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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: 04/30/2021	17. Reporting Period End Date: 03/31/2021
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 will commence 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.

CIMES 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.

A major achievement of the past year was the completion of the GFDL Earth System Model (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.

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.

A significant achievement of the past year was the publication of Harris et al 2020, describing the newly developed System for High-resolution Prediction on Earth-to-Local Domains (SHiELD), a unified weather modeling system, which can be configured for a variety of applications. Several CIMES researchers have made important contributions to this model and publication, including to the FV3 dynamical core and the GFDL microphysics. Continuing development of SHiELD carried out by CIMES researchers includes several significant upgrades in SHiELD version 2020 and version 2021, to the FV3 dynamical core, the GFDL cloud microphysics (GFDL MP), and the planetary boundary layer parameterization.

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.

Using theory, observations, and global climate model, CIMES researchers Stephan Fueglistaler and Yi Zhang examine tropical heat stress in a warming climate (Zhang Y. 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.

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 2 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. 30 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 pandemic, in summer 2020, four 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). A fifth student is currently completing a remote internship. The students, their home institutions, and their projects are as follows:

Akira DiSandro, Oberlin College: Validating Tropical Pacific circulation in GFDL ocean models
Avery Barnett, Grinnell College: Validation of WAVEWATCH III simulations under hurricanes in shallow and deep water
Quiana Berry, Bronx Community College: Drivers of primary productivity in the Humboldt current ecosystem
Natalie O'Leary, Princeton University: A walk in the cloud: Facilitating climate research using Amazon web services
Mackenzie Blanusa, University of Connecticut: Unified data access

2/5 of these interns are under-represented minorities, and all 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. Avery Barnett presented her work at AGU and SACNAS 2020 fall meetings, and received an award for her SACNAS poster presentation.

The CIMES Visiting Faculty Exchange Fellow program brings a faculty member from a minority serving institution to work with scientists at GFDL/Princeton. While no appointment was made under this program in 2020, the links made with Bronx Community College and Hunter College, City University of New York, through 2018 Visiting Faculty Exchange Fellows, Dr Monika Sikand and Dr Randye Rutberg, continue through seminars presented to the BCC STEM club 2-3X per semester, by CIMES researchers, and through the continuing recruitment of BCC and Hunter College students to the CIMES internship program.

Additional educational and training activities undertaken through CIMES include: attendance at the "Artificial Intelligence for Earth System Science (AI4ESS)" virtual summer school (Wei Zhang); attendance at the SACNAS Diversity in STEM conference, as a mentor (Sonya Legg); mentoring of two Princeton university undergraduates in climate research by postdoc Sirisha Kalidindi; participation in an international stratospheric dynamics journal club by Pu Lin; presentation of a tutorial on behalf of the FV3 team at the 2020 UFS Medium-Range weather application users' training (Linjiong Zhou); completion of the Princeton University teaching

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

While the COVID-19 pandemic restricted many of the public outreach programs to which CIMES usually contributes, some online activities did continue. In November 2020, Sonya Legg presented a series of live virtual workshops on oceanography as part of the Boys and Girls Clubs of Mercer County Teen STEM workshop. A video of hands-on oceanographic experiments was submitted to the virtual New Jersey Ocean Fun Days event in October 2020, organized by New Jersey Seagrant. CIMES researcher Maike Sonnewald taught a class on climate change to a virtual summer school for middle schoolers organized by SynergyEd, gave a seminar to the Bronx Community College STEM club, and participated in Oceanhackweek 2020. Several CIMES researchers presented their research in webinars targeting relevant user groups, for example the UNESCO global ocean oxygen network and the European Center for Medium Range Forecasting.

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.

Some 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 and SHiELD, the new ice-stream/ice-shelf component embedded in MOM6, 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, specifically focusing on reductions in hurricane track bias in T-ShiELD beyond 5 days lead time, in line with the National Hurricane Center research priority to deliver reliable hurricane track forecasts 6-7 days in advance, and continue upgrades to the SHiELD microphysics.

