COOPERATIVE INSTITUTE FOR MODELING THE EARTH SYSTEM (CIMES)

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ACCOMPLISHMENTS

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

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

ii. To apply this model to the problem of prediction across time and space scales, from high resolution simulations of extreme events, to prediction of climate phenomena from seasons to centuries.

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

iv. To train the next generation of leaders in earth system science, through the world-leading graduate Atmospheric and Oceanic Sciences program at Princeton University, and the AOS postdoctoral program.

v. To develop a more diverse workforce by broadening participation in earth system science training, through summer internships, visiting faculty exchange fellowships and increasing research collaborations with diverse institutions.

vi. Computational platform - CIMES acquired and is maintaining and utilizing an independent research high performance computational platform. This enables CIMES to collaborate with NOAA in the development, testing, and measurement of NOAA models using standard metrics of computational performance.

25. What was accomplished under these goals?*

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

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

Following the successful development of the MOM6 global ocean model used in the GFDL climate models CM4 and ESM4, the current focus of Cooperative Institute MOM6 development has been the development of open boundary conditions to allow MOM6 to be more widely used for regional simulations. In particular, postdoc Wenhao Chen has explored the influence of open boundary conditions on the generalized vertical coordinate system used in MOM6; Enrique Curchitser (Rutgers University) has developed a suite of North Atlantic regional implementations of MOM6 with resolutions from 1/12th to 1/25th of a degree, and Kate Hedstrom and Seth Danielson (University of Alaska Fairbanks) have constructed MOM6 Arctic configurations.

The MOM6 ocean model continues to be advanced through the development of parameterizations of subgrid-scale processes, including submesoscale symmetric instability (Yankovsky, Legg and Hallberg, 2021), internal wave mixing in canyons (Nazarian..Legg et al, 2021), density anomalies due to sub-grid temperature variance (Kenigson, Adcroft et al, 2022), and bubble-mediated gas transfer (Deike, 2022). Several CIMES researchers are engaged in applying machine learning to improve parameterizations of sub-grid-scale ocean processes, such as turbulent diffusion in the ocean surface boundary layer. Machine learning approaches are also being applied to improved predictions of nitrification rates for ocean ecosystem models by Princeton faculty Bess Ward.

A significant development over the past year has been the development of a continental-scale ice-sheet model, MOM6ice, as a component of the MOM6 ocean modeling system, by CIMES researchers Alistair Adcroft and Olga Sergienko, with GFDL colleagues.The MOM6ice model simulates flow of ice sheets, ice streams and ice shelves and interactions between ocean circulation in sub-ice-shelf cavities with ice shelves. Two coupled configurations of MOM6ice and MOM6 have been developed – a regional configuration of the Pine Island Glacier (West Antarctica), and a pan-Antarctic configuration that includes Antarctica and the Southern Ocean up to 55oS. Other developments in cryosphere modeling development include a parameterization of iceberg decay which produces realistic meltwater distributions from a realistic iceberg calving distribution (Huth, Adcroft and Sergienko, 2022), and a model of ice floe-floe interactions on pressure ridging in sea ice (Damsgaard, Sergienko and Adcroft, 2021).

Cooperative Institute researchers have made significant contributions to the GFDL land models in the past year, for example enhancing the land model capabilities through satellite soil moisture data assimilation (Vergopolan et al, 2021; Chaney, Vergopolan et al, 2021). Several CIMES researchers (Zun Yin, Enrico Zorzetto and Khaled Ghannam) have focused on improving representation of sub-grid land heterogeneity and its impacts on land-atmosphere interactions, including the development of a parameterization capturing the modulation of radiative fluxes by complex topography in mountainous regions, and implementation of a planetary boundary layer parameterization which includes the coupling between the land and atmosphere into the GFDL models (CLASP-EDMF). This new planetary boundary layer scheme leads to an earlier onset of convection over land. Another aspect of heterogeneity being explored by Princeton faculty Elie Bou-Zeid is that of coastal microscale dynamics, such as land-sea breezes, and their parameterization in coarse global models. As part of Climate Process Teams focused on the atmospheric boundary layer and clouds, several CIMES researchers have continued developing and implementing improved parameterization schemes, including the NCEP Turbulent Kinetic Energy-based eddy diffusivity mass-flux boundary scheme (Zhihong Tan), and the Mellor-Yamada-Nakanishi-Niino Eddy-Diffusivity/ Mass-flux scheme to address marine stratocumulus representation (Yi-Hsuan Chen). Youtong Zheng has implemented the framework for improvement by vertical enhancement (FIVE) to improve model representation of marine shallow cumulus, and conducted evaluations of the representation of polar low clouds by GFDL AM4.

CIMES researchers are contributing to improvements in representation of atmospheric aerosols and chemistry in GFDL models. For example, Chloe Gao is evaluating a new representation of the stratospheric sulfur cycle in the GFDL ESM4.1, which replaces previously prescribed distribution of aerosol optical properties with a newly implemented capability to simulate stratospheric sulfur aerosols prognostically, driven by volcanic and non-volcanic sources. For this model, stratospheric sulfate mass burden and AOD are found to be most sensitive to volcanic SO2 injection height.

