capabilities through satellite soil moisture data assimilation (Vergopalan et al., 2021).

Members of the Cooperative Institute have contributed to the development of the GFDL Finite-Volume Cubed Sphere Dynamical Core, documented in the technical memorandum by Harris et al. (2020). This dynamical core development team is also contributing to the Dynamics of the Atmospheric general circulation modeled on non-hydrostatic domains (DYAMOND) project, a multi-institutional project to compare global storm-resolving models, described by Stevens et al. (2019).

B: Specific Contributions to Physical Process Representation and Parameterizations

Cooperative institute researchers have conducted studies of fundamental physical processes in the ocean, atmosphere and cryosphere, and their parameterization, including: mixing by symmetric instability in oceanic gravity currents, cloud microphysics, anvil cloud physics, tropical convection, and tabular ice-bergs. The representation of biological processes such as mangroves and tropical forests in climate models has been explored. An example of improved process representation resulting from these studies is the new parameterization of gas transfer to the ocean described in Reichl and Deike (2020). This model uses understanding obtained from theoretical simulations (Mostert and Deike, 2020; Berny, Deike et al., 2020) together with the WaveWatchIII model incorporating the effect of both wind and waves, and finds the bubble-mediated gas transfer contributes to about 40% of the total CO2 flux into the ocean.

Through participation of CIMES researchers in several Climate Process Teams (CPTs), there has been substantial development of new parameterizations of sub-gridscale processes in the climate models. One CPT focuses on eddy diffusivity-mass flux (EDMF) parameterizations of the convective boundary layer. The NCEP turbulent kinetic energy (TKE) based eddy diffusivity (ED) mass flux (MF) scheme has been incorporated in the GFDL AM4 model and the numerical discretization in the EDMF scheme has been improved to better capture the sharp jump in buoyancy and TKE across the top of stratocumulus (Sc) layer, reducing the low bias in Sc cloud cover. A dry, stochastic entrainment, multi-plume mass-flux (MF) scheme has been implemented into the GFDL atmospheric model AM4, aiming to represent non-local eddies in the boundary layer. Compared to the standard AM4, this implemented dry MF produced a more well-mixed temperature profile and had a better agreement with the “ground-truth” large-eddy simulation results. Inclusion of this dry MF increases the low cloud amount particularly over the ocean, which reduces the low cloud underestimation bias in the AM4. Another CPT focuses on improving the modeled momentum flux in the atmospheric boundary layer, using the CLUBB (Cloud Layers Unified by Binormals) framework to implement prognostic momentum flux and understand its impacts. A new version of CLUBB code has been implemented in AM4, which works well with MG (Morrison and Gettelman) microphysics.

We also highlight the significant development of a continental-scale ice-sheet model, MOM6ice, as a component of the MOM6 ocean modeling system, by CIMES researchers Alistair Adcroft and
Olga Sergienko, with GFDL colleagues. MOM6ice simulates flow of ice sheets, ice streams and ice shelves and interactions between ocean circulation in sub-ice-shelf cavities with ice shelves.

CIMES research has made important contributions to land model development. As part of the land-surface CPT, a new parametrization to improve the representation of turbulent mixing and aerodynamics in the heterogeneous soil-vegetation-atmosphere system has been implemented and tested within the land model LM4.2, using stand-alone land model experiments (driven by AM4 atmospheric output) to test the effects of the new parameterization on land surface climate. The new parametrization has important effects on land evaporation and sensible heat fluxes, with a tendency to increase the transpiration to evapotranspiration ratio (more plant transpiration than bare soil evaporation), but decrease the evaporative fraction (more sensible heat than latent heat). The new parametrization also significantly improves the deposition velocity modeling for chemical tracers (e.g. Ozone, SO4, HNO3, etc.) over vegetated surfaces, and leads to higher near-surface winds than previous parameterizations. Another land surface CPT project focuses on developing and validating radiation parameterizations which account for the effects of 3-D topography.

2.2 Seamless Prediction Across Time and Space Scales

There are two main prediction model systems configured and applied to a variety of phenomena by CIMES researchers in collaboration with GFDL colleagues. SPEAR (Seamless system for Prediction and EArth system Research) is applied mainly to subseasonal-to-seasonal (S2S) and seasonal-to-decadal (S2D) prediction. The second prediction system, SHiELD (System for High-resolution Prediction on Earth- to-Local Domains), is a unified weather modeling system, which can be configured for a variety of applications.

A: Seasonal-to-Decadal Prediction

The new SPEAR (Seamless system for Prediction and EArth system Research) seasonal prediction system reached the operational stage with the contributions of several CIMES researchers over the past cycle. It contributes monthly real-time seasonal forecasts to the North American Multi-Model Ensemble (NMME). The new SPEAR seasonal prediction system leverages GFDL’s latest advancement in component model development. CIMES researcher Feiyu Lu has led the development of the new bias correction scheme (Ocean Tendency Adjustment or OTA) that significantly reduces model drift compared to GFDL’s previous seasonal prediction systems and most contemporary operational systems, described in recent publication (Lu et al., 2020). CIMES researcher Aparna Radhakrishnan collaborates with the NOAA Big Data Program to host SPEAR data in the cloud. CIMES researchers have been involved in several applications of SPEAR, including S2S predictions of wintertime cold extremes; assessment of stratospheric biases in S2S models, and how they affect prediction skill; atmospheric rivers; and Antarctic sea-ice. Key findings include: the stratospheric vortex strength in initial conditions can affect the predictability at the surface; Atmospheric rivers can be skillfully forecast 9 months in advance over certain regions, including California and Alaska, while over other regions, such as Washington/Oregon and British Columbia, prediction skill is only significant for the first season. The prediction skills (and limits) are closely related to ENSO and PDO variability, which modulates the interannual storm track activity.

SPEAR is being applied to seasonal prediction of Arctic sea ice (Zhang et al., 2021). A set of experiments have been designed to test whether the assimilation of observed initial sea-ice concentration (SIC) and sea-ice extent (SIE) improve the forecasts of sea ice concentration, ice free probability (IFP) and ice free date (IFD) at lead times of 0-2 months. Results show that the SPEAR system can make skillful subseasonal-to-seasonal forecasts for Arctic sea ice cover. The prediction skill for the
area-integrated SIE and grid cell level SIC exceeds the reference anomaly persistence forecasts within the first month of the forecast period, indicating that SPEAR is among the most skillful dynamical prediction systems. By constraining the sea ice initial conditions with assimilated SIC, improvements in SIC skill are prominent in summer-initialized forecasts, moderate in spring, small in winter and autumn, and forecast skill of IFP and IFD are improved. SPEAR is being used to examine the representation, predictability, and prediction skill of Kuroshio Extension (KE) decadal variability. Skillful KE predictions in SPEAR retrospective decadal and seasonal forecasts are found for lead times up to 3 years and 12 months, respectively. Skill above persistence for long lead forecasts is confined to winter initialization. The results suggest that the long lead skillful prediction derives primarily from the winter intensification of the North Pacific atmospheric forcing that efficiently impacts the KE region locally and remotely.

CIMES researcher Feiyu Lu has analyzed the prediction skill of the SPEAR S2S system on the extreme heatwave that occurred in western North America in early summer of 2021. The SPEAR S2S system shows good skill in predicting the severity of the heatwave at 7 and 12 days in advance compared to other operational S2S prediction systems. Attribution analysis based on both the SPEAR S2S and seasonal prediction systems shows that land initial conditions played an important role in amplifying the heatwave prediction. Feiyu Lu is also applying machine learning methods to reduce model bias and improve parameterization, using ocean data assimilation (ODA) increments from SPEAR.

B: Unified Weather-to-Climate Atmospheric Modelling

The unified forecast system, SHiELD (System for High-resolution Prediction on Earth- to-Local Domains) has been configured to a variety of applications by CIMES researchers over the past five years.

CIMES researcher Joseph Mouallem has upgraded the two-way single-nest capability in the FV3 dynamical core, used in SHiELD and many other applications, to allow multiple same-level and telescoping nests. This advanced nesting capability was tested within SHiELD to simulate the landfall of hurricane Laura 2020 and an atmospheric river in California in 2021 (Mouallem et al., 2022) and was proven to capture these events in greater detail. Container technology has been used to enhance the accessibility of SHiELD across platforms, allowing deployment on supercomputers across nodes (Cheng et al., 2022). CIMES researcher Linjiong Zhou has continued developing the GFDL cloud microphysics package (GFDL MP) for SHiELD. This latest version, GFDL MP v3, includes realistic particle size distributions and scientific modifications to the microphysical processes. Improvements to the GFDL MP, the FV3 dynamical core, and boundary layer turbulence lead to more skillful weather prediction. The new model version, SHiELD 2021, was frozen and released in late 2021, with substantial improvements in predicting height, wind, cloud, surface temperature, and radiation compared to SHiELD 2020.

One of the applications of SHiELD, known as T-SHiELD, applies SHiELD to realtime hurricane forecasting, using the two-way nesting feature in the GFDL FV3 dynamical core, with a 3km resolution nest over North Atlantic is led by Kun Gao (CIMES). With the goal of developing a computationally efficient system that demonstrates superior skill in hurricane track and intensity prediction, the 2-way nested grid and choice of horizontal advection schemes have been refined, substantially improving the prediction of hurricane track. Re-tuning of the physical parameterizations, including the convection schemes, mixed layer ocean model, and GFDL cloud microphysics have improved the model performance in capturing rapid intensification. T-SHiELD was run in real-time during the 2021 hurricane season, and performed better than the operational GFS and HWRF in terms of track forecasts. The T-SHiELD performance on forecasting post-landfall tropical cyclone
wind field has been examined by CIMES researcher Jie Chen, demonstrating that the existing theoretical TC structural model can generate the full azimuthal wind profile of real-world U.S. landfalling hurricanes with limited, simple input parameters (HURDAT and surface property information). T-SHiELD generally reproduces the evolution of the high wind region of the landfalling hurricanes (2015-2021).

Another configuration of SHiELD under development by CIMES researchers is S-SHiELD, a near real-time subseasonal to seasonal (S2S) prediction system. Unlike many S2S models, S-SHiELD is non-hydrostatic and uses sophisticated microphysics. While these features make S-SHiELD more expensive than analogous hydrostatic models, non-hydrostatic dynamics and better microphysical-dynamical coupling yields a better representation of mesoscale convective systems and in particular of tropical cyclones. Hindcast experiments using S-SHiELD show good prediction skill for the Madden-Julian Oscillation (correlation > 0.7) out to 19 days and useful skill (correlation > 0.5) out to 28 days.

