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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: 04/28/2022	17. Reporting Period End Date: 03/31/2022
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.

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. 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 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. In the full report we highlight a subset of the achievements of the past year.

Goals 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; and Goal 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; accomplishments are described in the next section, on training and professional development/dissemination.

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 15 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. 38 postdoctoral and early career researchers were trained through participation in this project during the past year.

The CIMES summer internship program is a corner-stone of our activities to broaden participation in earth system science. Despite the ongoing restrictions due to the pandemic, in the spring and summer of 2021, seven undergraduate students spent 8-10 weeks working remotely in internships in collaboration with hosts based at GFDL (some of whom were also CIMES-funded researchers). The students, their home institutions, and their projects are as follows:

¿ Victor Araya, St Cloud University, Minnesota, The structure analysis of winter storms in the Greater New York using JRA55 data and SPEAR simulations
¿ Blaise Enama, Hunter College, New York, Forecasting Estuarine and Coastal Salinity to Improve Fisheries
¿ Kanoe Aiu, Stanford University, Ocean Surface Mixed Layers in GFDL's OM4 ocean model
¿ Nuzhat Khan, Hunter College, New York, Retrieving Iceberg Characteristics from Satellite Images
¿ Tyler Barbero, UC San Diego, Potential Vorticity Diagnosis of Hurricane Track Forecasts in IFS, GFS, and GFDL SHiELD
¿ Zouberou Sayibou, Bronx Community College, Linking ENSO to Oceanic Dynamical Regimes using Transparent Machine Learning
¿ Mackenzie Blanusa, University of Connecticut, CMIP6 multimodel analysis and scalable python-based software stack

Four of the seven interns are under-represented minorities, and two of the seven interns are women. While engaged in their internships at Princeton, the students also attended online tutorials on computational skills and aspects of climate science, and a discussion on applying to graduate school, and gave a final online presentation on their research to the GFDL/CIMES community. Several interns gave presentations on their CIMES research at national conferences such as Fall AGU 2021 or Ocean Sciences Meeting 2022.

Our Task III funding also supported a Princeton University undergraduate, Benjamin Henry, an under-represented minority, who worked with Professor James Smith on his project Extreme Rainfall and Flooding the Lower Mississippi River Basin.

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

CIMES researchers presented their work in numerous conferences and seminars. Other activities disseminating results to wider audiences included: involvement in a Science for Rural India team (Akshaya Nikumbh); organizing an informal weekly climate dynamics community seminar (Jie Chen); chairing a Town Hall meeting about the development of a nitrification database at the 2022 Ocean Sciences Meeting (Weiyi Tang); presentation at the Trenton Computer Festival (Enrico Zorzetto); participation in the Amazon Web Services ASDI CMIP6 Data Informational Session (Aparna Radhakrishnan); presentation at the NCAR CESM Advisory Board (CAB) Meeting (V. Balaji); participation in the NOAA Science snapshots K-12 outreach series, the NJ Ocean Fun Days and Princeton Plasma Physics Laboratory Young Women's conference virtual outreach events, and Boys and Girls clubs teen STEM conference (Sonya Legg).

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. 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 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.

During the next reporting period, CIMES researchers will continue to contribute to the development of the different components of the GFDL earth system models, including to the ocean model MOM6, the atmospheric models AM4/AM5 and SHiELD, the new ice-stream/ice-shelf component embedded in MOM6 (MOM6ice), and the Land Model LM4 and ocean biogeochemical model COBALT. CIMES researchers will also contribute to the modernization of the earth system modeling enterprise through fusion of computation, data, and machine learning, and collaborate with NOAA groups on strategies for management of the associated large data-sets.

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.

CIMES researchers will continue to contribute to improvements in the SHiELD unified forecasting system. These will include implementation of the Duogrid capability in the FV3 dynamical core, reducing noise at edges and corners of the grid; integration of the dynamics and physics coupling; improving the GFDL cloud microphysics by implementing cloud water activation and cloud ice nucleation that interacts with active aerosol, and using the redefined particle size distribution for the cloud radiative properties.

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 will continue to apply the GFDL earth system models to a variety of problems of societal importance, including marine ecosystems, weather extremes, droughts and air quality.

See the attached document for further details of plans for the next year.

PRODUCTS

29. Publications, conference papers, and presentations

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

Conferences/workshops

Aparna Radhakrishnan organized a series of teleconferences for the Model Diagnostics Task Force, and participated in the Pangeo/Earth System Grid Federation working group.

Seth Danielson and Kate Hedstrom participated in the Bureau of Ocean Energy Management Landfast Ice Study annual review panel.