Princeton researcher George Hagstrom has completed development of the ATOM-COBALT model, which incorporates dynamic elemental stoichiometry of small, large, and diazotroph phytoplankton groups within the COBALT food-web model. ATOM-COBALT incorporates several physiological mechanisms that impact phytoplankton elemental stoichiometry. A set of global, 60-year retrospective simulations in ESM-4, revealed the biogeochemical signatures of the physiological mechanisms proposed to control phytoplankton elemental stoichiometry and the new biogeochemical feedbacks induced by dynamic stoichiometry. Another model development focused on ecosystems is the new Freshwater Algae, Nutrient, and Solid cycling and Yields (FANSY) model, incorporated within the land model, which simulates global coupled algae, nitrogen, phosphorus, and solid dynamics in rivers and lakes.

An important component of model development is the examination of model biases. Yanda Zhang has examined precipitation biases in ESM4 and CM4, and found that over a 100-yr time period (1915-2014), these models simulated a drier precipitation trend than observations, especially at middle-high latitudes and over East Asia. Compared to the CM4 simulation, the ESM4 historical run simulated stronger drying and weaker wetting trends. The bias in precipitation trends simulated by the ESM4 and CM4 models is probably caused by weaker GHG warming effects in the ESM4 model due to the lower climate sensitivity and overestimation of the negative contribution from aerosol effects. Pu Lin has examined the impact of the equatorward bias in the extratropical jet position in CM4 on the climate system by comparing the standard CM4 historical simulation to those with stratospheric winds nudged to MERRA2 reanalysis data. The stratospheric-nudged CM4 shows a more poleward jet in both hemispheres as well as a stronger global-mean warming trend over the past few decades. The anomalous warming mainly occurs over the southern subpolar region and is brought about by the adjustment of the oceanic circulation to the more poleward jet.

Many of these model developments are made possible by advances in software infrastructure achieved by CIMES technical specialists Aparna Radhakrishnan and Sergei Nikonov, working with GFDL Modeling Systems, including the Process Orientated Diagnostics created by the Model Diagnostics Task Force (MDTF) under a unified software framework integrated into GFDL's modeling workflow, and cloud-computing developments using Amazon Web Services. Additionally, the machine learning tool THOR (Tracking global heating with ocean regimes), which is being considered for inclusion in the Model Diagnostics Taskforce package, has been used to extract understanding from GFDL and CMIP6 simulations for a variety of global ocean phenomena (Sonnewald..Balaji et al, 2021, Sonnewald and Lguensat, 2021).

Goal ii. To apply this model to the problem of prediction across time and space scales, from high resolution simulations of extreme events, to prediction of climate phenomena from seasons to centuries.

There are two main prediction model systems configured and applied to a variety of phenomena by CIMES researchers in collaboration with GFDL colleagues. SPEAR (Seamless system for Prediction and EArth system Research) is applied mainly to subseasonal-to-seasonal (S2S) and seasonal-to-decadal (S2D) prediction. CIMES researcher Feiyu Lu has analyzed the prediction skill of the SPEAR S2S system on the extreme heatwave that occurred in western North America in early summer of 2021.

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

SPEAR has been applied to prediction of Atmospheric rivers (ARs) (intense lower tropospheric plumes of moisture) on subseasonal to seasonal (S2S) by CIMES researcher Wei Zhang, evaluating the global forecast skill of wintertime AR activities out to a 4-week lead and examining the sources of S2S predictability using an average predictability time (APT) analysis. The SPEAR model shows reliable AR forecast skill in the first two weeks, which becomes less evident in week 3 in the midlatitudes. Higher forecast skill is detected for strong AR (3-7 days/week) than weak AR (1-2 days/week) activities at 1-4-week lead times, despite that the occurrence probability of weak AR activity outperforms strong AR activities. The potential sources of predictability are examined, and three leading modes identified, interpreted as the El Niño–Southern Oscillation, the Pacific North American, and the Arctic Oscillation patterns. Reconstruction of AR forecast skill using these three leading modes provides results comparable with raw forecast estimation.

Application of SPEAR to prediction of the Pacific Western Boundary Current system (Yongji Joh et al 2022) shows that assimilating subsurface observations appears to be critical to reproduce the narrow front and related oceanic variability of the Kuroshio Extension (KE) jet. Skillful retrospective predictions of KE SSH variability in monthly (up to 1 year) and annual-mean (up to 5 years) KE forecasts are produced in the seasonal and decadal prediction systems, respectively. The prediction skill varies seasonally, peaking for forecasts initialized in January and verifying in September due to the winter intensification of North Pacific atmospheric forcing. Strong large-scale atmospheric anomalies generate deterministic oceanic forcing (i.e., Rossby waves), leading to skillful long-lead KE forecasts.

SPEAR is being applied to seasonal predictions of tornado activity over the continental USA by Kai-Chih Tseng, and to predictions of extreme precipitation over the Northeast USA by Bor-Ting Jong. The predictability of Arctic sea-ice has been examined by Yong-fei Zhang, who has identified the need for data assimilation of Sea Ice Thickness to improve predictions of sea-ice thickness anomalies at regional and local scales.

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

The development of T-SHiELD, an application of SHiELD to real-time hurricane forecasting, has been continued by Kun Gao, with recent improvements to boundary layer scheme and shallow convection scheme leading to reductions in track and gale wind radii biases. The updated T-SHiELD was run in real-time during the 2021 hurricane season, and performed better than the operational GFS and HWRF in terms of track forecasts. The T-SHiELD performance on forecasting post-landfall tropical cyclone wind field has been examined by CIMES researcher Jie Chen, demonstrating that the existing theoretical TC structural model can generate the full azimuthal wind profile of real-world U.S. landfalling hurricanes with limited, simple input parameters (HURDAT and surface property information). T-SHiELD generally reproduces the evolution of the high wind region of the landfalling hurricanes (2015-2021).

