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DEPARTMENT OF COMMERCE
RESEARCH PERFORMANCE PROGRESS REPORT (RPPR)

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AWARD INFORMATION	
1. Federal Agency: Department of Commerce / NOAA	2. Federal Award Number: NA18OAR4320123
3. Project Title: Cooperative Institute for Modeling the Earth System (CIMES)	
4. Award Period of Performance Start Date: 07/01/2018	5. Award Period of Performance End Date: 06/30/2024
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR	
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REPORTING INFORMATION	
Signature of Submitting Official: Laura Rossi	
16. Submission Date and Time Stamp: 04/30/2023	17. Reporting Period End Date: 03/31/2023
18. Reporting Frequency: (●) Annual ( ) Semi-Annual ( ) Quarterly	19. Report Type: (●) Not Final ( ) Final
RECIPIENT ORGANIZATION	
20. Recipient Name: THE TRUSTEES OF PRINCETON UNIVERSITY	
21. Recipient Address: 1 NASSAU HALL, PRINCETON, NJ 08544-2001 USA	
22. Recipient UEI: NJ1YPQXQG7U5	23. Recipient EIN: 210634501

ACCOMPLISHMENTS

24. What were the major goals and objectives of this project?

i. To develop the world leading earth system model, in collaboration with NOAA-GFDL, by providing expertise in key processes, physical and biological components, and software development.
ii. 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.
iii. To apply this model to understand impacts of a changing climate on societally-relevant problems, including marine ecosystems, weather extremes, droughts and air quality.
iv. To train the next generation of leaders in earth system science, through the world-leading graduate Atmospheric and Oceanic Sciences program at Princeton University, and the AOS postdoctoral program.
v. 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.
vi. Computational platform - CIMES acquired and is maintaining and utilizing an independent research high performance computational platform. This enables CIMES to collaborate with NOAA in the development, testing, and measurement of NOAA models using standard metrics of computational performance.

25. What was accomplished under these goals?

Goal i. To develop the world leading earth system model, in collaboration with NOAA- GFDL, by providing expertise in key processes, physical and biological components, and software development.

Cooperative Institute researchers have contributed to the development of GFDL's earth system model through investigations into physical, chemical, and biological processes in the ocean, atmosphere, cryosphere, and land-surface; development of parameterizations of these processes implemented in the ocean, atmosphere, and land components of the GFDL earth system models; development of dynamical core algorithms for the MOM6 ocean model and FV3 atmospheric model; and development of the software infrastructure required to efficiently run the climate models and examine their results. Here we highlight only a small subset of the exciting advances in earth system model development achieved in the past year.

Ocean model development has been advanced by a combination of incorporating additional earth system component interactions (e.g., MOMice) and by improving the representation of small-scale, unresolved processes.

Atmospheric model development and evaluation in the Cooperative Institute has had many strands, including boundary layer parameterization and convection scheme development, radiative transfer improvements for AM5 development, and a focus on Arctic cloud simulation.

Goal ii. 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.

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.

Goal iii. To apply this model to understand impacts of a changing climate on societally- relevant problems, including marine ecosystems, weather extremes, droughts and air quality.

CIMES researchers have applied GFDL models to a wide range of societally relevant problems. Below we highlight a subset of the achievements of the past year, covering earth-system modelling of biogeochemical cycles, hydroclimate extremes, and human impacts.

ACCOMPLISHMENTS *(cont'd)*

26. What opportunities for training and professional development has the project provided?

CIMES provides excellent training to both students and early career scientists in the Princeton Atmospheric and Oceanic Sciences Program. CIMES-funded students and postdocs receive scientific guidance from GFDL scientists and have access to all education and career-development resources at Princeton University. During the past year, the project has provided support to 16 graduate students in the AOS graduate program, of whom 3 have obtained their PhDs during this reporting period. In addition to funding their research, the students' participation in professional meetings was also supported by this project. 43 postdoctoral and early career researchers were trained through participation in this project during the past year.

