# COOPERATIVE INSTITUTE FOR MODELING THE EARTH SYSTEM (CIMES)

**Federal Award Number: NA18OAR4320123**

**ANNUAL PROGRESS REPORT**

**April 1, 2020 - March 31, 2021**

**Director and Principal Investigator: Gabriel A. Vecchi**

## 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.

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.
A major achievement of the past year was the completion of 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.

CIMES researchers continue to advance development of the atmospheric dynamical core, FV3, redesigning the algorithm to take advantage of modern GPU acceleration hardware architecture, and the hybrid coordinate ocean model, MOM6 (Griffies, Adcroft and Hallberg, 2020), including expanding the continuous-integration system, and development of a regional MOM6 model for the Northwest Atlantic Ocean, with open boundary conditions for tidal elevation and velocity. In addition, during the past year, an ice-stream/ice-shelf model directly embedded into MOM6 has been developed, allowing for fully coupled simulations of ice flow and ocean circulation underneath it.

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.

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 LM4P2, 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. As part of this effort, a hierarchical clustering algorithm already used in the GFDL land model has been extended to explicitly include terrain variables relevant for the radiative budget. This new algorithm can now classify land in homogeneous regions (i.e., “tiles”) based on how local topography modulates atmospheric radiative fluxes. A Monte Carlo ray tracing algorithm has been developed to simulate the effect of 3-dimensional terrain features on the shortwave radiative balance.

Other parameterization achievements include the development of a parameterization of submesoscale symmetric instability in the deep ocean; parameterization of gas fluxes at the sea-surface induced by bubble bursting during wave-breaking; and a new parameterization for the prediction of ammonium oxidation rates in ecosystem models which outperforms the current parameterization used in ocean biogeochemistry model COBALTv2.

Other additional improvements to the earth system models include: expansion in the capability of the iceberg model to represent the giant tabular icebergs carrying most of the frozen export from Antarctica to the open ocean, using aspects of the Discrete Element Method and including a fracturing model to provide a breakup mechanism; a precipitation disaggregation scheme developed and implemented in GFDL ESM4.2, allowing precipitation to be varied across below the model grid-scale, dependent on fine-scale orographic factors; extension of the NOAA/GFDL Land Model LM3-Terrestrial and Aquatic Nitrogen (TAN) to simulate global river suspended solid loads from drainage basins to the coastal ocean, with detachment of sediment from hillslopes or small drainage basins modeled as a function of hillslope, soil texture, rainfall, and leaf area index; and improvement of the Land Model 4 tropical vegetation model to include a new vegetation type resembling the traits of shade tolerant tree species.

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 model components described under Goal i have been configured to provide model prediction systems focused on different applications. 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.

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. 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. As a system without data assimilation, the 2020 T-SHiELD even showed superior intensity skill compared to the operational HWRF model (with storm-scale data assimilation). Positive definite tracer advection schemes have been shown to play a critical role in improving the intensity prediction of major hurricanes.

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 nonhydro static and uses sophisticated microphysics. While these features make S-SHiELD more expensive than analogous hydrostatic models, nonhydrostatic 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-Julien Oscillation (correlation > 0.7) out to 19 days and useful skill (correlation > 0.5) out to 28 days, giving confidence that S-SH iELD simulates the MJO well enough for useful S2S prediction.

The new SPEAR (Seamless system for Prediction and EArth system Research) seasonal prediction system, to which several CIMES researchers have contributed, is now operational and 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, as described in recent publication, Zhang Y-F. 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.

A new effort in CIMES involves application of machine learning to many aspects of earth system modeling. Particularly relevant to the prediction goal is the Watching OceaN Dynamics Employing Remote Sensing (WONDERS) project proposed to develop an advanced ML framework with the end goal of monitoring the 3D ocean state in real time using satellite fields in support of subseasonal to seasonal forecasting. The work builds on Sonnewald et al. (2019) where the 3D ocean in a low resolution realistic model was represented by 2D barotropic vorticity (BV) dynamical regimes fields with, climate and ocean heat content relevance using ML. A low resolution deep neural network (DNN) was developed to recognize the dynamical regimes, using data available from satellite fields. The DNN was applied to explain the weakening of the AMOC in ESM4.1 for future scenarios.

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.

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.

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.

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.

Recent publication Xie et al, 2020, uses observations and model simulations (ESM4.1) for the period 1988–2018, to show large year-to-year variability in western U.S. fine particulate matter (PM2.5) pollution caused by regional and distant fires (Xie et al. 2020). Large uncertainties in modeling surface PM2.5 and aerosol optical depth result from uncertainties in fire emission source strength and injection height, posing challenges to accurately assessing the impacts of fire smoke on air quality, radiation, and climate. Projections of wildfires coupled to climate and vegetation in three Earth system models from the Coupled Model Intercomparison Project Phase 6 (CMIP6) are combined with a statistical model developed from observations, to predict PM2.5 pollution in the late 21st century (2080-2100) under a suite of shared socioeconomic pathways (SSPs). Total CO2 emissions from fires over western North America during August-September (fire season) are projected to increase by 50-100% under SSP126, 80-150% under SSP245, and 120–300% (model spreads) under SSP585 in 2080-2100. Fire outbreaks under the SSP585 extreme scenario cause a twofold to threefold increase in western U.S. summer mean PM2.5. In contrast, the PM2.5 change is only 19% in the CMIP6 chemistry-climate model projections not accounting for the impact from interactive fires. The massive fires which burned across the U.S. West in 2017, 2018, and 2020 might therefore become a new norm by the late 21st century, posing challenges for regional air quality management.