Seasonal-to-interranual ocean habitat forecasts are possible with the regional MOM6 configurations described in the previous theme coupled with the COBALT ecosystem model (Drenkard…Ross et al, 2021). Andrew Ross competed multi-decadal hindcast simulations for the Northwest Atlantic Ocean physics and biogeochemistry taking advantage of new support for generic tracer boundary conditions in MOM6, and ran a set of simulations using the Northwest Atlantic Ocean regional MOM6 model to downscale a subset of GFDL's SPEAR retrospective seasonal forecasts. These simulations were able to forecast sea surface temperature in the Northeast US Large Marine Ecosystem region at higher resolution than SPEAR and with overall skill roughly comparable to the larger SPEAR ensemble.

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.

GFDL earth system models have been used to investigate several topics involving climate and ecosystems. CIMES researcher Hyung-Gyu Lim has examined the coupling between the El Niño–Southern Oscillation (ENSO) and phytoplankton in the tropical Pacific using ESM4.1. This model captures observed ENSO-chlorophyll patterns ($r=0.57$) much better than GFDL's previous ESM2M ($r=0.23$). Most notably, the observed post-El Niño “chlorophyll rebound” is substantially improved in ESM4.1 ($r=0.52$). An anomalous increase in iron propagation from western Pacific (WP) subsurface to the cold tongue via the equatorial undercurrent (EUC) and subsequent post-El Niño surfacing, unresolved in ESM2M, is the primary driver of chlorophyll rebound. This chlorophyll rebound is augmented by high post-El Niño dust-iron deposition anomalies in the eastern EP, and provides a previously unrecognized source of marine ecosystem resilience independent from the La Niña that sometimes follows.

CIMES researcher Hubert du Pontavice has used GFDL ocean models to provide environmental information for groundfish sock assessments over the Northeast U.S. continental shelf using ocean models (du Pontavice et al., 2022). This study demonstrated that incorporating environmental effects on yellowtail flounder recruitment may improve the predictive skills of recruitment and, to a lesser extent, spawning stock biomass. The performance of stock assessment models that incorporated ocean model-based indices was improved compared to the model using only the observation-based index. The predictive skill improvement in recruitment and spawning stock biomass with ocean model-based indices suggests that ocean models may benefit stock assessments when ocean observations are limited.

Princeton faculty Laure Resplandy has applied ESMs including GFDL-CM4 and ESM4 to investigate the evolution of the largest oxygen minimum zone (OMZ) in the Pacific ocean. The ESMs project volume changes falling into three regimes: an expansion of low oxygenated waters ($O2 < 120umol/kg$); a contraction of the OMZ core ($O2 < 20umol/kg$); and at the transition from contraction to expansion, a spatial redistribution but near-zero change in hypoxic waters ($O2 < 60umol/kg$). Circulation and biology dictate the shift from expansion to contraction. Model complexity stabilizes the OMZ response, suggesting that future changes might lie in the lower bound of projections. The expansion of low oxygenated waters which delimit the optimum habitat of numerous marine species would lead to severe impacts on ecosystems. Additionally, Resplandy has investigated the risk of coastal hypoxia in the northern Indian Ocean. Using a database merging in-situ temperature and oxygen profiles from different platforms, the risk of coastal hypoxia is found to be highest south of the Indian Peninsula during boreal summer/fall, and in the eastern Bay of Bengal during winter/spring. IOD can increase the likelihood of hypoxia by modulating wind-driven and wave-driven upwelling.

CIMES researcher Minjin Lee has explored responses of the global terrestrial and freshwater nitrogen transport to anthropogenic land use and climate change, using the GFDL Land Model LM3-TAN to project 21st-century pathways of river nitrogen loads across socioeconomic and climate scenarios. Globally, fertilizer use is high in scenarios with large biofuel crop production to meet climate mitigation goals. The imprint of fertilizer applications on river nitrogen loads is reduced by ecosystem processes under elevated CO2, but remains manifest. While the highest emission scenario achieves the best outcomes in terms of water nitrogen pollution, the favorability of projections must be weighed against myriad and likely severe climate change impacts. River nitrogen loads generally increase in low per capita gross domestic product (PCGDP) regions and remain stable or decrease in high PCGDP regions. Careful consideration of unintended effects of bioenergy production on water quality and rapid transfer of agricultural advances from high to low PCGDP regions may help avoid inequitable outcomes from climate mitigation.

The response of tropical forests to climate change has been examined by CIMES researcher Isabel Martinez Cano, using GFDL-ESM4.1, finding that under extreme emission scenario SSP5-8.5, Amazon forests may begin to convert to savanna before mid-century as a consequence of increased forest fires. Projected fires resemble contemporary responses to dry conditions associated with El Niño Southern Oscillation and the Atlantic Multidecadal Oscillation, exacerbated by an overall decline in precipitation. Following the initial disturbance, grassland dominance promotes recurrent fires and competitive exclusion which lead to an arrested successional state that prevents forest recovery and impairs the tropical carbon sink.