Last, CIMES research Kai-Yuan Cheng has performed several X-SHiELD simulations at 3.5 km resolution for one-to-two years on the CIMES HPC platform Stellar. This lead to the 2022 Cheng et al. publication showing substantial increases in extreme vertical velocity in response to warmed SSTs.

2.3 Earth System Science: Analysis and Applications

CIMES researchers have applied GFDL earth system models to many different societally relevant problems. Highlights include forecasts of estuarine systems (Ross et al., 2020); tropical heat stress (Zhang et al., 2021); impact of climate-biosphere feedbacks on ozone air pollution (Lin et al., 2020); wildfire impacts on air pollution extremes (Xie et al., 2020; Xie et al, 2022); large-scale environmental impacts on tropical cyclones (Ng and Vecchi, 2020; Hsieh et al., 2020); drought risk (Pascale et al., 2020); coastal ecosystem responses to increasing river nitrogen loads (X. Liu et al., 2021); impacts of land nitrogen input and drought on water pollution (M. Lee et al., 2021); increased risk of wildfires due to anthropogenic activity (Yu et al., 2021); enhancement of precipitation in the Sahel by remote irrigation (Zeng et al., 2022); and ground fish stock assessments (de Pontavice et al., 2022).

A: Heat stress in the tropics, and urban heat islands.

Using theory, observations, and global climate model, CIMES researchers Stephan Fueglistaler and Graduate student Yi Zhang examine tropical heat stress in a warming climate (Zhang et al., 2021). They find that the annual-maximum wet-bulb temperature will increase uniformly by 1°C for each 1°C of tropical mean warming, suggesting that limiting global warming to 1.5 °C could prevent tropical regions between 20°S and 20°N of the equator from reaching the limit of human adaptability, which is a wet-bulb temperature of 35°C. This study by a CIMES supported AOS graduate student received also much attention in the media, including an article in the New York Times.

The urban heat island and its sensitivity to projected climate warming over the 21st century is being explored through a series of simulations, by Gabe Vecchi and collaborators, with a particular focus on the temporal characteristics and intensity of heat waves, and the impact of patterns of ocean temperature change in the projected changes in heat wave statistics. Additional work is examining regional humidity responses, and their implication for directly-transmitted respiratory diseases (Respiratory Syncytial Virus or RSV, influenza and coronaviruses), and the differences in response between rural and urban regions, and connections between ENSO and the urban heat island in South Asia.
B: Vegetation changes and wildfires.

Simulations with GFDL earth system models show that land use change from natural vegetation (forest) to crops, pastures, and secondary vegetation lead to a net cooling effect, mostly in midlatitudes where crops and pastures are concentrated. This cannot be explained by energetic changes only (albedo effect), but also due to changes in soil moisture-atmosphere feedback, where crops and pastures tend to reduce the dryness index in a given region (make land more energy-limited than water-limited).

Several studies use the capabilities of GFDL ESM4.1 to explore wildfire in a changing climate. CIMES researcher Martinez Cano examined the dynamics of tropical forests, showing that abrupt declines in Amazonian carbon stocks due to wildfires by the end of the 21st century are possible under the high emission scenario SSP5-8.5. Using the modeling capability of the GFDL ESM4.1, CIMES researcher Yan Yu has simulated the complex interactions between fire, climate, land ecosystem, and human activity in order to assess the influence of anthropogenic activities on extreme fires in Alaska. By sorting out controlling factors of wildfires in Alaska, this study found that the three-fold increase in the risk of an extreme fire season in Alaska during recent decades was primarily caused by human ignition and secondarily caused by biofuel abundance.

C: Marine ecosystems.

GFDL earth system models have been used to investigate several topics involving climate and ecosystems by CIMES researchers over the last five years. This has lead to novel results concerning the interaction between the physical climate system and marine ecosystems: we selectively highlight recent accomplishments that vary from regional to global scales.

At the regional (continental shelf) scale, Ross et al. (2021) examined whether anthropogenic climate change has altered the risk of experiencing an extreme amount of freshwater discharge from the Susquehanna River into Chesapeake Bay. A comparison of these projections under scenarios of historical (with anthropogenic emissions) and natural (without) radiative forcing showed that around 1/3 of the present-day risk of experiencing a year of extreme freshwater discharge similar to 2019 can be attributed to anthropogenic climate change. CIMES researcher Hubert du Pontavice has used GFDL ocean models to provide environmental information for groundfish sock assessments over the Northeast U.S. continental shelf using ocean models (du Pontavice et al., 2022). This study demonstrated that incorporating environmental effects on yellowtail flounder recruitment may improve the predictive skills of recruitment and, to a lesser extent, spawning stock biomass. This suggests a pathway for ocean models may benefit stock assessments when ocean observations are limited. Last, Princeton faculty member Laure Resplandy has investigated the risk of coastal hypoxia in the northern Indian Ocean, examining how the likelihood of hypoxis is modulated by wind-driven and wave-driven upwelling.

At the ocean-basin scale, CIMES researcher Hyung-Gyu Lim has examined the coupling between the El Niño–Southern Oscillation (ENSO) and phytoplankton in the tropical Pacific using ESM4.1. This model captures observed ENSO-chlorophyll patterns much better than GFDL’s previous ESM2M. This included an improvement in simulating the observed post-El Niño “chlorophyll rebound” via ocean advection of iron and dust-iron deposition anomalies. This highlights, the synergy possible when observationally validated ESMs can be used for process-oriented scientific understanding. Princeton’s Resplandy has applied ESMs including GFDL-CM4 and ESM4 to investigate the evolution of the largest oxygen minimum zone (OMZ) in the Pacific ocean. This research shows ESMs project volume changes fall into three regimes: an expansion of low oxygenated waters, a contraction of the OMZ core, and a spatial redistribution but near-zero change in hypoxic waters. Circulation and biology dictate the shift from expansion to contraction. The expansion of low oxygenated waters,
demarcating the boundary of the optimum habitat of numerous marine species would lead to severe impacts on ecosystems, is a critically important aspect of future ESM-based projections of marine ecosystems.

### 2.4 CIMES’s HPC Platform Stellar

In February and March 2021, CIMES paid $1,940,337 on purchase orders (including indirect costs of $27,184) with Dell and IBM to provide HPC hardware, peripherals and warranties. In June 2021, CIMES paid $57,333 for NVMe shared storage system. The new cluster has been fully operational since July 2021. Our HPC Cluster, named Stellar, has an active userbase, and several NOAA models have been ported. In February 2022, Dr Timothy Merlis (formerly Associate Professor, McGill University) began in the role of High Performance Computing Manager. The new user account creation process was streamlined in March 2022 and there are approximately two new CIMES users per month. The NOAA models available on the HPC cluster currently include GFDL’s AM4, MOM6, TSHiELD, XSHiELD, as well as key parts of GFDL’s post-processing workflow. The HPC cluster is enabling CIMES personnel to contribute to the development of Machine Learning techniques for ocean models and the evaluation of prototype Global Storm Resolving Models of the atmosphere.

The HPC system Stellar is a key component of CIMES’ cross-theme objective to serve as catalyst for collaborative research as described in Section 3.4.
3 Project description

3.1 Introduction

This proposal to renew the Cooperative Institute for Modeling of the Earth System (CIMES) would continue and extend the research and educational programs of CIMES as supported 2018-2023. CIMES 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 and mentor the next generation of climate and earth system scientists. The three linchpins of the GFDL/Princeton relationship, on which CIMES was built and which we propose to continue, are:

A: 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 mentored by GFDL scientists appointed to the AOS program faculty. As of February 2023, the program has hosted over 420 postdoctoral, research and visiting scientists, and awarded over 130 PhD degrees. The excellence of the graduate and postdoctoral training program enabled by the GDFL/Princeton collaboration is seen in the current success of those former students and postdoctoral researchers. Roughly half of the PhD students currently hold (or held) faculty appointments at leading national and international research Universities, and about a quarter work at national research laboratories sponsored by NOAA, NASA or DoE (for detailed breakdown see Attachments: AOS Graduate Alumni, Section 4.10); with similar numbers for former postdoctoral researchers. CIMES researchers are highly successful and productive, and contribute to about half of all GFDL peer-reviewed publications, and write about 80 peer-reviewed papers per year (see graphic below, Attachments:CIMES Publications; Section 4.3.)

Top: Number of publications by CIMES supported researchers, per year. Bottom: Fraction of publications by GFDL with CIMES supported researchers, per year. Data as available May 2022.
B: The academic expertise of Princeton faculty and investigators has played an important role in the progress of GFDL science, beginning with developments in computational fluid dynamics pioneered by Princeton Professor George Mellor, continued through contributions of ocean biogeochemistry and carbon cycle model components by Professor Jorge Sarmiento’s group, and development of the land biosphere models of Professor Stephen Pacala. More recently, collaborations between Princeton University and NOAA/GFDL through CIMES has broadened and now encompasses a large number of faculty across several departments. Directly supported by CIMES, AOS Senior Research Oceanographers Adcroft and Legg, and Research Glaciologist Sergienko provide core expertise in ocean and ice-sheet model development, as well as development of software infrastructure for climate modeling. In the Department of Geosciences, Profs. Fueglistaler and Vecchi provide expertise in the Physics and Dynamics of the Atmosphere and Ocean, and coupling thereof, and extreme events. Profs. Resplandy, Ward, Sigman, and Deutsch provide expertise in oceanic biogeochemical cycles, and Prof. Lai provides expertise in ice sheet dynamics and machine learning. In the Department of Environmental and Evolutionary Biology, Profs. Metcalf and Grenfell work on the connection between climate and disease, and Prof. Pacala plays a key role in the development of land biosphere models. In the Department of Mechanical and Aerospace Engineering, Prof. Deike collaborates with GFDL on a sea spray aerosol parametrization, and in the Department of Civil and Environmental Engineering, Profs. Bou-Zeid, Smith, Ling, and Porporato provide expertise in boundary layer process, extreme weather events and hurricanes, and hydrological processes, respectively. Finally, Professors Oppenheimer and Mauzerall in the Princeton School of Public and International Affairs provide expertise on science policy, and Prof. Kapstein, together with Prof. Ramsay in the Department of Politics, analyze the relation between climate and conflict. Many of the above listed faculty are also affiliated with the High Meadows Environmental Institute (Director: Prof. Vecchi). Thus, expertise from Princeton University broadens and deepens the expertise at GFDL. The Cooperative Institute for Modeling the Earth System provides the critical conduit to leverage the full potential of the collaboration.