Several CIMES researchers apply the GFDL earth system model to examine marine ecosystems, and their sensitivity to anthropogenic and climate forcings. Using LM3-TAN to simulate the past two and half centuries of global land nitrogen budgets and fluxes to the ocean and atmosphere, considering the combined effects of changes in atmospheric CO2, climate, land use, and anthropogenic nitrogen inputs, Lee et al 2021 show that land nitrogen memory effects – impacts of antecedent dry conditions on land nitrogen accumulation that disproportionately increase subsequent river nitrogen loads – contribute to freshwater and coastal ecosystem pollution. Land N memory effects are globally prevalent but vary widely in strength. Strong memory effects are most prominent in areas with high hydroclimate variability, warm climates, and ecosystem disturbances. In 48 of the 118 basins analyzed, strong memory effects produce 43% (21%–88%) higher dissolved inorganic nitrogen loads following drought years than following average years. Such a marked influence supports close consideration of prevalent land N memory effects in water-pollution management efforts (Lee et al., 2021).

The recent publication Ross et al 2021 examines whether anthropogenic climate change has altered the risk of experiencing an extreme amount of freshwater discharge from the Susquehanna River into Chesapeake Bay. Projections of annual mean Susquehanna River discharge are developed by driving a simple water balance model with projections of temperature and precipitation from CMIP6 climate models. 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.

Previous generations of Earth system models (ESMs) have failed to provide a consistent picture of how global ocean de-oxygenation will influence oxygen minimum zones (OMZs), in particular the largest OMZ in the tropical Pacific Ocean. Using the latest generation of ESMs (CMIP6), including GFDL-CM4 and GFDL-ESM4, CIMES researchers Laure Resplandy and Julian Busecke showed that the Pacific OMZ expands by the end of the century in response to high anthropogenic emissions due to a reduction of the shallow overturning circulation and weakening of the oxygen supply in the upper OMZ. Models with more complex biogeochemistry (including GFDL-ESM4) project weaker changes in the lower OMZ and stronger overall OMZ expansion. The fact that the OMZ largely expands in the upper ocean maximizes its ecological, economic and climatic impacts.

Coastal hypoxia is a mounting problem that jeopardizes ecosystems and economies in the northern Indian Ocean. A database which merges in-situ temperature and oxygen profiles from different platforms, shows that the risk of coastal hypoxia is highest south of the Indian Peninsula during boreal summer/fall, and in the eastern Bay of Bengal during winter/spring. The Indian Ocean Dipole can also increase the likelihood of hypoxia by modulating wind-driven and wave-driven upwelling.

Other aspects of marine ecosystems of societal importance examined by CIMES researchers in the past year include the effects of the cold pool between Cape Hatteras and Southern Georges Bank on the recruitment of the Southern New England-Mid Atlantic yellowtail flounder, an exploited groundfish in the US Northeast Shelf System, forecasting changes in the abundance and distribution of bigeye tuna in the Pacific Ocean, and the predictability of fish range dynamics along the NE US coast.

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

Goal 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.

CIMES was awarded $3,003,285 ($118,285 in Task 1 and $2,885,000 in Task 2) of PAC Research Supercomputing funding in September 2020 to support the purchase of a High Performance Computer (HPC) cluster as well as to support related costs, such as software engineers to manage the HPC.

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. It is anticipated that the new cluster will be fully operational in July 2021. Recruitment is underway for a High Performance Computing Manager and it is anticipated that a selection will be made in the near term.

**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 transcript program (Elizabeth

Yankovsky); supervision of a Princeton university undergraduate intern (Fernando Gonzalez Taboada).

**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.

**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 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.

The Climate process teams focused on Land energy and moisture exchanges; the atmospheric boundary layer and convection; and ocean transport and eddy energy, will continue in the next year. Specific CPT activities planned for the next year are as follows. A moist Eddy Diffusivity Mass Flux (EDMF) scheme will be implemented into AM4, which has been shown to realistically represent boundary layer processes and associated clouds, potentially addressing some long-standing problems in AM4, such as insufficient marine stratocumulus and incorrect transition between stratocumulus to shallow cumulus. Further improvements will be made to AM4-EDMF, focused on improvement of the coupled of the EDMF scheme to the surface, and improvement of the coupling between EDMF and the UW moist convection scheme. The overarching goal is to improve model realism in representations of both present-day climatology and response in boundary layer properties such as cloudiness, temperature and winds, which are key to coupled model performance. The CLUBB (Cloud Layers Unified by Binormals) scheme will be used to improve AM4's representation of boundary layer momentum flux, and through this to reduce AM4's biases in the surface wind stress and the winds, especially the wind biases associated with tropical cyclones, shallow cumulus trade wind boundary layer, and low-level jets. An improved parameterization of shortwave fluxes over mountainous terrain tailored to the GFDL land model will be developed, and coupled experiments will explore the implications of the newly developed land-surface flux parameterizations on the global climate, including effects on convection, land-atmosphere exchange, and surface hydrology.

A growing aspect of model development and analysis at CIMES focuses on the use of machine learning. Multiscale Machine Learning in Coupled Earth System Modeling (M2LInES) is an international multi-institution project, which started in early 2021, funded by VESRI, with involvement of several CIMES researchers. The project aims to reduce climate model biases using machine learning, and will contribute to improvements in MOM6, coupled model data assimilation, and parameterizations, leveraging CIMES-funded research. Another proposed application of ML is a Process Oriented Diagnostic (POD) for CMIP6 model development. The POD will deliver throphodynamic regime identification methods that are directly linked to fisheries productivity. This POD would enable the tracking of the regimes' expanse and estimation of impact on fisheries productivity.

Other model development activities planned for the coming year include: the development and evaluation of a comprehensive freshwater biogeochemistry model of coupled sediment, nitrogen, phosphorus, and algae dynamics within the globally implemented LM3-TAN; biogeochemical evaluation of GFDL LM4; development of parameterizations of coastal circulations for climate models; new plant hydraulics for representation of the carbon cycle of a mangrove forest; open boundary conditions for biogeochemical tracers and tides in regional implementations of MOM6; examination of the sensitivity of the carbon and nutrient cycle behavior of ESM4.1 to dynamic stoichiometry; combination of ammonia oxidation and nitrite oxidation processes in COBALTv2, to capture the distribution of nitrite or nitrite accumulation when the two processes are decoupled; testing of submesoscale mixed layer parameterizations against high resolution Arctic simulations.