GFDL ESMs have been applied to understand links between climate change and air-quality by Yuanyu Xie and Meiyun Lin, focusing on the role of biosphere-atmospheric interactions on air pollution through particulates from wildfires (Xie et al 2022) and impacts of drought-stressed vegetation on ozone pollution extremes.

Another key societal impact of climate which has received attention from numerous CIMES researchers is precipitation, including extremes. Princeton faculty James Smith has focused on extreme flooding events, including from the remnants of Hurricane Ida and in the lower Mississippi Basin where an increase in atmospheric rivers is leading to an increase in extreme flooding. CIMES researcher Abigail Lute used medium and high resolution SPEAR model outputs to analyze historical and future changes in snowpack in High Mountain Asia, where millions of people depend on the snow for water supply and agriculture. In the SSP585 scenario, elevation dependent trends in historical and future winter air temperatures are found across the domain such that higher elevations warm more quickly than lower elevations, with important implications for snow sensitivity to climate change in this region. Whereas historical trends (1940-2014) in annual peak snow water equivalent (SWE) were spatially variable, future trends in peak SWE (2015-2100) were negative, despite increasing winter precipitation in some basins. The greatest declines in maximum SWE were found at mid-elevations. The time of emergence of anthropogenic climate change signals were examined in a variety of climate and snow metrics.

CIMES researcher Yujin Zeng has applied GFDL ESMs to understand the links between irrigation and precipitation, finding that irrigation in the Middle East and South Asia may enhance rainfall in a large portion of the Sahel-Sudan Savanna (SSS) to an extent comparable and opposite to its suppression by other anthropogenic climate drivers during the last several decades (Zeng et al, 2022). The enhancement arises through a reduction in the meridional gradient of moist static energy from the Sahara Desert to the tropical rainforests. Remote irrigation is therefore a possible factor affecting the risk of drought and famine and, thus, future water security in the SSS region.

Extreme heat is another societally-relevant impact of climate change being examined by CIMES researchers, including projections of tropical heat stress under global warming (Zhang et al, 2021) and the role of historical urbanization in the extreme heat wave event in the Pacific Northwest of North America in the summer of 2021 (Philip…Vecchi et al, 2021).

Goals iv: To train the next generation of leaders in earth system science, through the world-leading graduate Atmospheric and Oceanic Sciences program at Princeton University, and the AOS postdoctoral program; **and Goal v:** To develop a more diverse workforce by broadening participation in earth system science training, through summer internships, visiting faculty exchange fellowships and increasing research collaborations with diverse institutions;

Accomplishments are described under question 26 on opportunities for training and professional development/dissemination.

Goal vi. Computational platform - CIMES acquired and is maintaining and utilizing an independent research high performance computational platform. This enables CIMES to collaborate with NOAA in the development, testing, and measurement of NOAA models using standard metrics of computational performance.

CIMES was awarded PAC Research Supercomputing funding of $3,003,285 ($118,285 in Task I and $2,885,000 in Task II) in September 2020 and $3,003,285 ($112,732 in Task I and $2,890,553 in Task II) in July 2021 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. In June 2021, CIMES paid $57,333 for NVMe shared storage system. The new cluster has been fully operational since July 2021. Our HPC Cluster, named Stellar, has an active userbase, and several NOAA models have been ported. In February 2022, Dr Timothy Merlis (formerly Associate Professor, McGill University) began in the role of High Performance Computing Manager. The new user account creation process was streamlined in March 2022 and there are approximately two new CIMES users per month. The NOAA models available on the HPC cluster currently include GFDL's AM4, MOM6, TSHiELD, XSHiELD, as well as key parts of GFDL's post-processing workflow. The HPC cluster is enabling CIMES personnel to contribute to the development of Machine Learning techniques for ocean models and the evaluation of prototype Global Storm Resolving Models of the atmosphere.

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

CIMES provides excellent training to both students and early career scientists in the Princeton Atmospheric and Oceanic Sciences Program. CIMES-funded students and postdocs receive scientific guidance from GFDL scientists, and have access to all education and career-development resources at Princeton University. During the past year, the project has provided support to 15 graduate students in the AOS graduate program, of whom 3 have obtained their PhDs during this reporting period. In addition to funding their research, the students' participation in professional meetings was also supported by this project. 38 postdoctoral and early career researchers were trained through participation in this project during the past year.

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

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

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

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

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 2021, 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 the continuing recruitment of BCC and Hunter College students to the CIMES internship program.

Additional educational and training activities undertaken through CIMES include: mentoring of NOAA Hollings and Lapenta interns by CIMES researchers; mentoring of AOS graduate students and postdocs; mentoring by Princeton faculty of Princeton undergraduates, graduate students and postdocs on CIMES-funded projects or related projects; teaching or providing guest lectures for Princeton university courses; participation in Princeton University courses by CIMES-funded students and postdocs, including scientific writing, coding, and pedagogy courses; professional development courses provided by Princeton's career center. Other specific examples include participation in the Young Earth System Scientists (YESS community) Machine Learning group (Hyung-Gyu Lim), NOAA Artificial Intelligence (AI) Hackathon and Vulcan Workshop on DSLs for Weather and Climate (Joseph Mouallem); Teaching a tutorial workshop at the Society for Industrial and Applied Mathematics (SIAM): Conference on Mathematical and Computational Issues in Geoscience, for 60 graduate and undergraduate level participants (Maike Sonnewald); participating as a mentor for the nationwide MPOWIR (Mentoring physical oceanography women to increase retention) program (Sonya Legg); attendance at the SACNAS Diversity in STEM conference as a mentor (Marion Alberty); participation in the MPOWIR Pattullo professional development conference (Yongfei Zhang); Lectures at the University of Reading Climate Modeling Summer School, and the University of Bologna Physical Sensing and Processing Summer School (V. Balaji).