C: The flexibility of the academic enterprise at Princeton University to respond to new initiatives and opportunities. Research performed through CIMES and the proposed CIMES collaboration between Princeton and GFDL will necessarily evolve through the next 5 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 CIMES 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 CIMES research performed by students and postdoctoral researchers early in their careers, CIMES has been able to respond quickly to changing priorities, enabling GFDL access to new ideas and fresh talent.

CIMES has developed a strong set of processes 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 CIMES leadership has been responsive to current GFDL needs and concerns and will continue to be so going forward.
3.2 Vision, Mission and Goals

**Vision.** In parallel with GFDL’s 2019 Strategic Science Plan, and in response to the Federal Funding Opportunity, the history of the GFDL/Princeton relationship, and the recommendations of the External Review Panel, 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 Announcement of Federal Funding Opportunity (NOAA-OAR-CIPO-2018-2005422), namely:

1. To develop the world leading earth system model, in collaboration with GFDL, by providing expertise in key processes, physical, chemical and biological components, and software development; and by providing support for innovative collaborations.

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-class 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 expressed in the Department of Commerce’s strategic plan FY22-26.

Goal 1: CIMES’ goal of “developing the world’s leading earth system model, ..., expertise in key processes” aligns directly with NOAA’s goal of a “Climate ready nation”, and the associated objectives. In particular, CIMES offers major contributions to the objectives “Modeling, predicting and projection”, “Research and development”, and “Advance integrated breakthrough climate research”. CIMES proposes to contribute to enhanced modeling technology addressing challenges posed by extreme weather, 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 NOAA’s strategic objective “Improve environmental predictions and projections” by “decreasing sub-seasonal forecast timescales and longer timescale baseline climate studies”, building on “… achieved through improved modeling of land, ocean and ice eco-systems, atmosphere-land-ice interactions, as well as data assimilation ...” addressed in CIMES Goal 1. The resultant codes, tools and analyses contribute to NOAA’s objective to provide “service delivery and decision support tools”. Princeton faculty and researchers are involved in both the development and use of computer models of the earth system. Specifically, CIMES research will focus on understanding and predicting changes in climate and oceans. This prediction goal is also aligned with NOAA’s mitigation and adaptation and mitigation strategies.

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.

3.3 Research

In the following sections, we outline a comprehensive program of research focused on modeling of the earth system, and how this program maps onto CIMES’ three research themes. 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. The three research themes are (further detailed in Sections 3.3.1, 3.3.2, and 3.3.3 below):

**Theme: 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, though 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.

**Theme: Seamless Prediction across Time and Space Scales.** Earth System Models 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 research theme “Earth System Modeling” 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. There are also aspects of prediction that depend on how the forecast model is initialized and what data is feasible to include. Here again, there is an interplay between the theme of seamless prediction and earth system modeling, as predictions provide a distinct dimension of model evaluation.

**Theme: Earth System Science: Analysis and Applications.** The earth system models developed in collaboration with GFDL will be applied to understanding a wide range 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 3.3.2, “Seamless Prediction across Time and Space Scales”). This theme also includes more overt aspects of climate impacts on human activity, such as the magnitude of future heat stress, and human activity’s affect on climate (e.g., anthropogenic changes in atmospheric composition during the COVID-19 pandemic).
3.3.1 Theme: Earth System Modeling

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.

It is helpful to introduce the model families and their respective components from which future development will build. The schematic below shows four families of models: SHiELD (described in the Seamless Prediction Theme), SPEAR (described in the Seamless Prediction Theme), CM4, and ESM4 (both described later in this section). The atmospheric dynamical core (FV3) is common to all, as is the ocean model (MOM6) for those that have interactive ocean circulations. The treatment of land and atmospheric model components differs between the ESM version and the CM version to simulate the tracers needed to represent the requisite chemical cycles for interactive climate composition, including carbon. Likewise, ESM4 has a more thorough treatment of the ocean biogeochemical cycles with the Carbon Ocean And Lower Trophics (COBALT) ecosystem model than CM4.

The proposed renewal of CIMES will advance ocean (part A), cryosphere (part B), atmosphere (part C), land (part D), and biogeochemical (part E) components of these coupled earth system models and improve the coupled climate and earth system models (part F).

A: Ocean physics

Ocean dynamics and circulation modeling: MOM6 development. The GFDL Modular Ocean Model version 6 (MOM6) was introduced in the documentation of GFDL’s OM4 model (Adcroft et al. 2019). The GFDL Ocean Working Group, that developed the model as a component of CM4 (Held et al., 2019), was led by Princeton researcher Alistair Adcroft. MOM6 differs from previous generations of MOM in the use of the Lagrangian-Remap Method (LRM), applied in the vertical to permit arbitrarily general coordinates. LRM enables MOM6 to use arbitrary vertical coordinates, including the hybrid coordinates (Bleck, 2002) that better represent certain processes. OM4 and CM4 are now the workhorse models for climate change and earth system studies at GFDL.

MOM6 and OM4 have been, or are being, adopted by other national centers and universities, in addition to GFDL and Princeton. NOAA-EMC (Environmental Modeling Center) uses MOM6,
with an OM4-based configuration, for the 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 2/3° resolution configuration. CIMES researchers are collaborating with Hycom developers who in turn are helping the US Navy evaluate 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 MOM6 and OM4, and the adoption of the “open development” paradigm for code management and collaboration.

The largest remaining biases in OM4 are one focus of CIMES researchers and include the shallow depth of AMOC, weak high-latitude ocean stratification, equatorial thermocline structure, and missing water masses resulting from ice shelf-ocean interactions. Diabatic mixing in the Arctic appears to project onto two of these biases and so Princeton Researcher Sonya Legg is leading a task force looking at Arctic mixing. Other biases seem related to the algorithm, so vertical algorithm development will continue, led by Princeton Researcher Alistair Adcroft. Ice-ocean interactions are a major process in sea-level rise and water mass formation and the development of fully coupled ice shelf-ocean models is being led by Princeton Researcher Olga Sergienko.

**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 an “open development” paradigm, in which every single code change 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. OM4 was the first attempt to have end-to-end reproducibility (from model grid generation to final figures) reproducible by third parties. A key ingredient to successful open development is the use of continuous integration (testing of code 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, as well as integrating CIMES computing facilities into the continuous integration process to support the MOM6 open development community. This remains an important element of the MOM6 strategic plan.

**Regional implementations of MOM6.** A collaboration with Rutgers faculty Enrique Curchitser has successfully developed several MOM6 regional applications. Conventional methods for open boundaries have been implemented (such as the Flather and Orlanski boundary conditions) and innovations are being evaluated. Configurations span both western and eastern boundary current domains for the purpose of evaluation. Various resolutions of the North Atlantic and Arctic ocean have now been produced for science purposes and new 2 km models are planned. The Rutgers team has developed and provided a suite of tools for building and analyzing regional models. They are interested in developing new approaches to open boundaries that take advantage of the MOM6 algorithm. A regional capability in MOM6 allows high-resolution deployment of the model for ecological and fisheries applications and accelerates model development for high-resolution applications such as ocean-ice-shelf interactions. GFDL is already evaluating and using some of these regional configurations.

**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. 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 resolved flow-interactions with topography in z-coordinate ocean models. Adcroft (2013) later proposed a statistical approach to finite volume representation of topography that captures the leading order geometric effects of unresolved fine-scale topography by means of thin-walls and porous barriers. Princeton Professor Laure Resplandy and student Sam Ditkovsky have been implementing and evaluating porous barriers in a MOM6 model of the Red Sea and outflow. Further development and evaluation of porous barriers is planned, both at Princeton, CIMES researchers, and with other collaborators, to address the representation of fracture zones, impact on barotropic and internal tides, and the possibility of additional parameterization connected with unresolved topography.

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 gasses key to the climate system such as O2, CO2, 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 is being 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) and applied to gas exchange at the ocean-surface (Deike and Melville 2018, Reichl and Deike 2020) and ocean spray aerosols (Deike 2022, Deike et al. 2022). This work integrates laboratory and high fidelity simulations supported in parts by CIMES (Neel et al. 2021, 2022, Berny et al. 2021, Farsoiya et al. 2021, 2022, Wu et al. 2022). This has led to new understanding of microscale processes at the air-sea interface integrated into 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 is being applied to sea spray, momentum flux, and drag coefficient in the future. Implications of the new physics based formulations and effects of the sea state induced variability are being investigated into coupled large scale NOAA models.
A snapshot of a simulated ocean-surface wave on the verge of breaking. Shown in the backdrop is a section of the oct-tree grid used for adaptively resolving structures in the two fluids.

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 are due to standing eddies. CIMES researcher Alistair Adcroft is part of the Climate Process Team (CPT) on Eddy Energy and Ocean Transport, and he will continue to work on mesoscale eddy parameterization development, including data-driven approaches using machine learning.

OM4 has a nominal horizontal resolution of $1/4^\circ$ 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. CIMES researcher Alistair Adcroft, working with CPT postdoc Jenny Chang, are examining and explaining the impact of a negative viscosity model of backscatter. Alternative approaches which we are evaluating 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. We propose to improve MLE, accounting for heterogeneity of vertical convection (Ilicak et al., 2014). A newer formulation
of MLE by Bodner et al. (2022) has been implemented and is being evaluated in OM4. The CPT is currently examining the connection between the submesoscale and the mesoscale energy budgets. We will also explore parameterization of submesoscale instabilities associated with the bottom boundary layer adjacent to topography (Yankovsky and Legg, 2021; Naveira Garabato et al., 2019).

**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; Nazarian et al., 2021). 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, incorporating new understanding of the efficiency and location of lee-wave breaking (Legg, 2021).

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.

**Machine Learning in MOM6 and OM4.** CIMES researchers are currently working on two distinct machine learning ideas that use data in ocean models; a data-driven approach to parameterizing unresolved processes, and dynamics-discovery using unsupervised learning. In conventional development of SGS parameterizations, theory and LES simulations are used to develop closed form expressions for SGS fluxes which are then implemented in code. The data-driven approach models the same LES simulation data using a machine-learning architecture (e.g. neural networks). CIMES has developed several parameterizations that are implemented in MOM6 and being evaluated in OM4. Princeton researcher Maike Sonnewald has developed the tool THOR (Tracking global Heating with Ocean Regimes) to find dynamical regimes in ocean model data, and to predict dynamical regimes using surface data. The sensitivity of these dynamical regimes to model state can be used to understand and explain response to climate change and used for model development.