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. Several CIMES researchers will apply SPEAR to a variety of prediction problems, including diagnosing the signal-to-noise paradox in SPEAR S2S ensemble hindcasts in terms of temperature and wintertime cold extremes, as well as major modes of variability; extended range prediction (especially at seasonal timescales) of severe weather including tornado and hail storms; evaluating the overall model skill in predicting the frequency and duration of wintertime cold extremes in S2S predictions; analyzing SPEAR hindcast ensemble simulations for the SNAP (Stratospheric Network for the Assessment of Predictability) S2S community project focused on enhanced surface predictability connected with stratospheric dynamics; assimilating sea ice thickness (SIT) and sea ice age observations and testing the additional benefits of the improved SIT field in predicting Arctic sea ice from seasonal to interannual time scales. The predictive skill of Pacific Marine Heatwaves in SPEAR will be assessed, and the modes of variability that influence the statistics of marine heatwaves will be identified.

Another predictability activity will focus on the relationship between the climate variability diversity in CMIP6 earth system models, and the predictability of chlorophyll variance. All of these prediction and predictability activities will be underpinned by the expansion in the computing capability available to CIMES researchers through the new CIMES high performance computer Stellar.

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 the impact of urban and rural climate variability and change on directly-transmitted respiratory diseases; investigation of the effects of land heterogeneity on potential changes in the frequency and intensity of droughts and their implications for ecosystem dynamics; examination of air pollution means and extremes over East Asia under current and future climate using GFDL ESM4 model simulations; investigation of the influence of climate variability and climate warming in the late 21st century on ozone and particulate air quality in northern mid-latitude populated regions;  understanding the mechanisms underlying the observed relationship between ENSO and MJO on the Australian dust variability, and exploring the driving mechanisms of the East Asian extreme dust event in March 2021.

## 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-convener 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).

**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

https://doi.org/10.22033/ESGF/CMIP6.1408

https://doi.org/10.22033/ESGF/CMIP6.1411

https://doi.org/10.22033/ESGF/CMIP6.1414

https://doi.org/10.22033/ESGF/CMIP6.2262
https://doi.org/10.22033/ESGF/CMIP6.2264
https://doi.org/10.22033/ESGF/CMIP6.1645

**31. Inventions, patent applications, and/or licenses***
N/A

**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

SPEAR climatological SST simulations with varying Gulf of California land-sea boundaries

## 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
**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?***
No

**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.

**36. Have other collaborators or contacts been involved?***
No

## 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.

**38. What was the impact on other disciplines?***
N/A

**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.

**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.

**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.

**44. What percentage of the award's budget was spent in foreign country(ies)?***
**Enter percent:** 1%
**Enter explanation:**
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***
None