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

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

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

In the next year, CIMES researchers will continue to i. contribute to the development of NOAA-GFDL's earth system models, ii. apply these models to problems of prediction across time and space scales, from extreme events to climate phenomena, and iii. apply these models to understand the impacts of a changing climate on societally-relevant problems. Additionally, CIMES will continue to iv. train the next generation of leaders in earth system science and v. develop a more diverse workforce by broadening participation in earth system science.

Specific plans for the next year are as follows:

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

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

Efforts to improve parameterizations of atmospheric boundary layer processes and land-atmosphere interactions with heterogeneous land surfaces will continue, including: examining the performance of the MYNN Eddy-Diffusivity Mass Flux scheme, implementing the Framework for Improvement by Vertical Enhancement (FIVE) in AM4-EDMF to investigate the sensitivity on the vertical resolution, making the EDMF scheme scale aware, extending the EDMF scheme to represent shallow cumulus, evaluating the performance of the AM4-EDMF and FIVE schemes in global simulations. A new parameterization of land-sea breezes will be developed and embedded into the EDMF scheme.

Development of MOM6 ice will continue in the coming year. It will be coupled to the GFDL sea-ice model SIS2, and poorly constrained parameters will be optimized using available observations and inverse-method techniques. Simulations of the pan-Antarctic configuration with atmospheric forcing reanalysis will be performed.

Planned improvements to MOM6 in the next year include refinement of regional implementations, by developing and implementing open boundary conditions in an ice-ocean coupled model, and implementing ECMWF ERA5 atmospheric forcing fields and COBALT biogeochemistry. The behavior of open boundary conditions with different generalized vertical coordinates will be investigated and improved OBCs will be implemented. For the global ocean model, new OM4.1 physics will be evaluated, a new parameterization of mixed-layer eddies will be implemented, new mesoscale eddy parameterizations and various machine-learning parameterizations will be evaluated in MOM6. Other new parameterizations to be implemented and evaluated include internal tide farfield mixing, including in continental slope canyons. Simulations coupling wave and ocean models will test the implications of sea-state dependent formulations for gas-transfer and sea spray.

As a member of the core development team of GFDL's next generation atmospheric model (AM5), Pu Lin will be closely engaged in AM5 development, assessing model sensitivity to model top and vertical resolution in the stratosphere as well as gravity wave parameterization, in terms of the simulated climatology and variability in the stratosphere.

Improvement and evaluation of the GFDL land model LM4 will continue, including evaluation of the hydrology-related performance of the latest version LM4p2, further study of the impacts of topographic disaggregation on surface climate, improvement of the representation of tropical forest and savanna vegetation types, and improvement in the representation of the land nitrogen cycle. The 3D topography parameterization implemented to date will be further evaluated and work will focus on the effects of the new 3D parameterization on effective albedo and snow cover. A parameterization that explicitly describes the internal mixing of impurities (black carbon, dust) in snow grains will be implemented and evaluated in LM4.

The efficiency of the RRTMG-P radiation code implementation in AM4 will be improved, along with the representation of radiation-microphysics interactions. The model of volcanic emissions will be extended to include aerosol microphysics, including a dynamic size distribution. Representation of marine nitrification will continue to be improved, with revised mechanisms implemented in COBALT, and evaluated in ESM simulations.

Many of these model improvements will make use of the Model Diagnostics Task Force Process Oriented Diagnostics (PODs), including the machine learning based "Watching OceaN Dynamics Employing Remote Sensing (WONDERS)". The further expansion of machine learning techniques to improve model parameterization and development will continue.

Goal ii: To apply this model to the problem of prediction across time and space scales, from high resolution simulations of extreme events, to prediction of climate phenomena from seasons to centuries.

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

The application of T-SHiELD to tropical cyclone forecasts will continue, addressing: reasons for the gap in track performance between T-SHiELD and SHiELD at longer lead times; refinement of the boundary layer parameterization under hurricanes; examination how the change in particle size distributions affects the eyewall convection and outer rainband activity; determining the processes responsible for the reduction of storm intensity when the updated GFDL Microphysics is used; and exploring simulation approaches, such as initial conditions and environmental conditions, to reduce forecast bias.

The SPEAR forecasting system will continue to be advanced. The OTA data assimilation will be improved using machine learning, and these machine learning models will be applied in coupled SPEAR model simulations. The SPEAR S2S prediction system will incorporate aspects from the seasonal prediction system (ODA initial conditions and OTA bias correction), unifying SPEAR prediction capabilities across timescales, and applying the system to S2S heatwave prediction. SPEAR's Earth system prediction capability will be expanded to biogeochemistry and fishery applications. Eddy-permitting SPEAR simulations will be applied to prediction of Pacific seasonal to decadal variability, focusing on the role of the Pacific WBC system.