**New MOM6 capabilities and applications.** In addition to the above research and development
topics, CIMES researchers are planning new capabilities in MOM6 and related codes, along with discussing new applications. These include alternative gridding of the sphere that would allow more natural modeling of polar ice sheets (see section on Modeling the cryosphere); non-hydrostatic capabilities that could take advantage of the novel MOM6 algorithm and be used for ultra-fine regional modeling, as well as permit new process studies; past-climate ocean configurations that could test the parameterizations used in the GFDL climate models; embedding within MOM6 of machine-learning parameterizations, both for inference and training, could accelerate parameterization development; coupling between internal waves and eddies that can modulate mixing; parameterization and resolving land-ocean interactions; and simulation of ice-sheet breakup.

B: Cryosphere

The cryosphere and its interactions with other components of the climate system are represented in the GFDL ESM by the ice-sheet, sea-ice and iceberg models. All these models have been actively developed by Princeton scientists, led by Olga Sergienko, in collaboration with GFDL scientists.

Ice-sheet/ocean interactions and development of a cryosphere-ocean configuration, iOM4

In order to accurately account for strong interactions between the ocean and cryosphere (Fyke et al., 2018), an ESM requires tight coupling between these components. To achieve that, we are developing a global configuration of the ocean and cryosphere (iOM) that includes the ocean-circulation (MOM6), ice-sheet dynamics (MOM6-IS), sea-ice (SIS2) and iceberg model (iKID) components. The MOM6 ability to use multiple vertical coordinates is being 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 and is a unique advantage of the MOM6 formulation. The iOM4 configuration has ¼ degree horizontal resolution and will be used to project the ice-sheets’ contribution to sea level on the decadal to centennial timescales. Comparison between iOM4 and OM4 (with no ice sheets) will allow us to assess the effects of the ice-sheet discharge on the ocean circulation on the regional and global scales as well the effects on sea ice formation.

GFDL Ice Sheet Model, MOM6-IS

The increasing mass loss observed on Antarctic and Greenland ice sheets (Shepherd et al., 2018, Khan et al., 2022) indicate their increasing contributions to sea level and increasing impacts on densely populated low-elevation coastal areas. Remote-sensing observations show that interactions between ice shelves (floating extensions of ice sheets) and the surrounding ocean control ice discharge from the interior of ice sheets into the ocean, and as a result the magnitude and the rate of their contributions to sea level (Pritchard et al., 2012, Paolo et al., 2015). Accurate projections of the ice-sheet contributions on the decadal to centennial timescales require a tight coupling between the ice-sheet and the ocean components of any ESM. To achieve such a tight coupling, a Princeton researcher Sergienko has developed an ice-sheet model, which is a component of MOM6 (Figure 2). As the two models share the same horizontal grid, the two-way interactions between the ocean and ice shelf and the grounding line (the location where the grounded ice goes afloat) are captured as accurately as possible.
MOM6-IS is initialized using present-day observations and uses parameters (e.g., basal sliding coefficients) optimized for the present-day ice-sheet flow, based on inverse modeling techniques developed and applied by Sergienko (e.g., Sergienko and Hindmarsh, 2013; Sergienko et al., 2014). Currently, a configuration of MOM6-IS is being developed for the Antarctic Ice Sheet. We are developing a global configuration (iOM4) of MOM6/MOM6-IS, and also using the regional capabilities of MOM6 in a regional pan-Antarctic configuration to focus on the interactions of the Antarctic Ice Sheet with the Southern Ocean.

The current ice-sheet contributions to sea level are predominantly from the Greenland Ice Sheet (Khan et al., 2022). In order to account for their effects as well as project its future contributions, we will develop a configuration of MOM6-IS for the Greenland Ice Sheet, and a global configuration of MOM6/MOM6-IS that will include both Antarctic and Greenland ice sheets.

In order to accurately represent the ice-shelf mass loss caused by calving, we propose to couple MOM6-IS to the GFDL iceberg model (iKID) described below. Using this coupled configuration, we will investigate the effects of calving on the dynamics of the grounding line as well as simulate such extreme events as collapse of an ice shelf.

Parameterizations and data assimilation for MOM6-IS. Numerous processes that exhibit strong controls of the ice flow of both ice sheets are poorly known. Among such processes are basal sliding and calving. We will focus on developments of physically based parameterizations capable of accurately capturing the effects of these processes in the continental scale ice-dynamics models.

Basal sliding. Studies using stand-alone ice sheet models show that simulations with different functional forms of the basal sliding exhibit very different behavior (Sun et al., 2020). We propose to develop sliding laws that capture distinct regimes of the basal sliding (e.g., in the presence and absence of subglacial water) and transitions between these regimes. We will use inverse methods as well as machine learning techniques to establish functional forms of the sliding laws from the existing remote-sensing and in situ observations.

Iceberg calving. Despite calving of icebergs being one of the two modes of mass loss of ice shelves (Greene et al., 2022) and controlling the dynamics and stability of marine ice sheets (Haseloff and Sergienko, 2022), it is poorly understood and its representation in ice-sheet models remains very challenging. Developments in understanding of the role of ice-shelf flexure (MacAyeal et al., 2021) indicate that it plays an important role in rift formation that leads to calving. Using a formulation of ice flow and flexure recently derived by Sergienko and collaborators, we propose to develop a
parameterization suitable for large-scale ice dynamics models and implement it in MOM6-IS. We will also develop a parameterization capable of representing ice damage that is critical for the rift formation. We will test and optimize the combination of these parameterization using existing geophysical observations and satellite imagery.

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**Iceberg Model, iKID.** Icebergs transport approximately half of the mass loss from Antarctica away from the continent (Depoorter et al., 2013). As they drift away, icebergs melt and modify ocean hydrography by releasing fresh water, and affect ocean circulation on a variety of spatial scales, sea-ice formation and biological productivity. Over the years Princeton researchers have developed representation of icebergs in a global circulation model ranging from point particles representing small bergy-bits (Martin and Adcroft, 2010) to conglomerates of Lagrangian particles connected by numerical bonds representing large tabular icebergs (Huth et al., 2022). This model was used to discover a new mechanism for the break of up giant tabular icebergs (Figure 3). We propose to further develop this model and account for interactions between icebergs and sea ice, and between the icebergs and ice-shelf fronts and marine outlet glaciers.

Our recent analysis (Sergienko, 2022) shows that ice mélange (a mixture of sea ice and icebergs)
plays an important role in the dynamics and stability of marine outlet glaciers that are widespread around Greenland and Antarctic Peninsula. We propose to extend the iKID capabilities and represent mélange using the same approach of particles connected by numerical bonds.

**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. Recent improvements include a Delta-Eddington radiation scheme, revised thermodynamic algorithms with exact conservation of enthalpy, salt, and mass, and a C-grid discretization which allows for improved representation of ice transport through narrow channels. SIS2 is the critical component of the sea-ice data assimilation and prediction project of which Princeton Researcher Yongfei Zhang is the lead. The seasonal forecast of Arctic summer sea ice is very much improved by assimilating sea ice observations of concentration and thickness into a coupled ice-ocean forecast model (Zhang et al., 2022).

**Lagrangian Sea Ice and Unified Cryosphere Model.** Princeton researchers Adcroft and Sergienko explored an approach that treats ice flows as Lagrangian elements, as an alternative to the conventional Eulerian sea-ice models like SIS2. Lagrangian sea-ice models are normally too computationally expensive for climate integrations (e.g., Hopkins, 2004; Herman, 2016) but our new approach is more efficient and capable of simulating realistic behavior of sea-ice floes (Damsgaard, 2018). The model was used to study floe-floe interactions and the representation of ridging (Damsgaard, 2021) and could have advantages 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). We also propose exploring a unification of the Lagrangian models for sea-ice and icebergs, and then extending the model to represent ice shelves (Sonnewald and Lgeumsat, 2021). This would allow a natural representation of the interactions between these components and with the ocean.

**C: Atmosphere**

NOAA/GFDL’s atmospheric model development is centered around the Finite-Volume Cubed-Sphere Dynamical Core (FV3) (Lin 2004 and 2016). The nonhydrostatic version of FV3 is the basis Unified Forecast System (UFS), formerly the Next Generation Global Prediction System project (NGGPS). The UFS is designed to unify the National Weather Service’s suite of prediction models, including the operational Global Forecast System (GFS) and regional models to run as a unified, fully-coupled system in the NOAA Environmental Modeling System infrastructure. FV3 is the dynamical core of GFDL’s CMIP6 model AM4 (Zhao et al., 2018). Future CIMES contributions to atmospheric model development will have aspects that improve on the physical processes that the dynamical core is coupled to as a means of improving weather and climate simulation.

The Cooperative Institute will be contributing extensively to the fifth generation Atmospheric Model (AM5) development process. This model development cycle began in 2022 with a three-year development timeline.

The science statement of the project is that, “AM5 will help advance NOAA’s goals to increase the Nation’s ability to prepare for, adapt to, and mitigate the negative impacts of weather and climate extremes associated with an evolving climate. The focus of AM5 development is to produce a model with realistic representation of weather and climate phenomena, to improve predictions and projections from the sub-seasonal to centennial.” The goals of the development overlap extensively with CIMES and include climate extremes, subseasonal-to-seasonal timescale prediction, and regional surface climate change over the last century. As such, CIMES researchers are extensively involved.
This development cycle is comprised of nine focus subgroups spanning (in the vertical) from the land surface to the stratosphere. Each of these subgroups has participants from CIMES, including several post-docs and Associate Research Scholars. Zhihong Tan and Pu Lin (both CIMES) lead or co-lead subgroups. Zhihong Tan will play a key role in the development of the boundary layer and convection schemes. Pu Lin leads the stratosphere development and evaluation process. Over the course of the next several years CIMES researchers will contribute extensively to AM5 development and the overlapping and ensuing coupled model development. Jing Feng (CIMES) is contributing to updated the radiative transfer scheme to RRTMg.

Given the importance of precipitation and efforts to examine “gray zone” resolution moments, Pu Lin and Joseph Clark are assessing convection, convectively coupled waves, and the mean circulation in AM4 simulations that span the range of resolution from conventional GCM (≈ 50 km) to global storm-resolving models (≈ 5 km). Systematic examination of simulations over these resolutions, with the convection scheme on and off, will be valuable to configuring high-resolution atmospheric model versions that are used for decade+ long integrations. (See also the description of Unified Weather-to-Climate Atmospheric Modelling below.) Yanda Zhang will assess the precipitation changes in response to different forcings in AM4 and AM5.

D: Land

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 on-going development and application of GFDL’s land surface model LM4 will have extensive participation of CIMES researchers.