The SPEAR forecasting system will continue to be advanced, through improvements in the OTA data assimilation and ensemble prediction with additional statistical and machine learning techniques.

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. Specific plans for the next year include: application of regional MOM6 to the Northeast US large marine ecosystem, evaluating the model capabilities for simulation of fisheries-relevant metrics; application of MOM6 to forecast stock estimates of yellowtail flounder, other groundfish species, and American lobster; exploration of

PRODUCTS

29. Publications, conference papers, and presentations

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

Conferences/workshops:

Maike Sonnewald was a co-convenor and/or session chair for the following conference sessions: 2021 EGU, ITS4.4/AS4.1: Machine learning for Earth system modelling; 2020 AGU, OS014: Innovation and exploration in observed and model oceanographic data using interpretable machine learning; 2020 AGU, A084: Machine Learning for Weather and Climate Modeling, oral and poster; 2020 The 2nd NOAA Workshop on Leveraging AI in Environmental Sciences "Exploiting Space- and Ground-Based Observations and Enhancing Earth System Prediction".

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

Methods to reduce the warm-biased ROMS model, estimate cold pool index and persistence based on bottom temperature and introduce cold pool indices into the stock assessment model will be soon available on the GitHub account https://github.com/h-du-pontavice)

Global data infrastructure for climate data: Earth System Grid Federation (ESGF) hosting data from CMIP6, data hosted Amazon Web Services AWS/S3 and AWS/EC2: https://esgf-world.s3.us-east-2.amazonaws.com/index.html and https://aws-cloudnode.esgfed.org/thredds/catalog/esgcet/catalog.html

Accessing AWS/S3 cloud data via intake-esm catalogs in JupyterHub, enabled by Dask.

Developments to GFDL Flexible Modeling System (FMS), Runtime Environment (FRE), and Data Portal

CMIP6 Data Citations:

https://doi.org/10.22033/ESGF/CMIP6.1402

https://doi.org/10.22033/ESGF/CMIP6.1641

https://doi.org/10.22033/ESGF/CMIP6.1642

https://doi.org/10.22033/ESGF/CMIP6.1403

https://doi.org/10.22033/ESGF/CMIP6.1643

https://doi.org/10.22033/ESGF/CMIP6.9242

https://doi.org/10.22033/ESGF/CMIP6.1407

https://doi.org/10.22033/ESGF/CMIP6.1404

https://doi.org/10.22033/ESGF/CMIP6.1405

https://doi.org/10.22033/ESGF/CMIP6.1981

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
OM4p5B: ½ degree implementation of MOM6 ocean model
FV3: Atmospheric dynamical core
AM4: Atmospheric model
AM4 EDMF: Eddy-diffusivity mass flux parameterization
LM4: Land model
CM4: coupled climate model
ESM4.1: earth system model
COBALTv2: Ocean biogeochemical model
BLING: simplified biogeochemical model
SHiELD: System for High-resolution prediction on Earth-to-Local Domains
SPEAR: Seamless system for Prediction and EArth system Research
UFS: Unified forecast system

Tools

MDTF: Model diagnostics task force framework
AWS/S3; AWS/EC2/ESGF; AWS/EC2/Synda: cloud hosted data and software utilities
Amazon cloud application under development for THOR
FRE E2E workflow encompassing various facets, including MDBI, Curator Database, pyCurator API, showstats, CMIP6 tracker.

Databases

SPEAR S2S hindcasts

Large database (>1000 model-years) of output from climate model experiments (idealized and realistic) using GFDL's AM4/LM4-urban model.

Database of nitrification rates (ammonia oxidation ~2000 data entries, nitrite oxidation ~800 data entries) and accompanying environmental data

PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

33. What individuals have worked on this project?

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

Senior Personnel:
Alistair Adcroft, 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?

Nothing to Report

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 30 postdoctoral researchers and 16 graduate students in the Princeton University Atmospheric and Oceanic Sciences Program in the past year. Additionally, 4 undergraduate students, 3 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 2020. 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 new postdocs were unable to relocate to the United States due to travel restrictions and the inability to obtain a visa. 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.