In addition to graduate students and postdocs, the CIMES summer internship program is a cornerstone of our activities to broaden participation in earth system science. Six summer interns joined campus in summer of 2022 to work with GFDL hosts on various research projects. The students, their home institutions, and their projects are as follows:
Allan Cruz, University of Puerto Rico, A Study of Changes in Atmospheric Blocking Statistics in Response to Global Warming Using GFDL GCMs
Josephine Elumeze, LaGuardia Community College, New York, Climate Cloud Containers Continuous Integration Continuous Delivery (C5-id)
Max Sasser, University of Oklahoma, Evaluating Observation Innovation of Surface Temperature and Humidity for the Assimilation of the Observations in GFDL SHiELD Model
Gavin Fry, Dartmouth University, the Increase in the U.S. Northeast Extreme Precipitation: Past, Present, and Future
Juleanna De La Cruz, UCLA, the Interactions between Ice shelves, Calving, Icebergs and Climate
Megan Schaaf, University of Wisconsin, the Tracking the Origins of the Forecast Errors for the Madden-Julian Oscillation

Four of the interns identify with groups that are historically underrepresented or underserved in science with respect to gender, race, and ethnicity. While engaged in their internships at Princeton, the students participated in professional development opportunities including online tutorials on computational skills and climate science, a discussion on applying to graduate school, and final online presentations on their summer research to the GFDL/CIMES community. Gavin Fry and Josephine Elumeze also presented their CIMES internship research at the American Geophysical Union Fall 2022 meeting.

Additional educational and training activities undertaken through CIMES include: mentoring of NOAA Hollings and Lapenta interns by CIMES researchers; mentoring of AOS graduate students and postdocs; mentoring by Princeton faculty of Princeton.

27. How were the results disseminated to communities of interest?

CIMES researchers presented their work in numerous conferences and seminars with scientific and academic audiences. Beyond formal conferences, there has been substantial activity disseminating results to wider audiences and educating local communities about the Earth's climate more broadly. Between April 1, 2022 and March 31, 2023, the AOS/CIMES outreach group participated in the following events.

PPPL Young Women's Conference, May 6, 2022
This annual event for middle/high school girls organized by Princeton Plasma Physics Laboratory (PPPL) was held virtually in 2022. AOS contributed a virtual booth with several movies showing lab experiments and model output, and AOS participants engaged in live discussion with attendees.
AOS/CIMES participants: Elise Ohlson, Sonya Legg, Jacinta Clay

NJ Ocean Fun Days, May 21-22, 2022
Organized by the NJ Sea Grant, this annual event is held at the NJ shore, at Island Beach State Park (May 21st) and Sandy Hook (May 22nd). Access is free for all, and most visitors are families with young children who live locally in Central and South Jersey.
Activities: Tabletop demonstrations of ocean/atmosphere fluid dynamics including tornado in a bottle, iceberg melting, and DIY dynamics rotating tank.
AOS/CIMES participants: Sonya Legg, Yushi Morioka, Akaash Sane, Spencer Hill, Akshaya Nikumbh, Sofia Menemenlis, Yang Wang

Bronx Community College visit, October 27, 2022
Presentation on climate science, career paths and opportunities, followed by Q&A with college students.
AOS/CIMES/GFDL participants: Mingyu Park, Veeshan Narinesingh, Bor-Ting Jong, Akshaya Nikumbh, Latoyia Kirton.

City College New York visit, October 28, 2022
Presentation on climate science, career paths and opportunities, followed by Q&A with college students.
AOS/CIMES participants: Veeshan Narinesingh, Cindy Wang, Gabriel Rios (all CCNY alums)

Boys and Girls Clubs of Mercer County, Teen STEM workshop, November 10, 2022
Conducted 3 workshops each for 15-20 middle school students, focused on climate physics, featuring rotating tank experiments.
AOS/CIMES participants: Maya Chung, Matthew Lobo

Bronx Community College visit, December 8, 2022
Presentation on climate science, career paths and opportunities, followed by Q&A with college students
AOS/CIMES participants: Allison Hogikyan, Tsung-Lin Hsieh, Graeme MacGilchrist, Maya Chung