Attributes of land heterogeneity in LM4 are represented by tiles

Schematic of land model tiles (left) and the associated sub-grid heterogeneity in turbulent exchange in the planetary boundary layer (middle) and objective interactions (right), c/o Khaled Ghannam (CIMES).

On-going and future LM4 development includes assimilation of satellite soil moisture data (Noemi Vergopolan, CIMES), coupling of land and atmospheric subgrid heterogeneity (Khaled Ghannam and Zun Yin, CIMES), nitrogen downregulation of carbon uptake in forest (Isabel Martínez Cano, CIMES), and investigating the effects of irrigation and orographic scaling for surface climate (Yujin Zeng).

There will be LM4 development that focuses on the atmospheric coupling. First, GCMs tradi-
tionally use Monin-Obukhov similarity theory to model turbulent exchange between canopies and the atmosphere. This, however, underestimates drag coefficients because of the canopy sublayer. Updating the wind profile in the sublayer will affect tracer deposition, such as ozone. Second, the development of eddy diffusivity mass flux (EDMF) planetary boundary layer scheme for AM5 faces choices about how to account for the land model tiles—representing land surface heterogeneity—that exist within an atmospheric grid cell (see illustration of land model tiles in schematic below).

There will also be land model improvements to capture complex topography and snow. Topography’s three-dimensional nature modulates solar radiation over land, which, for example, modulates direct radiation incident over mountains. The GFDL land-atmosphere-snow scheme (GLASS) will be updated to link the grain properties of the snowpack with the albedo parameterization, using ‘SnowMIP’ sites located in the northern hemisphere extratropics for evaluation. These land model advances will affect the surface albedo and its climate climate state dependence.

E: Biogeochemistry

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 both physical–chemical and biological 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 CaCO$_3$ 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.

Over the renewal period, there will be developments to COBALTv2: Second generation comprehensive 30 tracer Carbon Ocean And Lower Trophics (COBALT) ecosystem implemented in ESM4.1 (Stock et al., 2020) and BLINGv2: Second generation 6 tracer version of TOPAZ-like ecological parameterization of Biogeochemistry with Light, Iron, Nutrients and Gas (BLING) implemented in CM4.0 (Dunne et al., 2020). This will address biases in BLINGv2 that include structural ones of regional and biases in the spatial structure in phosphorus and hypoxia. ESM4.1’s biases include some areas of too large phosphorus limitation and open ocean hypoxic regions, as well as subsurface iron concentrations exhibited reduced values in oceanic oxygen minimum zones, and regional NPP and chlorophyll biases. On-going development will address the climatology and how the response to anthropogenic emissions is affect.

One avenue of ESM development is to develop a trait-based representation of zooplankton diversity and its role in the carbon cycle and marine food webs, and to parameterize this diversity for computationally tractable simulations of climate responses and feedbacks. The ecophysiological framework will link empirically-calibrated physiological traits for temperature and size-dependent metabolism and oxygen (O$_2$) tolerance, to the biogeography of marine species (C. Deutsch, and Justin Penn, Princeton Geosciences). This effort will interface with projects underway to add zooplankton behavior to the GFDL ecosystem model COBALT.

F: Coupled and high-resolution models

GFDL’s CM4, a coupled model of the physical climate (Held et al., 2019), that participated in the CMIP6 process consists of:
1. AM4 atmosphere at approximately 1° resolution with 33 levels and sufficient chemistry to simulate aerosols (including aerosol indirect effect) from precursor emissions

2. OM4 MOM6-based ocean at \(\approx 1/4°\) resolution with 75 levels using hybrid pressure/isopycnal vertical coordinate

3. SIS2 sea ice with radiative transfer and C-grid dynamics for compatibility with MOM6

4. LM4 land model with dynamic vegetation

With this foundation for further CIMES coupled model research and development, the renewal will (i) configure higher horizontal resolution versions of CM4 and (ii) incorporate the advances in component models (e.g., AM5) into the coupled models. We describe the proposed horizontal resolution efforts here. As stated above, the CIMES coupled model development process will proceed in an overlapping phase of AM5 development.

CM4-hires Task Force was initiated in 2020 and reached a \(1/8°\) ocean horizontal resolution with a \(\approx 1/2°\) atmosphere horizontal resolution configuration in summer 2022. The goal of this high-resolution coupled modeling initiative is to address un(der) resolved scales. There are several scientific questions that this coupled model will be used to investigate. These include ocean heat uptake and the associated global thermosteric sea level rise, as well as regional sea level changes (especially on better resolved continental shelves). The mesoscale eddy effects on heat uptake in transient simulations, ocean heat waves and coastal processes are areas of simulation resolution dependence that this CM4 configuration will be used for.

A particular area of interest for this high-resolution model is in the subpolar-to-polar climate dynamics. In the Southern Hemisphere, these include better resolving the Southern Ocean dynamics with a resolved Antarctic Slope Current and the coupling to ice shelves (ice shelf cavities, in particular). In the Northern Hemisphere, this includes capturing the eddy processes that affect the Atlantic Meridional Overturning Circulation’s mean state, its temporal variability, response to perturbations, and connections to the Arctic climate. As also described in the context of high-resolution atmospheric modeling, this \(1/8°\) ocean resolution can be taken as a “truth” for parameterization development, where there will be further research stemming from the Climate Process Team on Ocean Transport and Eddy Energy (Adcroft and C.-Y. Chang, both CIMES)

3.3.2 Theme: Seamless Prediction across Time and Space Scales

Here we focus on two different aspects of prediction across time and space scales, the predictability of different weather and climate phenomena on the seasona-to-decadal timescale (part A) and the very high resolution modeling necessary to resolve extreme weather phenomena (part B).

A: Seasonal-to-Decadal Prediction

Seasonal-to-decadal prediction is an important component of developing and delivering actionable information to society. The development and use of SPEAR, Seamless System for Prediction and EArth System Research, is a key and on-going focus of Cooperative Institute research. In fact, the scope of SPEAR is a more ambitious one: from subseasonal to centennial.

SPEAR was developed as a next generation GFDL modeling system for seasonal to multidecadal prediction and projection. SPEAR real-time seasonal predictions were made available as part of the North American Multi-Model Ensemble (NMME) in winter 2021 and SPEAR decadal predictions will be made available as part of an international decadal prediction program through the UK Met Office (decadal forecast). Additional data from the SPEAR large ensemble, described in Delworth
et al. (2020) is available through the GFDL Data Portal. Previously, the GFDL CM2.1 and FLOR models were used for real-time seasonal-to-decadal prediction and research.

The SPEAR models share many components with the recently developed GFDL CM4 (Held et al., 2019) model but with configuration and physical parameterization choices in SPEAR geared toward physical climate prediction and projection on seasonal-to-decadal timescales.

Here we provide an overview of two timescales of future research using this new coupled prediction system will be used for in the next five years: seasonal prediction vs. decadal and climate timescale prediction.

Seasonal prediction efforts will focus on coupled ocean-atmosphere predictions, where the El Ninó-Southern Oscillation is a longstanding phenomena of interest because of its slowly evolving nature and the knock-on impacts on seasonal hydrological and atmospheric prediction. The atmospheric phenomena of interest include tropical cyclones, midlatitude weather extremes from baroclinic waves and atmospheric rivers, as well as coupled land–atmosphere extremes such as heat waves. There is also substantial scientific and social interest in seasonal sea ice forecasting. Here, SPEAR will continue to participate in the Sea Ice Prediction Network, as recently initiated by Yongfei Zhang (CIMES).

As a seamless prediction system, the same SPEAR models, which include atmospheric resolutions that vary from 0.25° to 1°, will be used for decadal prediction and large-ensemble climate simulations. Briefly, this seamless system enables innovative research, as follows: The on-going and future model evaluations offered by real-time predictions, where SPEAR has competitive skill levels, lend credibility to model projections. Model projections, in turn, provide references and implications for predictions. Predictions at different timescales help validation and attribution. The phenomena of on-going and future research include the seasonal-to-decadal variability of the Kuroshio extension, decadal variability of the Southern Ocean, and high-impact weather events such as atmospheric rivers and tropical cyclones. The seamless system allows for timely research about categories of events with acute society impacts, such as the recent South African drought where water resources in Cape Town reached new lows (Pascale et al., 2020) or the recent unprecedented heat waves in western North America.

B Unified Weather-to-Climate Atmospheric Modelling

SHiELD is a Unified Forecast System (UFS) prototype atmosphere model showing the power of a unified prediction system across a variety of time and space scales designed for a wide array of applications. It shows the abilities of the Finite-Volume Cubed-Sphere Dynamical Core (FV3), especially its flexible nonhydrostatic dynamics, variable-resolution capabilities, and integrated physics, coupled with the elegance of the Flexible Modeling System (FMS) framework. Improvements in FV3 or the physics in SHiELD can be easily transferred into other FV3-based models, including the GFDL Modeling Suite and the Unified Forecast System.

SHiELD is an open-source model with code and drivers available on GitHub. A container, SHiELD-in-a-Box, is also available for convenient portable usage of SHiELD. Multiple real-time configurations have been developed and this will be an on-going aspect of atmospheric modelling for seamless prediction. Kai-Yuan Cheng, Linjiong Zhou, and Kun Gao (all CIMES) lead global, continental U.S., and tropical prediction systems. Additional overview is available at https://www.gfdl.noaa.gov/shield/, and we reproduce the schematic showing the SHiELD model family below.
C-SHiELD is a Contiguous United States nested model used for prediction of high-impact weather events, especially severe thunderstorms and heavy precipitation. This model is capable of simulating individual convective storms without a parameterization, thereby giving better information on the impacts of these events. The global-nested configuration of C-SHiELD allows it to make useful predictions much farther in advance than do limited-area prediction models typically used for convective-scale prediction, allowing for unique medium-range prediction of these events. C-SHiELD is contributed in real-time to the Hazardous Weather Testbed’s Spring Forecasting Experiment every May. A lower-resolution version of C-SHiELD will be used to explore subseasonal prediction of severe thunderstorm outbreaks.

The SHiELD models include a telescoping nest capability. As shown in the figure above, Joseph Mouallem (CIMES) has recently used for this tropical cyclone research, where the rainbands of an individual are better simulated as a consequence of the improved resolution in the inner nest.

This unified SHiELD model family will contribute to the emerging area of $k$-scale (for kilometer scale horizontal resolution) or global-storm resolving modelling (GSRM). X-SHiELD is an eXperimental Global Storm Resolving Model (GSRM) run at a sufficiently high global resolution to explicitly simulate individual convection cells. X-SHiELD is GFDL’s contribution to the DYAMOND (the DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains) intercomparison, the first international intercomparison of GSRMs. There have been two cycles of this intercomparison to date, and X-SHiELD will continue to participate in the forthcoming rounds.