Alistair Adcroft contributed to the CESM Ocean Model Working Group Climate Process Team workshop, the CESM Ocean modeling working group, and the M2LInES project kickoff workshop.

Khaled Ghannam led an inter-agency meeting of the parametrization group of the CLASP (Coupling of Land and Atmospheric Subgrid Parametrization) climate process team on October, 23, 2020.

V. Balaji co-convened AGU 2020 Session OS022/023, December 2020: Innovation and Exploration in Observed and Model Oceanographic Data Using Interpretable Machine Learning; 5th Workshop on Coupling Technologies for Earth System Models, 21-25 September 2020, online Climate Informatics Workshop and Hackathon, 2019, Paris and 2020 (virtual).

PRODUCTS *(cont'd)*

30. Technologies or techniques

xWMT software package
https://github.com/jetesdal/xwmt

Implementation in dora/om4labs (GFDL model evaluation tool)
https://github.com/raphaeldussin/om4labs

Model Diagnostics Task Force Framework for Process Oriented Diagnostics

The THOR framework https://github.com/maikejulie/DNN4Cli which may be incorporated to run within the MDTF framework.

Open boundary conditions for the NOAA-MOM6 ocean circulation model; Grid generation tools; Initial and boundary condition preparation software.

The multiple nesting capability is being now used by UFS (Unified Forecast System) in Hurricane Analysis and Forecast System (HAFS)

The GFDL Cloud Microphysics Scheme (GFDL MP) and System for High Resolution Prediction on Earth-to-Local Domains (SHiELD)

31. Inventions, patent applications, and/or licenses

Nothing to Report

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
AM4 single-column model with FIVE
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
https://github.com/elisamantelli/Icestreamformation_SchoofMantelli_RSPA : Icestream code
RMC: radiation Monte Carlo code for shortwave radiation over complex terrain
Tools

MDTF: Model diagnostics task force framework
AWS S3: Cloud-hosted CMIP6 data
Tutorial for analyzing vorticity budget in https://mom6-analysiscookbook.readthedocs.io/en/latest/notebooks/Closing_vorticity_budget.html
Gridtools GitHub repository for grid generation for MOM6
THOR: https://github.com/maikejulie/DNN4Cli
https://esgf-world.s3.us-east-2.amazonaws.com/index.html#CMIP6/
MOM6 analysis tools: https://mom6-analysiscookbook.readthedocs.io/en/latest/notebooks/Closing_tracer_budgets.html
https://mom6-analysiscookbook.readthedocs.io/en/latest/notebooks/Watermass_transformation.html
https://mom6-analysiscookbook.readthedocs.io/en/latest/notebooks/Closing_layerwise_tracer_budgets.html

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
Meiyun Lin, Research Scholar
Olga Sergienko, Research Glaciologist

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?

The previous PI/Director Gabriel Vecchi has assumed the role of Deputy Director while the previous Deputy Director, Stephan Fueglistaler as assumed the role of Lead PI/Director. The previous PI/Director Gabriel Vecchi has assumed the role of Deputy Director while the previous Deputy Director, Stephan Fueglistaler as assumed the role of Lead PI/Director. Meiyun Lin, a Research Scholar at Princeton/CIMES, resigned on 9/27/21 to accept a position as a Physical Research Scientist at NOAA/GFDL.

35. What other organizations have been involved as partners?

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 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 38 postdoctoral researchers and 15 graduate students in the Princeton University Atmospheric and Oceanic Sciences Program in the past year. Additionally, 7 undergraduate students, 4 of whom were from groups under-represented in science, received training in earth system science and research methods as part of the CIMES research internship program in 2021. CIMES researchers have exposed the general public to earth system and climate science through outreach events such as the New Jersey Ocean Fun Days and the Climate Up Close program.

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.

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)?

1 , Due to the COVID-19 pandemic, two postdocs were unable to relocate to the United States due to travel restrictions and the inability to obtain a visa until August 2021. Since these two postdocs were considered the top candidates in the research area for which they were hired, Princeton University engaged a Professional Employer Organization (PEO) to employ these two researchers on our behalf. (A PEO is a firm that provides a service under which an employer can outsource employee management tasks, such as recruiting, employee benefits, payroll and workers' compensation, risk and safety management, and training and development. A PEO is able to do so by hiring a client company's employees, thus becoming their employer of record for tax and insurance purposes.) The individuals are not considered Princeton employees, but an employee of the PEO.

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 in the best scientists from within the USA and the rest of the world to work collaboratively with NOAA either collocated in the GFDL building and/or on common supercomputing platforms. Serious time delays in processing security paperwork to allow new hires access to both GFDL building and the Supercomputer. Fingerprints will now only be accepted if done in the USA.

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.