**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***
N/A

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

**49. Change of primary performance site location from that originally proposed***
N/A

**Publication Request Template for CI's**

FY21 Research Performance Progress Report Request

| CI Name | PI Name / Author Names | Publication Date | Publication Title | Published In (Journal Name, volume and page number) | Type of Publication | Citation No. (Digital Object Identifier) | Research Support Award No. | CI Lead Author | NOAA Lead Author | Other Lead Author |
|---|---|---|---|---|---|---|---|---|---|---|
| CIMES | Archibald, A.T., J. L. Neu, Y. Elshorbany, O. R. Cooper, P.J. Young, H. Akiyoshi, R.A. Cox, M. Coyle, R. Derwent, M. Deushi, A. Finco, G.J. Frost, I. E. Galbally, G. Gerosa, C. Granier, P.T. Griffiths, R. Hossaini, L. Hu, P.Jöckel, B. Josse, M.Y. Lin et al. | Dec. 2020 | Tropospheric Ozone Assessment Report: Critical review of changes in the tropospheric ozone burden and budget from 1960-2100 | Elementa: Science of the Anthropocene, 8(1): 034 | Journal Article | doi:10.1525/elementa.2020.034 | NA18OAR4320123 | | | X |
| CIMES | Atlas, R. L., Bretherton, C. S., Blossey, P. N., Gettelman, A., Bardeen, C., Lin, P., & Ming, Y. | Nov. 2020 | How Well Do Large-Eddy Simulations and Global Climate Models Represent Observed Boundary Layer Structures and Low Clouds Over the Summertime Southern Ocean? | Journal of Advances in Modeling Earth Systems, 12(11), e2020MS002205 | Journal Article | doi:10.1029/2020MS002205 | NA18OAR4320123 | | | X |
| CIMES | Baker R., Yang W., Vecchi G., Metcalf C.J.E., Grenfell B. | July 2020 | Susceptible supply limits the role of climate in the early SARS-CoV-2 pandemic | Science, 369(6501), 315-319 | Journal Article | doi:10.1126/science.abc2535 | NA18OAR4320123 | X | | |
| CIMES | Balaji, V. | April 2021 | Climbing down Charney's ladder: machine learning and the post-Dennard era of computational climate science | Phil. Trans Roy. Soc. A, 379(2194),20200085 | Journal Article | doi:0.1098/rsta.2020.0085 | NA18OAR4320123 | X | | |
| CIMES | Balaji, V. | January 2021 | «Science des données» versus science physique: la technologie des données nous conduit-elle vers une nouvelle synthèse? | Comptes Rendus Géoscience, 352(4-5), 297-308 | Journal Article | doi: 10.5802/crgeos.24 | NA18OAR4320123 | X | | |
| CIMES | Barton, A.D., F. González Taboada, A. Atkinson, C.E. Widdicombe, C. Stock | August 2020 | Integration of temporal environmental variation by the marine plankton community | Marine Ecology Progress Series, 647, 1-16 | Journal Article | doi:10.3354/meps13432 | NA18OAR4320123 | | | X |
| CIMES | Bieli, M., Sobel, A.H., Camargo, S.J., Murakami, H. and Vecchi, G.A. | April 2020 | Application of the Cyclone Phase Space to Extratropical Transition in a Global Climate Model | Journal of Advances in Modeling Earth Systems, 12(4), e2019MS001878 | Journal Article | doi:10.1029/2019MS001878 | NA18OAR4320123 | | | X |
| CIMES | Bolot, M. & Fueglistaler, S. | February 2021 | Tropical Water Fluxes Dominated by Deep Convection Up to Near Tropopause Levels | Geophysical Research Letters, 48(4), e2020GL091471 | Journal Article | doi:10.1029/2020GL091471 | NA18OAR4320123 | | | X |
| CIMES | Brumley DR, Carrara F, Hein AM, Hagstrom GI, Levin SA, Stocker R | July 2020 | Cutting through the noise: Bacterial chemotaxis in marine microenvironments | Frontiers in Marine Science, 7(527) | Journal Article | doi:doi.org/10.3389/fmars.2020.00527 | NA18OAR4320123 | | | X |
| CIMES | Cheeks S., Fueglistaler S., Garner S. | June 2020 | A Satellite-Based Climatology of Central and Southeastern U.S. Mesoscale Convective Systems | Monthly Weather Review, 148(6), 2607–2621 | Journal Article | doi:10.1175/MWR-D-20-0027.1 | NA18OAR4320123 | X | | |
| CIMES | Chen Y-H, Huang X, Yang P, Kuo C-P, Chen X | Dec. 2020 | Seasonal Dependent Impact of Ice Cloud Longwave Scattering on the Polar Climate | Geophysical Research Letters, 47(23), e2020GL090534 | Journal Article | doi:10.1029/2020GL090534 | NA18OAR4320123 | X | | |
| CIMES | Chen, X. | January 2021 | The LMARS Based Shallow-Water Dynamical Core on Generic Gnomonic Cubed-Sphere Geometry | Journal of Advances in Modeling Earth Systems, 13(1), e2020MS002280 | Journal Article | doi:10.1029/2020MS002280 | NA18OAR4320123 | X | | |
| CIMES | Chua X Rong, Ming Y | Dec. 2020 | Convective Invigoration Traced to Warm-Rain Microphysics | Geophysical Research Letters, 47(23), e2020GL089134 | Journal Article | doi:10.1029/2020GL089134 | NA18OAR4320123 | X | | |
| CIMES | Davies, J., Khatri, H. and Berloff P. | January 2021 | Linear stability analysis for flows over sinusoidal bottom topography | Journal of Fluid Mechanics, 911, A33 | Journal Article | doi:10.1017/jfm.2020.1082 | NA18OAR4320123 | | | X |
| CIMES | DeLang, Marissa; Becker, Jacob; Chang, Kai-Lan; Serre, Marc; Cooper, Owen; Schultz, Martin; Schröder, Sabine; Lu, Xiao; Zhang, Lin; Deushi, Makoto; Josse, Beatrice; Keller, Christoph; Lamarque, Jean-Francois; Lin, Meiyun; Liu, Junhua; Marecal, Virginie; Strode, Sarah; Sudo, Kengo; Tilmes, Simone ; Zhang, Li; Cleland, Stephanie; Collins, Elyssa; Brauer, Michael; West, J. Jason | In-Press | Mapping yearly fine resolution global surface ozone through the Bayesian Maximum Entropy data fusion of observations and model output for 1990–2017 | Environmental Science & Technology, es-2020-077425.R2 | Journal Article | doi:10.1021/acs.est.0c07742 | NA18OAR4320123 | | | X |
| CIMES | Dunne, J. P., Horowitz, L. W., Adcroft, A. J., Ginoux, P., et al. | Nov. 2020 | The GFDL Earth System Model Version 4.1 (GFDL-ESM 4.1): Overall Coupled Model Description and Simulation Characteristics | Journal of Advances in Modeling Earth Systems, 12(11), e2019MS002015 | Journal Article | doi:10.1029/2019MS002015 | NA18OAR4320123 | | X | |
| CIMES | Gallo, Burkely, et al., Zhou, Linjiong and Alexander,Curtis | February 2021 | Exploring Convection-Allowing Model Evaluation Strategies for Severe Local Storms Using the Finite-Volume Cubed- | Weather Forecast, 36, 3-19 | Journal Article | doi:10.1175/WAF-D-20-0090.1 | NA18OAR4320123 | | | X |
| CIMES | Garcia Catherine A., Hagstrom George I., Larkin Alyse A., Ustick Lucas J., Levin Simon A., Lomas Michael W. and Martiny Adam C. | May 2020 | Linking regional shifts in microbial genome adaptation with surface ocean biogeochemistry | Philosophical Transactions of the Royal Society B, 375(1798), 20190254 | Journal Article | doi:10.1098/rstb.2019.0254 | NA18OAR4320123 | | | X |
| CIMES | Germineaud, C., Cravatte, S., Sprintall, J., Alberty, M.S., Grenier, M. and Ganachaud, A. | In-Press | Deep pacific circulation: New insights on pathways through the Solomon Sea | Deep Sea Research Part I: Oceanographic Research Papers, 103510 | Journal Article | doi:10.1016/j.dsr.2021.103510 | NA18OAR4320123 | | | X |
| CIMES | Ghannam K. and Bou-Zeid E. | January 2021 | Baroclinicity and directional shear explain departures from the logarithmic wind profile | Quarterly Journal of the Royal Meteorological Society, 147(734), 443– 464 | Journal Article | doi:10.1002/qj.3927 | NA18OAR4320123 | X | | |