SPEAR-HI will continue to be applied to examine the increasing extreme precipitation over the U.S, expanding to study physical processes that have caused the increasing autumn extreme precipitation over the Northeast, including the thermodynamic and dynamical contributions. SPEAR-HI will also be used to perform statistical analysis associated with extreme events to estimate the decadal variability of climate extremes driven by long-term changes in regional wave interference. This study will also include an investigation of regional wave interference over the North Atlantic Ocean, which would shed light on explaining the increasing trends of climate extremes over Europe and rapid warming over the Atlantic sector of the Arctic Ocean on a decadal time scale.

Land data assimilation, using a machine learning model, will be included in SPEAR, and resulting changes in hydroclimate predictability (floods and droughts) will be assessed. SPEAR will also be applied to examine trends and prediction of subseasonal drought in the central USA, and regional dependence of seasonal tornado forecasts in the continental USA.

Seasonal sea ice forecasts will be improved by refining Seasonal Ice Thickness Data Assimilation (SIT DA), by perturbing sensitive parameters (e.g. snow conductivity) to improve representation of model uncertainty, and inflating ensemble members before filtering. Seasonal Ice Concentration (SIC) and Seasonal Ice Thickness (SIT) observations will be assimilated jointly, to examine the additional benefits of SIT DA in subseasonal-to-seasonal Arctic sea ice predictions. Another set of SPEAR reforecast experiments will be initialized from the SIC and SIT joint DA product, with analysis focusing on SIC, SIT, Sea Ice Extent, ice-free probability, and ice-free date.

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. Examples of specific plans for the next year include:

ESM4 model simulations will be applied to obtain global and regional perspectives on ocean acidification and marine ecosystem multi-stressor extremes under climate change and mitigation, using a coastal residence time tracer to map coastal residence times under the various historical, climate change, and mitigation scenarios. OAP buoy data and other ocean acidification data sets will be used for comparisons of model and observational variance on various temporal and spatial scales. Global and regional maps of trends and variability in stressor extremes will be generated.

Applications of GFDL models to marine stock assessments will continue with the assessment of the skills of the new high-resolution bottom temperature product over the NE USA continental shelf, using different sources of observation data. Environmental covariates will be incorporated into the stock assessment model for American lobster, to better understand the past dynamics of the population and forecast the key population components required to manage fisheries (biomass, recruitment, yield), using NOAA GFDL’s next generation ocean model MOM6 in order to link climate and life history parameters.

CM4 and ESM4.1 solutions will be examined to determine how different modes of climate variability (Pacific Decadal Oscillation and North Pacific Gyre Oscillation) are represented, so the influence of these modes in driving biogeochemical anomalies in the coast and open ocean regions off the California Current System can be assessed. The role of circulation and biogeochemistry in driving coastal oxygen anomalies in the different models will then be assessed.

The LM3-FANSY model will be applied to problems of direct relevance to coastal ecosystems, including changes in nitrogen:phosphorus ratios of river loads to the coastal ocean, which has been recognized as a major culprit of shifts in community composition towards more toxic or harmful algal species, and the effects of land-originated pollutant loadings on coastal ecosystems and resources.

LM4 will be applied to assess the resilience of tropical forests and potential ramifications of global change stressors, including the resilience to fires and droughts and the likelihood of reaching a tipping point during this century.

GFDL climate model ensemble simulations are being applied to examine the impact of marine cloud brightening geoengineering on US hydroclimate. Daily extreme precipitation event occurrences over the U.S. will be analyzed under the warming vs. geoengineering scenarios, with the goal of identifying the main factors under the geoengineering scenario that affect North American hydroclimate.

Research on extreme rainfall and flooding will continue in three settings: 1) the Lower Mississippi River basin, 2) the southern US, focusing on major severe weather and flooding episodes and 3) the Mid-Atlantic and Northeastern US, focusing on extreme rainfall and flooding from the remnants of Hurricane Ida (2021). A core objective of this study is assessing and enhancing the capabilities of Earth System Models to simulate extreme convective rainfall, especially the GFDL SHiELD model.

Urbanization and heat waves research will continue with a deeper analysis of the PNW heat wave and the role of urbanization, and a study on the overall impact of urbanization and climate on the urban heat island using AM4/LM4.

PRODUCTS

29. Publications, conference papers, and presentations*

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

Conferences/workshops

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

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

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

30. Technologies or techniques*
xWMT software package
https://github.com/jetesdal/xwmt

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

Model Diagnostics Task Force Framework for Process Oriented Diagnostics

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

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

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

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

31. Inventions, patent applications, and/or licenses*
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
FV3: Atmospheric dynamical core
AM4: Atmospheric model

AM4 EDMF: Eddy-diffusivity mass flux parameterization
AM4 single-column model with FIVE
LM4: Land model
LM3-FANSY: Freshwater Algae, Nutrient, and Solid cycling and Yields model
CM4: coupled climate model
ESM4.1: earth system model
COBALTv2: Ocean biogeochemical model
ATOM-COBALT: a food-web biogeochemical model which implements dynamic elemental stoichiometry within the framework of COBALT.
SHiELD: System for High-resolution prediction on Earth-to-Local Domains
SPEAR: Seamless system for Prediction and EArth system Research
UFS: Unified forecast system
GFDL MP: cloud microphysics scheme
https://github.com/elisamantelli/Icestreamformation_SchoofMantelli_RSPA : Icestream code
RMC: radiation Monte Carlo code for shortwave radiation over complex terrain
Tools