PPPL Young Women's Conference, March 17, 2023

ACCOMPLISHMENTS *(cont'd)*

28. What do you plan to do during the next reporting period to accomplish the goals and objectives?

In the next year, CIMES researchers will continue to i. contribute to the development of NOAA-GFDL's earth system models, ii. apply these models to problems of prediction across time and space scales, from extreme events to climate phenomena, and iii. apply these models to understand the impacts of a changing climate on societally- relevant problems. This work will be facilitated by vi. the CIMES computational platform Stellar. Additionally, CIMES will continue to iv. train the next generation of leaders in earth system science and v. develop a more diverse workforce by broadening participation in earth system science.
Specific plans aligned with CIMES goals for the next year are as follows:

Goal i. To develop the world leading earth system model, in collaboration with NOAA- GFDL, by providing expertise in key processes, physical and biological components, and software development.

Over the next year, several ocean and ice model development advances will take place.
The atmospheric model, AM5, development will continue over the next year with substantial contributions from Cooperative Institute researchers. Observational data and atmospheric reanalyses will be used to understand sub-grid cloud variability and improve the representation of sub-grid cloud and water vapor on radiative transfer in GFDL's AM5. The development of the new cloud optic scheme (J. Feng, CIMES), designed to improve the microphysics-radiation interaction, will be evaluated in the prototype AM5 configuration to determine its impact on the global climate simulation. The simulation of the stratosphere is a particular area of focus with a new parameterization scheme for the gravity waves (in collaboration with scientists at North West Research Associates) to be implemented by P. Lin (CIMES). The new scheme will be evaluated in terms of i) improvement to simulations of sudden stratospheric warming events and ii) the quasi-biennial oscillation (QBO).

Goal ii: 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.

The prediction across time and space scales will be organized around the two main prediction model systems: SPEAR (Seamless system for Prediction and Earth system Research), applied to subseasonal-to-seasonal (S2S) and seasonal-to-decadal (S2D) prediction, and SHiELD (System for High-resolution prediction on Earth- to-Local Domains), a unified weather modeling system, which can be configured for a variety of applications.

The SHiELD family of predictions will have improvements from both dynamical core development (the Duo-Grid, mentioned in question 25) and via planned improvements to the GFDL MicroPhysics (MP).

Goal iii: To apply this model to understand impacts of a changing climate on societally- relevant problems, including marine ecosystems, weather extremes, droughts and air quality.

PRODUCTS

29. Publications, conference papers, and presentations

The attached CIMES Publication Report has been submitted to NOAA's Institutional Repository.

CIMES researchers presented at many national and international conferences and workshops over the last year, including the 2022 American Geophysical Fall Meeting and the 2023 American Meteorological Society Annual Meeting.

Conferences/workshops organization:

Adcroft hosted a MOM6 tutorial workshop at Princeton University and posted the recordings of lectures online (October 2022).

Fueglistaler and Merlis organized Princeton Center for Theoretical Science Workshop "from Spectroscopy to Climate" (August 2022).

CIMES sponsored and supported PCD22: 4th Workshop on Physics-Dynamics Coupling in Weather & Climate Models (June 2022).

Merlis was program chair of American Meteorological Society's 23rd Conference on Atmosphere Ocean Fluid Dynamics (June 2022).

PRODUCTS *(cont'd)*

30. Technologies or techniques

Nothing to Report

31. Inventions, patent applications, and/or licenses

Nothing to Report

Attach a separate document if more space is needed for #6-10, or #24-50.