| CI Name | PI Name / Author Names | Publication Date | Publication Title | Published In (Journal Name, volume and page number) | Type of Publication | Citation No. (Digital Object Identifier) | Research Support Award No. | CI Lead Author | NOAA Lead Author | Other Lead Author |
|---|---|---|---|---|---|---|---|---|---|---|
| CIMES | Griffies, S. M., Adcroft, A., Hallberg, R. W. | October 2020 | A Primer on the Vertical Lagrangian-Remap Methodin Ocean Models Based on Finite Volume Generalized Vertical Coordinates | Journal of Advances in Modeling Earth Systems, 12(10), e2019MS001954 | Journal Article | doi:10.1029/2019MS001954 | NA18OAR4320123 | | X | |
| CIMES | Harris L., L. Zhou, J.-H. Chen, X. Chen, K. Gao and coauthors | October 2020 | GFDL SHiELD: A Unified System for Weather-to-Seasonal Prediction | Journal of Advances in Modeling Earth Systems, 12(10), e2020MS002223 | Journal Article | doi:10.1029/2020MS002223 | NA18OAR4320123 | | X | |
| CIMES | Hartzell, S., Bartlett, M.S., Inglese, P., Consoli, S., Yin, J. and Porporato, A. | January 2021 | Modelling nonlinear dynamics of Crassulacean acid metabolism productivity and water use for global predictions | Plant, Cell & Environment, 44(1), 34-48 | Journal Article | doi:10.1111/pce.13918 | NA18OAR4320123 | X | | |
| CIMES | Horowitz, L. W., Naik, V., Paulot, F., Ginoux, P. A., Dunne, J. P., Mao, J., Schnell, J., et al. | October 2020 | The GFDL global atmospheric chemistry-climate model AM4.1: model description and simulation characteristics | Journal of Advances in Modeling Earth Systems, 12(10), e2019MS002032 | Journal Article | doi:10.1029/2019MS002032 | NA18OAR4320123 | | X | |
| CIMES | Hsieh, Tsung-Lin, Gabriel A. Vecchi, Wenchang Yang, Isaac M. Held, and Stephen T. Garner | Dec. 2020 | Large-Scale Control on the Frequency of Tropical Cyclones and Seeds: A Consistent Relationship across a Hierarchy of Global Atmospheric Models | Climate Dynamics, 55(11-12), 3177-3196 | Journal Article | doi:10.1007/s00382-020-05446-5 | NA18OAR4320123 | X | | |
| CIMES | Iipponen, J., & Donner, L. | January 2021 | Simple analytic solutions for a convectively driven Walker circulation and their relevance to observations | Journal of the Atmospheric Sciences, 78(1), 299-311 | Journal Article | doi:10.1175/JAS-D-20-0014.1 | NA18OAR4320123 | X | | |
| CIMES | Jacobson TWP, Yang W, Vecchi GA, Horowitz LW | October 2020 | Impact of volcanic aerosol hemispheric symmetry on Sahel rainfall | Climate Dynamics, 55(7-8), 1733-1758 | Journal Article | doi:10.1007/s00382-020-05347-7 | NA18OAR4320123 | | | X |
| CIMES | Judt, Falco, et al., Zhou, Linjiong | In-Press | Tropical Cyclones in Global Storm-Resolving Models | Journal of the Meteorological Society of Japan | Journal Article | doi:10.2151/jmsj.2021-029 | NA18OAR4320123 | | | X |
| CIMES | Lee M, Stock CA, Shevliakova E, Malyshev S, Milly PCD | January 2021 | Globally prevalent land nitrogen memory amplifies water pollution following drought years | Environmental Research Letters, 16(1), 014049 | Journal Article | doi:10.1088/1748-9326/abd1a0 | NA18OAR4320123 | X | | |
| CIMES | Legg, S. | January 2021 | Mixing by Oceanic Lee Waves | Annual Review of Fluid Mechanics, 53:1, 173-201 | Journal Article | doi:10.1146/annurev-fluid-051220-043904 | NA18OAR4320123 | X | | |
| CIMES | Liao E, Resplandy L, Liu J, Bowman KW | Sept. 2020 | Amplification of the Ocean Carbon Sink During El Niños: Role of Poleward Ekman Transport and Influence on Atmospheric $CO_2$ | Global Biogeochemical Cycles, 34(9), 2020GB006574 | Journal Article | doi:10.1029/2020GB006574 | NA18OAR4320123 | | | X |
| CIMES | Lim, H.G., Park, J.Y., Dunne, J.P., Stock, C.A., Kang, S.H., Kug, J.S. | May 2021 | Importance of human-induced nitrogen flux increases for simulated Arctic warming | Journal of Climate, 34(10), 3799–3819 | Journal Article | doi:10.1175/JCLI-D-20-0180.1 | NA18OAR4320123 | X | | |