3.3.3 Theme: Earth System Science

Analysis and applications of GFDL ESMs allow for progress on a wide variety of societally-relevant climate and environmental problem is a key CIMES theme. GFDL ESMs include atmosphere, land, cryosphere, and ocean components and have contributed to many model intercomparison projects including CMIP. These world-leading modeling approaches offer capability for high-impact applica-
tions. The earth system models developed in collaboration with GFDL will be applied to research societally-relevant climate problems during the next five years. 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 including extreme events to natural and anthropogenic forcing (an application of the predictability methodologies described in the previous section). 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.

Air Quality Applications
The capability of simulating atmospheric composition, including both atmospheric chemistry and interactions with the biosphere is an important capability that allows for the investigation of air quality interactions with the earth system.

Tropospheric ozone is important as a greenhouse gas, has consequences for the health of humans and vegetation, and plays an important role in the atmospheric chemistry of pollutants and reactive greenhouse gases. The ability of ESM4 to simulate the tropospheric ozone will allow for assessments of the role of anthropogenic precursor emissions in historical simulations, as well as future projections. Quantifying the regional “climate penalty” of near-surface ozone in climate change scenarios depends on the climate change and variability that arise from vegetative feedbacks, such as drought stress.

GFDL ESMs have been applied to understand links between climate change and air-quality by Yuanyu Xie and Meiyun Lin, focusing on the role of biosphere-atmospheric interactions on air pollution through particulates from wildfires (Xie ., 2022). The connection of wildfires to air quality has substantial implications for human health and the ability of ESMs to make wildfire projections will improve.

The stratospheric composition will also be a focus in ESM development and applications. The most prominent constituent, ozone, has been a focus of ESM applications both because of the human health impacts of the ozone hole, but also because of the possibility that there are stratospheric feedbacks to anthropogenic climate change. The interactions between stratospheric ozone and the stratospheric circulation are an outstanding challenge to represent, which Pu Lin (CIMES) will lead an initiative to address in AM5 development. In addition, an interactive scheme for the stratospheric sulfur cycle is being developed (C. Gao, CIMES).

Extreme Weather Events and Drought
The renewal will build on and extend existing CIMES research into 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, Elie Bou-Zeid, Amilcare Porporato, and Mark Zondlo.

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 and Ning Lin address key areas of tropical cyclone modeling and hazards.
There has been an ongoing interest in tropical heat stress that connects theories for the atmospheric thermal structure to the magnitude of dew point or wet bulb temperatures, which capture the combined role of temperature and humidity on the physiological response of humans to climate change.

We note that the ESM applications to weather extremes are often driven by dramatic observed events (Superstorm Sandy in 2012 or Hurricane Ida in 2021) and novel extreme weather events will be the subject of future modeling and attribution CIMES research. The flooding of Hurricane Ida’s remnants and their connection to an increase in atmospheric rivers (James Smith, Princeton) and the extratropical track of Ida (Gabe Vecchi, Princeton) are the subject of research that will continue over the next couple of years.

Given that SPEAR is a coupled prediction system, it is well suited for attribution research and the multiple resolution configurations allow for assessment of topographic dependence of precipitation. Two examples of research under way that will continue during the renewal focus on i. snowpack and ii. precipitation extremes. One historical and on-going CIMES focus has been snowpack and climate. From then post-doc and current NOAA Chief Scientists Sarah Kapnick through recent CIMES researcher Abigail Lute, research on historical and future changes in snowpack have been underway because of the profound consequences for regional watersupply. Comparative medium and high resolution SPEAR model analysis is a valuable technique to isolate the role of topography. In the SSP585 scenario, elevation dependent trends in historical and future winter air temperatures are found across the domain such that higher elevations warm more quickly than lower elevations, with important implications for snow sensitivity to climate change in this region. Whereas historical trends (1940-2014) in annual peak snow water equivalent (SWE) were spatially variable, future trends in peak SWE (2015-2100) were negative, despite increasing winter precipitation in some basins. The greatest declines in maximum SWE were found at mid-elevations. The time of emergence of anthropogenic climate change signals were examined in a variety of climate and snow metrics. For Northeast U.S. precipitation extremes, Bor-Ting Jong (CIMES) is assessing the fidelity of SPEAR across resolution over recent decades. She is also analyzing the extent to which the simulation of TC statistics are essential to capturing the observed changes in extreme precipitation in this region.

CIMES researcher Yujin Zeng has applied GFDL ESMs to understand the links between irrigation and precipitation, finding that irrigation in the Middle East and South Asia may enhance rainfall in a large portion of the Sahel-Sudan Savanna (SSS) to an extent comparable and opposite to its suppression by other anthropogenic climate drivers during the last several decades (Zeng et al., 2022). The enhancement arises through a reduction in the meridional gradient of moist static energy from the Sahara Desert to the tropical rainforests. Remote irrigation is therefore a possible factor affecting the risk of drought and famine and, thus, future water security in the SSS region. Extreme heat is another societally-relevant impact of climate change being examined by CIMES researchers, including projections of tropical heat stress under global warming (Zhang et al., 2021) and the role of historical urbanization in the extreme heat wave event in the Pacific Northwest of North America in the summer of 2021 (Philip et al., 2021).

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
Ocean ecosystems are an important area of ESM development (see proposed zooplankton description above) and their application and evaluation will be an important aspects of CIMES research. One area of future investigation concerns the evaluation and application of ESMs to climate variability (e.g., how do models compare to observations available on the interannual timescale?). Research into tropical changes from ENSO variability has begun, with ESM4 showing post ENSO chlorophyll rebound (H.-G. Lim, CIMES). For fish stocks, ESM-based research will continue to investigate how aspects of physical climate, such as ocean bottom temperature variability, influence ecosystems (du Pontavice, CIMES). This is illustrated in the summary below.

**Illustration of ESM-based ecosystem research from du Pontavice et al. (2022): interannual variations in bottom temperature (top right) influence recruitment (bottom right) in age-structured stock assessment model, improving retrospective recruitment and biomass patterns (top left).**

ESM-based marine ecosystem research will also have branches that focus on forced changes. Moving from historical simulations, which allow past climate fluctuations to be related to contemporary patterns and trends, from centennial-scale projections of future conditions enables the climate impact on ecosystems to be assessed. This, in turn, has consequences on management scenarios. One prominent example of long-term changes is those of the oxygen minimum zones (OMZs). ESMs projections have a robust expansion of the vast volume of OMZ in Pacific (L. Resplandy, Princeton). This OMZ change has knock-on effects on ecosystems that will be investigated.

### 3.4 Catalytic CI Activities

The Cooperative Institute has an administrative structure with three Tasks and three Themes of Research Projects. Overlaid on this nominal organizational and scientific structure are catalytic CI activities that span across these and extend beyond them. There is a key strategic role of CIMES in the PU-NOAA collaboration: it adds agility, serving as an incubator or accelerator for new research projects, new collaborations through invitations and workshops, short-term visitors, short-term opportunities etc.

Here, we describe two major aspects of catalytic CI activities. First, the ambitious science
fostered by the acquisition of the HPC platform Stellar and future HPC-related Princeton University opportunities that the CI will pursue. Second, plans and activities to broaden the scope of the CI, both within the Princeton University-GFDL context (e.g., new university–GFDL collaborations) and in the research-community facing direction (e.g., hosting workshops with world-leading scientists).

### 3.4.1 Stellar HPC Platform

**Status and Accomplishments:** As described in section 2, the Stellar HPC platform was acquired in July 2021. In the intervening $\approx 18$ months, several key Earth System Model components have been installed and used for Cooperative Institute research. These include atmospheric models (AM4, SHiELD, and GFDL’s spectral core), ocean models (MOM6), ocean biogeochemistry models (MOM6-COBALT), and the land model (LM4). In addition to these massively parallel forward models that use CPUs, there have been a number of users who make use of Stellar’s GPUs, primarily for the machine learning algorithms.

This platform is also serving as an incubator for new partnerships. The rapid ability to on-board new users through Princeton University has facilitated several partnerships to date, with more over the next five year cycle.

**Machine Learning/Artificial Intelligence Approaches for Earth System Modelling:** Emerging machine learning/artificial intelligence applications in earth system modelling have been one recent locus of activity that will grow going forward. On the atmosphere side, the Allen Institute for Artificial Intelligence partnership with Princeton University and GFDL to use XSHiELD as a fine-resolution “truth” to augment traditional parameterizations in coarse-resolution simulations will grow in scope (new CIMES hire M. Radko started in winter 2023). On the ocean side, multiple CIMES Stellar users will make use of GPUs for ML training (M2Lines with NYU and MIT).

**External Research Partnerships for Earth System Modelling:** The catalytic role of this platform will also include traditional process-oriented science of the atmosphere, ocean, cryosphere, and land surface.

The National Science Foundation’s Partnerships for International Research and Education: International Partnership for Cirrus Studies (https://www.pire-cirrus.org/) will continue over the next two years. Cirrus clouds are critically important aspect of the planet’s energy balance, yet are challenging to simulation and parameterize. How well next generation atmospheric models capture these clouds will be an important multi-institution use of Stellar (enabling analysis of simulations performed at the University that are cumbersome to disseminate via conventional channels due to their size. Collaborators from Harvard University involved in the partnership have access to the platform.

Stellar will be used for MOM6 regional development in partnership with scientists at other (non-Princeton, non-GFDL) institutions (E. Curchitser, Rutgers University and K. Hedstrom, University of Alaska).

Finally, there will be research that uses idealized climate models, a longstanding hallmark of CI activity. An international collaborator, Pablo Zurita Gotor (Universidad Complutense de Madrid), has ported an idealized atmospheric model, based on the GFDL spectral dynamical core to Stellar. This class of climate model has formed the basis for several Cooperative Institute-supported AOS program Ph.D.s and will be used for both research—continuing to bridge its parameterizations with GFDL’s comprehensive AM class of models—and educational aspects of the CI activities (e.g., via the AOS program). Along these lines, the installation and use of codes to perform one-dimensional calculations will catalyze rapid, prototype-style research. In particular, the radiative transfer model RRTMG, which will be used in AM5, is a tool that is used for both research and education and will be used by CI researchers interested in radiative forcing and feedbacks.
Outlook: The Stellar HPC platform will continue to evolve via additional hardware purchases that meet the needs of the growing userbase. Beyond the existing and planned ESM software capabilities, future opportunities include coupled climate modeling and expanding the availability of publicly disseminated datasets (for example, common repositories of Coupled Model Intercomparison Project simulations and atmosphere and ocean reanalysis products and state estimates). Combined with a rapid account creation process that is open to wider group of scientists, Stellar will catalyze CIMES research in the next five years.