PRODUCTS *(cont'd)*

32. Other products

Model codes, configurations, and modules:

CIMES researchers have contributed to the following model codes and configurations in the past year:

MOM6: ocean model
FV3: atmospheric dynamical core
AM4: atmospheric model
AM4 EDMF: Eddy-diffusivity mass flux parameterization
LM4: land model
LM3-FANSY: Freshwater Algae, Nutrient, and Solid cycling and Yields model
CM4: coupled climate model
ESM4.1: earth system model
COBALTv2: ocean biogeochemical model
ATOM-COBALT: a food-web biogeochemical model which implements dynamic elemental stoichiometry within the framework of COBALT.
SHiELD: System for High-resolution prediction on Earth-to-Local Domains
SPEAR: Seamless system for Prediction and EArth system Research
UFS: Unified forecast system
GFDL MP: cloud microphysics scheme

SHiELD configurations: https://zenodo.org/record/6478536 and https://zenodo.org/record/6607070

Software for constructing topography-aware subgrid land tiled datasets:
https://zenodo.org/record/7720281#.ZCpYbS-B3T8

Model dataset used for developing a parameterization for spatial distribution of solar irradiance over rugged terrain:
https://zenodo.org/record/7720281#.ZCpYbS-B3T8

Code for analyzing the sub--grid distribution of shortwave radiation over mountainous terrain:
https://zenodo.org/record/7714735#.ZCpYwy-B3TM

Water mass transformation analysis package: https://github.com/NOAA-GFDL/xwmt

The LM3-FANSY v1.0 code: https://doi.org/10.5281/zenodo.7457981, Lee, 2022

PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

33. What individuals have worked on this project?

Stephan A. Fueglistaler, Director
Gabriel A. Vecchi, Deputy Director
Sonya A. Legg, Associate Director

Senior Personnel:
Alistair Adcroft, Senior Research Oceanographer
V. Balaji, Head, Modeling System Group
Olga Sergienko, Research Glaciologist
Timothy Merlis, HPC/Manager Science

PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS *(cont'd)*

34. Has there been a change in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period?

V. Balaji resigned on June 6, 2022 and accepted a position as a Distinguished Fellow at Schmidt Futures.

Sonya Legg stepped down as the CIMES Associate Director on June 30, 2022 to focus more on research in her position as Senior Research Oceanographer.

35. What other organizations have been involved as partners?

There have been no partners, but two subawards have been issued, Rutgers University and the University of Alaska to work on the development of open boundary conditions for the MOM6.

PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS *(cont'd)*

36. Have other collaborators or contacts been involved?

Nothing to Report

IMPACT

37. What was the impact on the development of the principal discipline(s) of the project?

Understanding generated through CIMES research has been published in the peer- reviewed literature, and presented at scientific conferences, workshops and seminars, enabling their use by the broader scientific and modeling community. Researchers trained as graduate students and visiting scientists funded through CIMES have gone to other universities and research labs. The computer models of the earth system developed through collaboration between CIMES and GFDL are among the best in the world. The computer simulations performed with the latest models advance our understanding of the climate and earth system and are part of the climate model intercomparison project CMIP6 database currently being examined by many climate and earth-system science researchers. The GFDL model components which CIMES researchers have contributed to are being adopted by many other groups in both government and academia, e.g. the ocean model MOM6 is being used by the National Weather Service and the National Center for Atmospheric Research; the atmospheric model FV3 is being used by the National Weather Service as the basis of its operational prediction system.

IMPACT *(cont'd)*

38. What was the impact on other disciplines?

Nothing to Report

39. What was the impact on the development of human resources?

CIMES has provided opportunities for training in research to 43 postdoctoral researchers and 16 graduate students in Princeton University's Atmospheric and Oceanic Sciences Program in the past year. Additionally, 6 undergraduate students, 4 of whom were from groups historically underrepresented and underserved in science, received training in earth system science and research methods as part of the CIMES research internship program in 2022. CIMES researchers have exposed the general public to earth system and climate science through outreach events such as the New Jersey Ocean Fun Days, Boys and Girls Clubs of Mercer County, Princeton Plasma Physics Lab's Young Women's Conference, and visits to Bronx Community College and the City College of New York.

IMPACT *(cont'd)*

40. What was the impact on teaching and educational experiences?

Several CIMES researchers are actively engaged in teaching at Princeton University, and incorporate the latest climate and earth system science into their courses. Guest lectures and summer school lectures by CIMES researchers introduce the earth system and climate science to additional educational audiences.