| CIMES | Lin, M., Horowitz, L.W., Xie, Y. et al. | April 2020 | Vegetation feedbacks during drought exacerbate ozone air pollution extremes in Europe | Nature Climate Change, 10, 444–451 | Journal Article | doi:10.1038/s41558-020-0743-y | NA18OAR4320123 | X | | |
| CIMES | Lin, P., & Ming, Y. | April 2021 | Enhanced Climate Response to Ozone Depletion From Ozone-Circulation Coupling | JGR Atmospheres, 126(7), e2020JD034286 | Journal Article | doi:10.1029/2020JD034286 | NA18OAR4320123 | X | | |
| CIMES | Lu, F., Harrison, M. J., Rosati, A., Delworth, T. L., Yang, X., Cooke, W. F., et al. | Dec. 2020 | GFDL's SPEAR Seasonal Prediction System: Initialization and Ocean Tendency Adjustment (OTA) for Coupled Model | Journal of Advances in Modeling Earth Systems, 12(12), e2020MS002149 | Journal Article | doi:10.1029/2020MS002149 | NA18OAR4320123 | X | | |
| CIMES | Mariotti A., Baggett C., Barnes E.A, Becker E., Butler A., Collins D.C, Dirmeyer P.A, Ferranti L., Johnson N.C, et al. | May 2020 | Windows of opportunity for skillful forecasts: S2S and beyond | Bulletin of the American Meteorological Society, 101(5), E608–E625 | Journal Article | doi:10.1175/BAMS-D-18-0326.1 | NA18OAR4320123 | | X | |
| CIMES | Martínez Cano I., Shevliakova E., Malyshev S., Wright S.J., Detto M., Pacala S.W. and Muller-Landau H.C. | August 2020 | Allometric constraints and competition enable the simulation of size structure and carbon fluxes in a dynamic vegetation model of tropical forests (LM3PPA-TV) | Global Change Biology, 26(8), 4478-4494 | Journal Article | doi:10.1111/gcb.15188 | NA18OAR4320123 | X | | |
| CIMES | Miller, G., Hartzell, S. and Porporato, A. | April 2021 | Ecohydrology of epiphytes: modeling water balance, CAM photosynthesis, and their climate impacts | Ecohydrology, 14(3), e2275 | Journal Article | doi:10.1002/eco.2275 | NA18OAR4320123 | | | X |
| CIMES | Ming, Y., Loeb, N. G., Lin, P., Shen, Z., Naik, V., Singer, C. E., Ward, R. X., et al. | February 2021 | Assessing the influences of COVID-19 on the shortwave radiative fluxes over the East Asian Marginal Seas | Geophysical Research Letters , 48(3), e2020GL091699 | Journal Article | doi:10.1029/2020GL091699 | NA18OAR4320123 | | X | |
| CIMES | Miyawaki, O., Z. Tan, T. A. Shaw, and M. F. T. Jansen | October 2020 | Quantifying Key Mechanisms That Contribute to the Deviation of the Tropical Warming Profile From a Moist Adiabat | Geophysical Research Letters, 47(20), e2020GL089136 | Journal Article | doi:10.1029/2020GL089136 | NA18OAR4320123 | | | X |
| CIMES | Mostert, W. and Deike, L. | May 2020 | Inertial energy dissipation in shallow-water breaking waves | Journal of Fluid Mechanics, 890, A12. | Journal Article | doi:10.1017/jfm.2020.83 | NA18OAR4320123 | X | | |
| CIMES | Muller-Landau H.C., Cushman, K.C., Arroyo E.E., Martínez Cano I., Anderson-Teixeira K.J. and Backiel B. | March 2021 | Patterns and mechanisms of spatial variation in tropical forest productivity, woody residence time, and biomass | New Phytologist, 229(6), 3065-3087 | Journal Article | doi:10.1111/nph.17084 | NA18OAR4320123 | X | | |
| CIMES | Ng C.H.J., Vecchi G.A. | May 2020 | Large-Scale Environmental Controls on the Seasonal Statistics of Rapidly Intensifying North Atlantic Tropical Cyclones | Climate Dynamics, 54(9-10), 3907–3925 | Journal Article | doi:10.1007/s00382-020-05207-4 | NA18OAR4320123 | X | | |
| CIMES | Oh, J.H., Park, W., Lim, H.G, Noh, K.M., Jin, E.K., Kug, J.S. | Nov. 2020 | Impact of Antarctic meltwater forcing on East Asian climate under greenhouse warming | Geophysical Research Letters, 47(21), e2020GL089951 | Journal Article | doi:10.1029/2020GL089951 | NA18OAR4320123 | | | X |