3.4.2 Coordination Across Disciplines within the University

The Cooperative Institute is a key mechanism by which the rapidly evolving frontiers of science and prediction that extend beyond NOAA’s existing operations can be initiated, vetted, and potentially enfolded into the mission. A key means of catalyzing these activities are the flexibility to rapidly onboard talented recent graduates on a short timescale (e.g., at the post-doctoral fellow career stage). This flexibility allows the CI to be a hub for targeted funding by NOAA.

One aspect of the university community that will grow in the future is the collaboration across disciplines. Active support by CIMES (particularly through Task III) broadens the scope of ESM research beyond the existing realms of physical and biogeochemical dimensions of climate science. Here, we describe three forward looking paths toward cross disciplinary cooperation:

First, Princeton University’s Andlinger Center for Energy and the Environment at Princeton University is a multidisciplinary research and education center, with the mission of developing technologies and solutions to secure our energy and environmental future. CIMES will be a pathway for facilitating research that encompasses this solution-oriented research which relies on the core modeling and prediction capabilities of GFDL.

Second, there is extensive policy expertise at the University in the Princeton School of Public and International Affairs. SPIA is dedicated to integrating world-class scholarship and a commitment to service in order to make a positive difference in the world and is home to climate policy experts. There is an existing relationship on the educational side of Princeton’s AOS program via the graduate certificate in Science, Technology, and Environmental Policy (STEP), which many Ph.D. students have completed. Going forward, the CI aims to facilitate opportunities to bridge the disciplinary divides between these world-class policy scholars, including justice and equity dimensions, and the realms of climate science that GFDL excels.

Third, the High Meadows Environmental Institute (HMEI) at Princeton University advances understanding of the Earth as a complex system influenced by human activities, and informs solutions to local and global challenges by conducting groundbreaking research across disciplines and by preparing future leaders in diverse fields to impact a world increasingly shaped by climate change. HMEI is a vibrant central resource for the university community interested in environmental topics and research, with more than 140 members of the Princeton faculty, representing 30 academic disciplines. HMEI’s director is CIMES Deputy Director Gabriel Vecchi, which ensures a close connection between this broad range of university researchers and the Cooperative Institute. CIMES will foster HMEI-GFDL connections via Task III funding. The previously funded climate–disease research (Baker et al., 2020) (including Metcalf and Vecchi) is a clear example of how this connection accelerates time-sensitive research.
3.4.3 Coordination with the Earth System Modeling Scientific Community

Workshops and Events: CIMES has routinely been host for workshops and events that connect Princeton University and GFDL and the broader international scientific community. These agenda-setting activities are often supported by Task I funding (e.g., in the form of time contributions of Task I-funded employees) and may also be aspects of Task III-funded projects.

Here, we highlight examples over the last five years of CIMES as representative of the types of events that will be supported in the next five years. We note that this time period included the COVID-19 pandemic:

1. WCRP/Tri-MIP Workshop Tri-MIP-athlon-2 The second joint AerChemMIP / RFMIP / PDR-MIP Workshop in support of CMIP6 in June 2019 with Local Organizing Committee: David Paynter, Vaishali Naik, and V. Ramaswamy (all GFDL) and Anna Valerio (AOS) http://splash.princeton.edu/trimip/

2. 4th Workshop on Physical-Dynamics Coupling in Weather and Climate Models in June 2022 with local hosts Lucas Harris (GFDL) and Anna Valerio (AOS) (http://splash.princeton.edu/pdc2022/)

3. From Spectroscopy to Climate in August 2022, organized by Stephan Fueglistaler and Tim Merlis (both CIMES, https://pcts.princeton.edu/events/2022/spectroscopy-climate)

Local Meetings and Series:

CIMES personnel lead and extensively participate in multiple new and ongoing catalytic, cross-lab and university meetings and series. The following are emerging or on-going and will continue over the upcoming years. Note that these are distinct from the array of model development meetings and are focused on key CI science topics.

In 2020, the GFDL Climate Sensitivity Journal Club was re-initiated, and it has been organized by Zhihong Tan (CIMES) from Fall 2022 onward. This topic is, of course, a core research focus of CIMES research and spans atmosphere, ocean, cryosphere, and land research and has about 60 participants.

In summer 2022, Timothy Merlis (CIMES) initiated a biweekly cross Princeton University–GFDL Atmospheric Dynamics meeting with approximately 30 participants. This meeting spans University researchers and three GFDL divisions.

In fall 2022, Mitch Bushuk (GFDL) initiated a monthly polar climate interest group with approximately 40 participants (including a substantial CIMES contingent), again spanning atmosphere, ocean, cryosphere, and land researchers.

3.5 Education and Professional Training of the next Generation Experts

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. 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 NOAA research at GFDL and elsewhere, has already been documented in Section 3.1.

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 postgraduate programs are given in the following two subsections, followed by a third section describing other ongoing and proposed education and outreach activities.

### 3.5.1 The 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 qualifying exam (consisting of an oral presentation and written report of their research project) 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. Students have 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, 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. Specifically, the program has a long-standing track record of gender balance.

Following the Princeton University Best Practices for Diversity ([https://gradschool.princeton.edu/academics/opportunities-resources-support/advising-mentoring](https://gradschool.princeton.edu/academics/opportunities-resources-support/advising-mentoring)) several new initiatives for increasing recruitment from historically underrepresented minorities have been established (ie., Visiting Faculty Exchange Fellowships and student summer internships, described in Section 3.5.3). 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 (see also Section 3.6.)
3.5.2 The AOS Postdoctoral and Visiting Scientist Program

Overview. The majority of CIMES research is and 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, senior CIMES researchers, and Princeton faculty. 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. As noted above, roughly half of the PhD students currently hold (or held) faculty appointments at leading national and international research Universities, and about a quarter work at national research laboratories sponsored by NOAA, NASA or DoE; with similar numbers for former postdoctoral researchers.

The AOS postdoctoral and visiting scientist program is making a concerted effort to increase diversity and broaden participation from under-represented groups. As of February 2023, Princeton University \(^1\) reports the following demographic breakdown: Graduate students enrolled in the AOS: 48% identify as female, and 17% identify as Black, Hispanic, Native American, or Native Hawaiian / Pacific Islander. For the postdoctoral program, the corresponding numbers are 38%, and 11%.

Following the Princeton University Best Practices for Diversity, 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. These are:

(i) An annual, widely-advertised open competition which invites applicants to submit a short proposal for research based at GFDL, in collaboration with a technical host at GFDL. Applications are evaluated based on the applicant’s research record and potential, and 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 about 5 appointments per year.

(ii) 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 (see also Section 3.4). For hiring in response to NOAA targeted funding, the position advertisement specifies the desired expertise, and the evaluation of the application is carried out with focus on the needs of the specific project, and with close consultation with the GFDL scientists working on the specific project. For this type of appointment, the number of hires varies greatly according to the availability of funding. We expect to typically appoint between 5 and 15 Postdoctoral researchers per year through this route.

(iii) 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.

\(^1\) Diversity & Inclusion Academic Department Dashboards; retrieved February 27, 2023.
In addition to the AOS postdoctoral appointments described above, an additional route for post-doc appointments supported by NOAA would be through the Cooperative Institute using Task III (competitive proposals submitted to CIMES) funds to support collaborative research between NOAA GFDL and Princeton University faculty (see also Section 3.6.)

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 CIMES leadership in close consultation with the NOAA hosts. 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 of the projects the appointees work on. 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 where GFDL expressed strong interest in keeping their expertise beyond the typical postdoctoral appointment.

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 host. 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 based on alignment with NOAA/GFDL goals, 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.

3.5.3 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 (see Section 3.6.2) 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. Further details, including the most current (2023) round of applications are available at https://cimes.princeton.edu/education-
Cooperative Institute Visiting Faculty Exchange Fellowships. 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. The successful start of the program with visits by Profs. Randye Rutberg (CUNY Hunter) and Monika Sikand (CUNY Bronx Community College) experienced a halt due to the COVID pandemic, but will resume as Federal buildings have become accessible again. Further information is available at https://cimes.princeton.edu/education-outreach/visiting-faculty-exchange-fellowships.

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, and we plan to continue the institutes at the same frequency under CIMES funding.

New Jersey Ocean Fun Days. The Cooperative Institute 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, CIMES 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.

Additional K-12 outreach activities. Several CIMES researchers and students undertake additional K-12 outreach activities, including talks and laboratory demonstrations to schools and community groups, for which the CIMES 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. In order to facilitate and provide capacity for innovative collaborations, and to better communicate GFDL/Cooperative Institute science to a wide range of interested parties, individual workshops and symposia will be supported by CIMES on a case-by-case basis. While the COVID pandemic has led to a halt of such activities for more than 2 years, CIMES
has contributed support to three workshops in Princeton related to CIMES supported research: The WCRP/Tri-MIP Workshop Tri-MIP-athlon-2 in support of CMIP6 in Princeton in June 2019 (see http://splash.princeton.edu/trimip/).

The 4th Workshop on Physics and Dynamics Coupling in Weather and Climate models (June 1-3, 2022; see http://splash.princeton.edu/pdc2022/), and the Spectroscopy to Climate workshop hosted at the Princeton Center for Theoretical Science (August 22-24, 2022; see https://pcts.princeton.edu/events/2022/spectroscopy-climate).

### 3.6 Business Plan

#### 3.6.1 Organization

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

**Organizational structure of the Cooperative Institute for Modeling the Earth System (CIMES), and relation to the AOS program.**

**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). 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 Postdoctoral researchers, the external CIMES review in 2022, and past reviews.

**CIMES Director and Deputy Director.** Stephan Fueglistaler (Director) is a Professor of Geosciences at Princeton with joint appointments in the Department of Geosciences (GEO) and AOS. He has over 20 years of experience in climate-related research, and has served as Director of the AOS Program since 2015, and Director of CIMES since 2021. Gabriel Vecchi (Deputy Director) is a Professor of Geosciences and the High Meadows Environmental Institute (HMEI) at Princeton University. He was formerly the head of the Climate Variations and Predictability Group at GFDL.

**Executive Board.** We propose that the CIMES leadership continues to be advised by a single Executive Board that encompasses both the management and budgetary responsibilities described in the 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 is 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 evaluation of and advice on CI development, program strategy, research plans, and comment on the annual progress reports prepared by CIMES staff. The Executive Committee advises on resource allocation, research and technology coordination, and the overarching goal of regional and disciplinary integration.