CIMES also sponsored QUEST, a summer institute in Climate and Weather, a professional development program designed to deepen teachers' content knowledge in science through self-directed investigations and hands-on laboratory experiments. This year the educators deepened their understanding of weather, climate and climate change.

41. What was the impact on physical, institutional, and information resources that form infrastructure?

CIMES research contributes to information resources through the development of software, forming the computer codes of the GFDL/CIMES models (e.g. MOM6, FV3, SHiELD, SPEAR). Increasingly, such code development is carried out in an open development paradigm, enabling the resource to be shared widely with the scientific community. Additionally, CIMES computer scientists develop software to enhance workflow, and facilitate the running and analysis of the earth system models.

IMPACT *(cont'd)*

42. What was the impact on technology transfer?

The computer models developed by CIMES researchers in collaboration with GFDL are being widely used by other government entities, e.g. the National Weather Service and the National Center for Atmospheric Research (NCAR).

43. What was the impact on society beyond science and technology?

Climate and earth system predictions developed by CIMES researchers in collaboration with GFDL provide important information for society, enabling long term planning for resilience to hazards such as tropical cyclones, extreme rainfall, droughts. Subseasonal-to-seasonal predictions using GFDL/CIMES models enables seasonal planning, for example by the agricultural and retail sectors. Earth system model applications enable the scientific basis for air quality policy, benefiting human health, and marine resources management, benefiting the fishing industry.

IMPACT *(cont'd)*

44. What percentage of the award's budget was spent in foreign country(ies)?

0 , N/A

CHANGES/PROBLEMS

45. Changes in approach and reasons for change

Nothing to Report

Attach a separate document if more space is needed for #6-10, or #24-50.

CHANGES/PROBLEMS *(cont'd)*

46. Actual or anticipated problems or delays and actions or plans to resolve them

CIMES research depends on bringing the best scientists from within the USA and the rest of the world to work collaboratively with NOAA. This is achieved through collocating CIMES personnel in the GFDL building and/or on federal high-performance computing platforms. There are often serious time delays in processing security paperwork to allow new hires access.

Delays in building access are resolved by temporarily using Princeton University office space in Sayre Hall, across Forrestal Road from GFDL's building.

Delays for access to GFDL HPC resources are resolved by access to the CIMES HPC system "Stellar" which may be used by incoming scientists from the first day of their employment at Princeton University. Many GFDL Earth System Models are installed on the CIMES HPC system, and when a specific model is not available, the CIMES scientist is authorized to install the specific model they need.

47. Changes that had a significant impact on expenditures

Nothing to Report

Attach a separate document if more space is needed for #6-10, or #24-50.

CHANGES/PROBLEMS *(cont'd)*

48. Significant changes in use or care of human subjects, vertebrate animals, biohazards, and/or select agents

Nothing to Report

49. Change of primary performance site location from that originally proposed

Nothing to Report

Attach a separate document if more space is needed for #6-10, or #24-50.

PROJECT OUTCOMES

50. What were the outcomes of the award?

Project is ongoing.

DEMOGRAPHIC INFORMATION FOR SIGNIFICANT CONTRIBUTORS (VOLUNTARY)

Gender:

- ◯ Male
- ◯ Female
- ◯ Do not wish to provide

Ethnicity:

- ◯ Hispanic or Latina/o Not
- ◯ Hispanic or Latina/o Do not
- ◯ wish to provide

Race:

- ◯ American Indian or Alaska Native Asian
- ◯ Black or African American
- ◯ Native Hawaiian or other Pacific Islander
- ◯ White
- ◯ Do not wish to provide

Disability Status:

- ◯ Yes
  - [ ] Deaf or serious difficulty hearing
  - [ ] Blind or serious difficulty seeing even when wearing glasses
  - [ ] Serious difficulty walking or climbing stairs
  - [ ] Other serious disability related to a physical, mental, or emotional condition
- ◯ No
- ◯ Do not wish to provide

Attach a separate document if more space is needed for #6-10, or #24-50.