| CI Name | PI Name / Author Names | Publication Date | Publication Title | Published In (Journal Name, volume and page number) | Type of Publication | Citation No. (Digital Object Identifier) | Research Support Award No. | CI Lead Author | NOAA Lead Author | Other Lead Author |
|---|---|---|---|---|---|---|---|---|---|---|
| CIMES | Pascale S, Kapnick SB, Delworth TL, Cooke WF | Nov. 2020 | Increasing risk of another Cape Town "Day Zero" drought in the 21st century | Proceedings of the National Academy of Sciences of the United States of America, 117(47), 29495-29503 | Journal Article | doi:10.1073/pnas.2009144117 | NA18OAR4320123 | X | | |
| CIMES | Petrik, C., F. González Taboada, C.A. Stock, J.L. Sarmiento | April 2021 | An updated life-history scheme for marine fishes predicts recruitment variability and sensitivity to exploitation | Global Ecology and Biogeography, 30(4), 870-882 | Journal Article | doi:10.1111/geb.13260 | NA18OAR4320123 | | | X |
| CIMES | Ross, A. C., Najjar, R. G., Li, M. | January 2021 | A Metamodel-Based Analysis of the Sensitivity and Uncertainty of the Response of Chesapeake Bay Salinity and Circulation to Projected Climate Change | Estuaries and Coasts, 44, 70–87 | Journal Article | doi:10.1007/s12237-020-00761-w | NA18OAR4320123 | X | | |
| CIMES | Ross, A. C., Stock, C. A., Adams-Smith, D., Dixon, K., Findell, K., Saba, V., Vogt, B. | January 2021 | Anthropogenic influences on extreme annual streamflow into Chesapeake Bay from the Susquehanna River | Bulletin of the American Meteorological Society 102(1), S25–S32 | Journal Article | doi:10.1175/BAMS-D-20-0129.1 | NA18OAR4320123 | X | | |
| CIMES | Ross, A. C., Stock, C. A., Dixon, K. W., Friedrichs, M. A. M., Hood, R. R., Li, M., Pegion, K. V., Saba, V. | October 2020 | Estuarine forecasts at daily weather to subseasonal time scales | Earth and Space Science, 7(10), e2020EA001179 | Journal Article | doi:10.1029/2020EA001179 | NA18OAR4320123 | X | | |
| CIMES | Saad-Roy CM, Wagner CE, Baker RE, et al. | Nov. 2020 | Immune life history, vaccination, and the dynamics of SARS-CoV-2 over the next 5 years | Science, 370(6518), 811-818 | Journal Article | doi:10.1126/science.abd7343 | NA18OAR4320123 | | | X |
| CIMES | Schiavone J., K. Gao, D. Robinson, P.Johnsen, M. Gerbush | February 2021 | Large roll vortices exhibited by Post-tropical Cyclone Sandy during landfall | Atmosphere, 12(2), 259 | Journal Article | doi:10.3390/atmos12020259 | NA18OAR4320123 | | | X |
| CIMES | Shao, A. E., Adcroft, A., Hallberg, R., Griffies, S. M. | Dec. 2020 | A General-Coordinate, Nonlocal Neutral Diffusion Operator | Journal of Advances in Modeling Earth Systems, 12(12), e2019MS001992 | Journal Article | doi:10.1029/2019MS001992 | NA18OAR4320123 | | | X |
| CIMES | Shen Z, Ming Y, Held IM | August 2020 | Using the fast impact of anthropogenic aerosols on regional land temperature to constrain aerosol forcing | Science Advances, 6(32), eabb5297 | Journal Article | doi:10.1126/sciadv.abb5297 | NA18OAR4320123 | X | | |
| CIMES | Silvers, Levi and Robinson, Thomas | February 2021 | Clouds and Radiation in a Mock-Walker Circulation | Journal of Advances in Modeling Earth Systems, 13(2), e2020MS002196 | Journal Article | doi:10.1029/2020MS002196 | NA18OAR4320123 | X | | |
| CIMES | Smyth, J.E. and Ming, Y. | Nov. 2020 | Characterizing drying in the South American monsoon onset season with the moist static energy budget | Journal of Climate, 33(22), 9735-9748 | Journal Article | doi:10.1175/JCLI-D-20-0217.1 | NA18OAR4320123 | X | | |
| CIMES | Sonnewald M, Dutkiewicz S, Hill C, Forget G | May 2020 | Elucidating ecological complexity: Unsupervised learning determines global marine eco-provinces | Science Advances, 6(22), eaay4740 | Journal Article | doi:10.1126/sciadv.aay4740 | NA18OAR4320123 | X | | |
| CIMES | Spingys, C. P., Naveira Garabato, A. C., Legg, S., Polzin, K. L., Abrahamsen, E. P., Buckingham, C. E., Forryan, A., & Frajka-Williams, E. E. | April 2021 | Mixing and Transformation in a Deep Western Boundary Current: A Case Study | Journal of Physical Oceanography, 51(4), 1205–1222 | Journal Article | doi:10.1175/JPO-D-20-0132.1 | NA18OAR4320123 | | | X |
| CIMES | Stanley, Z., Grooms, I., Kleiber, W., Bachman, S. D., Castruccio, F., Adcroft, A. | Dec. 2020 | Parameterizing the Impact of Unresolved Temperature Variability on the Large-Scale Density Field: Part 1. Theory. | Journal of Advances in Modeling Earth Systems, 12(12), e2020MS002185 | Journal Article | doi:10.1029/2020MS002185 | NA18OAR4320123 | | | X |
| CIMES | Su, Yibing and James A. Smith | In-Press | An Atmospheric Water Balance Perspective on Extreme Rainfall Potential for the Contiguous US | Water Resources Research, e2020WR028387 | Journal Article | doi:10.1029/2020WR028387 | NA18OAR4320123 | X | | |
| CIMES | Sun, Y.Q. and Zhang, F. | July 2020 | A New Theoretical Framework for Understanding Multiscale Atmospheric Predictability | Journal of the Atmospheric Sciences, 77(7), 2297–2309 | Journal Article | doi:10.1175/JAS-D-19-0271.1 | NA18OAR4320123 | X | | |
| CIMES | Tan, Z. and Shaw, T. A. | Sept. 2020 | Quantifying the Impact of Wind and Surface Humidity-Induced Surface Heat Exchange on the Circulation Shift in Response to Increased CO2 | Geophysical Research Letters, 47(18), e2020GL088053 | Journal Article | doi:10.1029/2020GL088053 | NA18OAR4320123 | X | | |
| CIMES | Titus M, Hagstrom G, Watson JR. | February 2021 | Unsupervised manifold learning of collective behavior | PLoS Computational Biology, 17(2), e1007811 | Journal Article | doi:10.1371/journal.pcbi.1007811 | NA18OAR4320123 | | | X |
| CIMES | Tong, Mingjing, Yanqiu Zhu, Linjiong Zhou, et al. | July 2020 | Multiple Hydrometeors All-Sky Microwave Radiance Assimilation in FV3GFS | Monthly Weather Review, 148(7), 2971-2995 | Journal Article | doi:10.1175/MWR-D-19-0231.1 | NA18OAR4320123 | | X | |
| CIMES | Tseng K.-C., N. C. Johnson., E. D. Maloney, E. A. Barnes, and S. B. Kapnick | In-Press | Mapping Large-scale Climate Variability to Hydrological Extremes: An Application of the Linear Inverse Model to Subseasonal Prediction | Journal of Climate | Journal Article | doi:10.1175/JCLI-D-20-0502.1 | NA18OAR4320123 | X | | |
| CIMES | Tsujino, H., Urakawa, L. S., Griffies, S. M., Danabasoglu, G., Adcroft, A., et al. | August 2020 | Evaluation of global ocean–sea-ice model simulations based on the experimental protocols of the Ocean Model Intercomparison Project phase 2 (OMIP-2) | Geoscientific Model Development, 13(8), 3643–3708 | Journal Article | doi:10.5194/gmd-13-3643-2020 | NA18OAR4320123 | | | X |
| CIMES | Wang C, Soden BJ, Yang W, Vecchi GA | February 2021 | Compensation Between Cloud Feedback and Aerosol-Cloud Interaction in CMIP6 Models | Geophysical Research Letters, 48(4), e2020GL091024 | Journal Article | doi:0.1029/2020GL091024 | NA18OAR4320123 | | | X |
| CIMES | Wang, Z., G. Zhang, T. Dunkerton, and F.-F. | Sept. 2020 | Summertime Stationary Waves Integrate Tropical and Extratropical Impacts on Tropical Cyclone Activity | Proceedings of the National Academy of Sciences of the United States of America, 117(37), 22605-22608 | Journal Article | doi:10.1073/iti3720117 | NA18OAR4320123 | | | X |
| CIMES | Xie, Y., Lin, M., & Horowitz, L. W. | August 2020 | Summer PM2.5 Pollution Extremes Caused by Wildfires Over the Western United States During 2017–2018 | Geophysical Research Letters, 47(16), e2020GL089429 | Journal Article | doi:10.1029/2020GL089429 | NA18OAR4320123 | X | | |