MDTF: Model diagnostics task force framework
AWS S3: Cloud-hosted CMIP6 data
Tutorial for analyzing vorticity budget in https://mom6-analysiscookbook.readthedocs.io/en/latest/notebooks/Closing_vorticity_budget.html
Gridtools GitHub repository for grid generation for MOM6
THOR: https://github.com/maikejulie/DNN4Cli
https://esgf-world.s3.us-east-2.amazonaws.com/index.html#CMIP6/
MOM6 analysis tools: https://mom6-analysiscookbook.readthedocs.io/en/latest/notebooks/Closing_tracer_budgets.html
https://mom6-analysiscookbook.readthedocs.io/en/latest/notebooks/Watermass_transformation.html
https://mom6-analysiscookbook.readthedocs.io/en/latest/notebooks/Closing_layerwise_tracer_budgets.html
xWMT software package: https://github.com/jetesdal/xwmt
Implementation in dora/om4labs (GFDL model evaluation tool): https://github.com/raphaeldussin/om4labs

Databases

SPEAR S2S hindcasts

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

Seasonal tornado forecast product

PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

33. What individuals have worked on this project?*
Stephan A. Fueglistaler, Director
Gabriel A. Vecchi, Deputy Director
Sonya A. Legg, Associate Director

Senior Personnel:
Alistair Adcroft, Senior Research Oceanographer
V. Balaji, Head, Modeling System Group
Meiyun Lin, Research Scholar
Olga Sergienko, Research Glaciologist

34. Has there been a change in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period?*
The previous PI/Director Gabriel Vecchi has assumed the role of Deputy Director while the previous Deputy Director, Stephan Fueglistaler as assumed the role of Lead PI/Director. Meiyun Lin, a Research Scholar at Princeton/CIMES, resigned on 9/27/21 to accept a position as a Physical Research Scientist at NOAA/GFDL.

35. What other organizations have been involved as partners?*
There has been no partners but two subawards have been issued; Rutgers University and 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 38 postdoctoral researchers and 15 graduate students in Princeton University Atmospheric and Oceanic Sciences Program in the past year. Additionally, 7 undergraduate students, 4 of whom were from groups under-represented in science, received training in earth system science and research methods as part of the CIMES research internship program in 2021. CIMES researchers have exposed the general public to earth system and climate science through outreach events such as the New Jersey Ocean Fun Days and the Climate Up Close program.