The CIMES Executive Board will be appointed upon successful renewal of the Collaborative Institute. Members of the executive board shall be the Director of CIMES, the Deputy Director of CIMES, the Director of AOS, the Director of GFDL, and additionally two tenured Princeton University faculty and two GFDL scientists.

Management and Staff. Responsibility for management of CIMES lies with the Director (Stephan Fueglistaler) and the Deputy Director (Gabriel Vecchi), who are listed as the Principal Investigators for this proposal. (Fueglistaler is the Principal Investigator and Vecchi is Co-Principal Investigator).

The budgeted support staff for administrative and fiscal oversight for CIMES comprises support for a suitability coordinator (working directly with GFDL), a project manager, and a part-time communications coordinator. (See also Attachments: Total Budget.) Additional support for staff is provided by Princeton University.

CIMES manages and supports currently about 50 researchers and postdocs, and about 10 Graduate Students in the AOS program. We expect that in particular the number of postdoctoral researchers further increases in the coming years, particularly also through Targeted Funding Opportunities.

In response to continuing massive growth of the CIMES budget (Proposal FY23-28: $17M/year, CIMES FY18-22: $8.6M/year; Cooperative Institute for Climate Sciences, FY 2012-2017: $3M/year), and NOAA’s requirements for managing Cooperative Institutes, two new positions have been created. The Manager Science and HPC (Tim Merlis) manages the computational resources of CIMES, and actively promotes and supports ongoing and new collaborative research projects between GFDL and Princeton University (supported primarily through Task III).

The Technical and Software Engineer (currently vacant) works with the Manager Science and HPC on all aspects of the CIMES HPC system, as well as planning and operational implementation of services related to the cross-theme “Catalytic CI activities”.

The Project Manager (currently vacant) supports the CI Director and AOS Manager in all administrative aspects of the Cooperative Institute. In particular, the Project Manager oversees, manages and follows the professional development of the 50+ research scientists and Postdoctoral researchers. The Project Manager is further responsible for the CIMES Annual Report, and actively promotes the mission of CIMES through liaising with NOAA GFDL and OAR leadership, Princeton University faculty and staff, and active communication of research accomplishments of CIMES scientists.

### 3.6.2 Funding Tasks

NOAA Cooperative Institutes typically break down their functions and budgets into three types of ‘tasks’ and related organizational structures (see also Attachments: Total Budget.)

**Task I:** Administration, Education and Outreach The activities under Task I will be carried out by the AOS Program.

**Task IA:** NOAA funding for Task IA will support a total of 3 months for the Director and Deputy Director. Further, Task IA will support the CIMES Project Manager, the CIMES
Science and HPC Manager, the Suitability Coordinator and the Communications Coordinator. Further, Task IA supports travel to attend the annual Cooperative Institute meeting, and other meetings NOAA may wishes CI leadership and staff to attend.

**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.

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

One of the most important and successful tasks of the Cooperative Institute has been the postdoctoral, 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.

All appointments are made in the AOS Program by the AOS Director upon recommendation by the CIMES Director, and after consultation with GFDL hosts and mentors. An annual advertisement for scientists would be broadly placed to attract highly qualified scientists to join the CI supported by base funding, while job openings related to Targeted Funding will be advertised whenever needed, and with a specific description of the opening.

The criteria used to evaluate applications 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.

Students advised by GFDL scientists are usually funded by Cooperative Institute Task II research funds. 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. In addition to the students advised by AOS faculty, on occasion students have also been, and likely will be, working with faculty in Applied Math, Geosciences, and Engineering on research relevant to CIMES’ research themes. Arguably, the partnership between Princeton University and NOAA has been one of the most successful collaborations of this nature in the country.

Finally, Task II provides a contribution to CIMES HPC resources.

**Task III:** Principal Investigator led research projects. Task III projects fall within the themes of CIMES, usually involving 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. Further details are provided in Section 3.6.4.

### 3.6.3 Strategic Planning and Project Coordination

Strategic planning would be undertaken by the 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 for example 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. 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.

### 3.6.4 Task III Science

CIMES Task III supports collaborative research projects in support of CIMES’ mission that emerge from conversations between GFDL and Princeton scientists where both parties recognize high potential for groundbreaking research arising from combining the expertise and resources of the two institutions. The CIMES Science Review 2022 (see Attachment: CIMES Science Review 2022) strongly recommended increased support for Task III projects. Correspondingly, the proposed budget allocates approximately $1M/year from NOAA, and Princeton University agreed to provide an annual cash support of $300k and an in-kind support (waived overhead) of $600k per year. In total, this proposal thus allocates funding of nearly $2M per year for Task III, a substantial increase (as suggested by the Science Review 2022) from the previous budget of $725k per year.

Task III funding provides salary for Postdoctoral Researchers and Graduate Students (but not PIs), conference attendance and publications costs. In addition to providing support for researchers, we propose to also provide financial support for ad-hoc visits of guest researchers of interest to NOAA/GFDL and Princeton University, and for collaborative workshops such as the workshops in 2019 and 2022 with partial support from CIMES (see Sections 3.4.3 and 3.5.3.)

Finally, CIMES provides access to HPC resources for collaborative projects through Task III; the projects may be funded by CIMES or other funding sources, but must be collaborative in nature, and have scientists from NOAA/GFDL and Princeton University involved.

Application for all funding through Task III requires a proposal with well-defined organizational structure and roles for scientists at NOAA/GFDL and Princeton University. For collaborative research projects and access to HPC resources, CIMES provides a proposal template. Calls for collaborative research project are generally issued annually, but in situations where rapid funding may be crucial, CIMES may announce more than one call for proposals per year. For example, transmission of pathogens such as COVID may be sensitive to climatic conditions, and in case of an emergency a rapid assessment is required (CIMES provided support and climate expertise for Princeton University public health experts during the COVID pandemic.)

CIMES project proposals are rigorously evaluated in a peer-review process. Reviewers are selected based on expertise primarily among GFDL, CIMES and Princeton researchers. A review template ensures that the proposals are evaluated with respect to CIMES’ mission. Specifically, proposals are evaluated for scientific excellence and likelihood of publications, career advancements of supported graduate students and PostDocs, alignment of the proposed research with NOAA’s and CIMES’
goals and science themes, leveraging synergies between NOAA/GFDL and Princeton University, and feasibility of the proposal research with the requested resources. Funding decisions by the CIMES Director and Deputy Director are based on the reviewers’ recommendations. The CIMES Executive Board may be consulted in cases of ambiguous reviews or potential conflicts of interests, and the funding decisions are reported and discussed with the Executive Board at the annual board meeting.

In cases where collaborative projects strongly benefit from external expertise, CIMES may also support subcontracts to other academic institutions. In such a situation, 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 Chichitser 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.

3.6.5 Fiscal Management and Accountability

Within the University as a whole, compliance with all government regulations is achieved by the combined efforts of the AOS Program 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 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.

CIMES’ fiscal management and accountability were subject to review in 2022 as part of the overall review of CIMES. CIMES passed the 1-day administrative review without issues raised other than some minor adjustments in some processes. Further, Princeton University had PWC audit the CIMES grant in September/October 2022, and again no issues were raised.

3.6.6 Human Resources Management

Hiring of professional (Master’s and PhD-level) researchers 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, the candidate’s 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, whereby each project produces an annual report on project progress and career development of the supported scientists.

For Task II collaborative projects, the GFDL technical host will provide scientific mentoring and technical guidance. Each supported scientist is part of a project, and for each project CIMES requires an annual progress report. Continuation of funding for Task II projects is conditional on satisfactory project progress.

For the professional development, the CIMES Project Manager will track the professional development in terms of scientific output as measured by contributions to project progress, scientific publications and national and international recognition and reputation.

The CI Administrator shall approve all vacation, travel and sick time of the CI scientists and will notify the GFDL technical host of any change of staffing to ensure work coverage.

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 Director) 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, in Princeton University’s Sayre Hall where the AOS Program has its offices, or possibly in a newly available building in case of lack of office space in GFDL or Sayre Hall. Having GFDL in close proximity allows us to stimulate and support collaborative research.

### 3.6.7 Communication between GFDL and Princeton University

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. Examples of informal meetings are meetings between GFDL Director and 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. 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 more than 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.

### 3.7 Performance Measures

CIMES’ 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 (see Section 3.1), 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.

3. Success of post-docs and graduate students. Currently, about half of the former AOS graduate students and Postdoctoral researchers hold faculty positions at leading national and international Universities, and a quarter works in national research laboratories supported by NOAA, NASA, NSF and DoE (see also Section 3.1).

4. Other ways in which the CI will be evaluated. 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. Successful professional development of CIMES scientists is an important aspect in the evaluation of the success of the Collaborative Institute.

### 3.8 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, 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 3.5.3, which are directed at recruiting underrepresented candidates. We have advertised these opportunities in the Institute for Broadening Participation’s Pathways to Science, Advancing Chicanos/Hispanics & 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.
As discussed in Section 3.5.3, for FY18-22, CIMES supported faculty visits from minority serving institutions (Prof. Randye Rutberg (CUNY Hunter), hosted by Dr. Sonya Legg; and Prof. Monika Sikand (CUNY Bronx Community College), hosted by Prof. S. Fueglistaler and Dr. V. Ramaswamy). The COVID pandemic put a halt to these visits, but CIMES proposes to resume these efforts. In parallel, CIMES scientists actively initiate and engage in opening new collaborations with minority serving institutions (for example, CI Director Fueglistaler and Dr. Yi Ming (GFDL) worked with Prof. Joseph Wilkins (Howard University) for a joint proposal submitted to the Princeton Alliance for Collaborative Research and Innovation (PACRI).

Finally, CIMES scientists are strongly committed to outreach and increasing diversity both at CIMES, and in the field in general. Further details of these efforts (the CIMES internship program, K-12 outreach, QUEST) are summarized in Section 3.5.3).

3.9 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 commonly used formats in the field such as: binary, GRIB2, NetCDF, ESRI Arc coverages and shapefiles. Analysis codes are frequently in Python, Matlab, and "R", and intermediate data may be stored in associated formats. Data presentations may use Excel, Word and PowerPoint files, as well as latex.

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.

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) may 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 Princeton University, data generated by CIMES HPC resources will be stored on servers owned by CIMES (see Section 3.4.1), and data generated on GFDL HPC resources in collaboration with GFDL scientists.
will be stored at GFDL. 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.

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.