| CI Name | PI Name / Author Names | Publication Date | Publication Title | Published In (Journal Name, volume and page number) | Type of Publication | Citation No. (Digital Object Identifier) | Research Support Award No. | CI Lead Author | NOAA Lead Author | Other Lead Author |
|---|---|---|---|---|---|---|---|---|---|---|
| *CIMES* | *Yu Y, Kalashnikova OV, Garay MJ, et al.* | *July 2020* | *Disproving the Bodélé Depression as the Primary Source of Dust Fertilizing the Amazon Rainforest* | *Geophysical Research Letters, 47(13), e2020GL088020* | *Journal Article* | *doi:10.1029/2020GL088020* | *NA18OAR4320123* | *X* | | |
| *CIMES* | *Yu Y, Mao J, Thornton PE, al. et* | *June 2020* | *Quantifying the Drivers and Predictability of Seasonal Changes in African Fire* | *Nature Communications, 11, 2893* | *Journal Article* | *doi:10.1038/s41467-020-16692-w* | *NA18OAR4320123* | *X* | | |
| *CIMES* | *Yu, Y., J. P. Dunne, E. Shevliakova, P. Ginoux, S. Malyshev, J. G. John, and J. P. Krasting* | *January 2021* | *Increased risk of the 2019 Alaskan July fires due to anthropogenic activity [in "Explaining Extremes of 2019 from a Climate Perspective"]* | *Bulletin of American Meteorological Society, 102 (1), S1-S7* | *Journal Article* | *doi:10.1175/BAMS-D-20-0154.1* | *NA18OAR4320123* | *X* | | |
| *CIMES* | *Zhang, G., H. Murakami, T. Knutson, R. Mizuta, and K. Yoshida* | *April 2020* | *Tropical cyclone motion in a changing climate* | *Science Advances, 6(17), eaaz7610* | *Journal Article* | *doi:10.1126/sciadv.aaz7610* | *NA18OAR4320123* | *X* | | |
| *CIMES* | *Zhang, G., H. Murakami, X. Yang, K. Findell, A. Wittenberg* | *March 2021* | *Dynamical Seasonal Prediction of Tropical Cyclone Activity: Roles of Sea Surface Temperature Errors and Atmosphere/Land Initialization* | *Journal of Climate, 34(5), 1743–1766* | *Journal Article* | *doi:10.1175/JCLI-D-20-0215.1* | *NA18OAR4320123* | *X* | | |
| *CIMES* | *Zhang, G., L. Silvers, M. Zhao, and T. Knutson* | *March 2021* | *Idealized Aqua-Planet Simulations of Tropical Cyclone Activity: Significance of Temperature Gradients, Hadley Circulation, and Zonal Asymmetry* | *Journal of the Atmospheric Sciences, 78(3), 877–902* | *Journal Article* | *doi:10.1175/JAS-D-20-0079.1* | *NA18OAR4320123* | *X* | | |
| *CIMES* | *Zhang, Li, Meiyun Lin, A Langford, et al.* | *Sept. 2020* | *Characterizing sources of high surface ozone events in the southwestern U.S. with intensive field measurements and two global models* | *Atmospheric Chemistry and Physics, 20(17), 10379–10400* | *Journal Article* | *doi:10.5194/acp-20-10379-2020* | *NA18OAR4320123* | *X* | | |
| *CIMES* | *Zhang, W., Kirtman, B. Siqueira, L. Clement, A., Xia, J.* | *In-Press* | *Understanding the Signal-to-Noise Paradox in Decadal Climate Predictability from CMIP5 and an Eddying Global* | *Climate Dynamics* | *Journal Article* | *doi:10.1007/s00382-020-05621-8* | *NA18OAR4320123* | *X* | | |
| *CIMES* | *Zhang, Y. F., Bushuk, M., Winton, M., Hurlin, B., Yang, X., Delworth, T., & Jia, L.* | *March 2021* | *Assimilation of Satellite-Retrieved Sea Ice Concentration and Prospects for September Predictions of Arctic Sea Ice* | *Journal of Climate, 34(6), 2107-2126* | *Journal Article* | *doi:10.1175/JCLI-D-20-0469.1* | *NA18OAR4320123* | *X* | | |
| *CIMES* | *Zhang, Y., Held, I., and Fueglistaler, S.* | *March 2021* | *Projections of tropical heat stress constrained by atmospheric dynamics* | *Nature Geoscience, 14, 133–13* | *Journal Article* | *doi:10.1038/s41561-021-00695-3* | *NA18OAR4320123* | *X* | | |
| *CIMES* | *Zhang, Y., Jeevanjee, N., and Fueglistaler, S.* | *Sept. 2020* | *Linearity of outgoing longwave radiation: From an atmospheric column to global climate models* | *Geophysical Research Letters, 47(2), e2020GL089235* | *Journal Article* | *doi:10.1029/2020GL089235* | *NA18OAR4320123* | *X* | | |
| *CIMES* | *Zhou, X., Atlas, R., McCoy, I. L., Bretherton, C. S., Bardeen, C., Gettelman, A., Lin, P., Ming, Y.* | *February 2021* | *Evaluation of Cloud and Precipitation Simulations in CAM6 and AM4 Using Observations Over the Southern Ocean* | *Earth and Space Science, 8(2), e2020EA001241* | *Journal Article* | *doi: 10.1029/2020EA001241* | *NA18OAR4320123* | | | *X* |