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

CHANGES/PROBLEMS

45. Changes in approach and reasons for change*

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

FY22 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	Abalos, M., et al., Pu Lin, and coauthors	Sept. 2021	The Brewer-Dobson circulation in CMIP6	Atmospheric Chemistry and Physics, 21(17), 13571–13591	Journal Article	doi:10.5194/acp-21-13571-2021	NA18OAR4320123			X
CIMES	Allouche M, Bou-Zeid E, Ansorge C, Katul GG, Chamecki M, Acevedo O, Thanekar S, Fuentes JD	April 2022	The Detection, Genesis, and Modeling of Turbulence Intermittency in the Stable Atmospheric Surface Layer	Journal of the Atmospheric Sciences, 79(4), 1171–1190	Journal Article	doi:10.1175/JAS-D-21-0053.1	NA18OAR4320123	X		
CIMES	Behl M, Cooper S, Garza C, Kolesar SE, Legg S, et al.	Sept. 2021	Changing the Culture of Coastal, Ocean, and Marine Sciences: Strategies for Individual and Collective Actions	Oceanography, 34(3), 53-60	Journal Article	doi:10.5670/oceanog.2021.307	NA18OAR4320123			X
CIMES	Berny, A, S. Popinet, T. Seon and L. Deike	May 2021	Statistics of jet drop production	Geophysical Research Letters. 48(10), e2021GL092919	Journal Article	doi:10.1029/2021GL092919	NA18OAR4320123			X
CIMES	Berny, A., L. Deike, S. Popinet and T. Seon	January 2022	Size and speed of jet drops are robust to initial perturbations	Physical Review Fluids, 7(1), 013602	Journal Article	doi:10.1103/PhysRevFluids.7.013602	NA18OAR4320123			X
CIMES	Bushuk, M., Winton, M., Haumann, F. A., Delworth, T., Lu, F., Zhang, et al.	August 2021	Seasonal Prediction and Predictability of Regional Antarctic Sea Ice	Journal of Climate, 34(15), 6207-6233	Journal Article	doi:10.1175/JCLI-D-20-0965.1	NA18OAR4320123			X
CIMES	Bushuk, M., Zhang, Y., Winton, M., Hurlin, B., Delworth, T., Lu, F., et al.	In-Press	Mechanisms of Regional Arctic Sea Ice Predictability in Two Dynamical Seasonal Forecast Systems	Journal of Climate	Journal Article	doi:10.1175/JCLI-D-21-0544.1	NA18OAR4320123			X
CIMES	Chaney, N., et al., Vergopolan, N., et al.	Nov. 2021	HydroBlocks v0.2: enabling a field scale two way coupling between the land surface and river networks in Earth system models	Geoscientific Model Development, 14(11), 6813–6832	Journal Article	doi:10.5194/gmd-14-6813-2021	NA18OAR4320123			X
CIMES	Cheng, K.-Y., Harris, L. M., and Sun, Y. Q.	February 2022	Enhancing the accessibility of unified modeling systems: GFDL System for High-resolution prediction on Earth-to-Local Domains (SHiELD) v2021b in a container	Geoscientific Model Development., 15(3), 1097–1105	Journal Article	doi:10.5194/gmd-15-1097-2022	NA18OAR4320123	X		
CIMES	Coffey NB, MacAyeal DR, Copland L, Mueller DR, Sergienko OV, Banwell AF, Lai C-Y	In-Press	Enigmatic surface rolls of the Ellesmere Ice Shelf	Journal of Glaciology	Journal Article	doi: 10.1017/jog.2022.3	NA18OAR4320123			X
CIMES	Damsgaard, A., Sergienko, O. & Adcroft, A.	July 2021	The Effects of Ice Floe-Floe Interactions on Pressure Ridging in Sea Ice	Journal of Advances in Modeling Earth Systems, 13(7), e2020MS002336	Journal Article	doi:10.1029/2020MS002336	NA18OAR4320123			X
CIMES	Deike, L.	January 2022	Mass transfer at the ocean-atmosphere interface: the role of wave breaking, drops and bubbles	Annual Review of Fluid Mechanics. 54, 191-224	Journal Article	doi:10.1146/annurev-fluid-030121-01413	NA18OAR4320123	X		
CIMES	DeLang M, Becker J;, Chang K-L, Serre M, Cooper O, et al.	April 2021	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, 55(8), 4389–4398	Journal Article	doi:10.1021/acs.est.0c07742	NA18OAR4320123			X
CIMES	Drenkard, E. J., Stock, C., Ross, A. C., Dixon, K. W., and coauthors	Sept. 2021	Next-generation regional ocean projections for living marine resource management in a changing climate	ICES Journal of Marine Science 78(6), 1969–1987	Journal Article	doi:10.1093/icesjms/fsab100	NA18OAR4320123		X	
CIMES	du Pontavice, H., Gascuel, D., Reygondeau, G., Stock, C., D., & Cheung, W. W. L.	June 2021	Climate-induced decrease in biomass flow in marine food webs may severely affect predators and ecosystem production	Global Change Biology, 27(11), 2608-2622	Journal Article	doi:10.1111/gcb.15576	NA18OAR4320123	X		
CIMES	Farsoiya, P. Kumar, S. Popinet and L. Deike	August 2021	Bubble mediated transfer of dilute gas in turbulence	Journal of Fluid Mechanics, 920, A34	Journal Article	doi:10.1017/jfm.2021.447	NA18OAR4320123			X
CIMES	Frazer, Michelle E. and Ming, Yi	April 2022	Understanding the Extratropical Liquid Water Path Feedback in Mixed-Phase Clouds with an Idealized Global Climate Model	Journal of Climate, 35(8), 2391–2406	Journal Article	doi:10.1175/JCLI-D-21-0334.1	NA18OAR4320123	X		
CIMES	Freidenreich, S., D. Paynter, P. Lin, V. Ramaswamy, A. L. Jones, D. Feldman and W. D. Collins	June 2021	An Investigation Into Biases in Instantaneous Aerosol Radiative Effects Calculated by Shortwave Parameterizations in Two Earth System Models	Journal of Geophysical Research Atmospheres, 126(11), e2019JD032323	Journal Article	doi:10.1029/2019JD032323	NA18OAR4320123		X	
CIMES	Gao, Kun, Lucas Harris, Linjiong Zhou, et al.	Sept. 2021	On the sensitivity of hurricane intensity and structure to horizontal tracer advection schemes in FV3	Journal of the Atmospheric Sciences, 78(9), 3007–3021	Journal Article	doi:10.1175/JAS-D-20-0331.1	NA18OAR4320123	X		
CIMES	Germineaud C., Cravatte S., Sprintall J., Alberty M.S., Grenier M., Ganachaud A.	May 2021	Deep pacific circulation: New insights on pathways through the Solomon Sea	Deep Sea Research Part 1: Oceanographic Research Papers 171, 103510	Journal Article	doi:10.1016/j.dsr.2021.103510	NA18OAR4320123			X
CIMES	Guo, Huan, et al., Linjiong Zhou, et al.	June 2021	Two-Moment Bulk Cloud Microphysics With Prognostic Precipitation in GFDL's Atmosphere Model AM4.0: Configuration and Performance	Journal of Advances in Modeling Earth Systems, 13(6)	Journal Article	doi:10.1029/2020MS002453	NA18OAR4320123		X	
CIMES	Hazelton, A., K. Gao, and co-authors	January 2022	Performance of 2020 Real-Time Atlantic Hurricane Forecasts from High-Resolution Global-Nested Hurricane Models: HAFS-globalnest and GFDL T-SHiELD	Weather and Forecasting, 37(1), 143–161	Journal Article	doi:10.1175/WAF-D-21-0102.1	NA18OAR4320123		X	
CIMES	Hazelton, A., Zhang, Z., et al., Bender, M., et al.	April 2021	2019 Atlantic hurricane forecasts from the global-nested Hurricane Analysis and Forecast System: Composite statistics and key events	Weather and Forecasting, 36(2), 519–538	Journal Article	doi:10.1175/WAF-D-20-0044.1	NA18OAR4320123		X	
CIMES	He J, Naik V, Horowitz L	August 2021	Hydroxyl Radical (OH) Response to Meteorological Forcing and Implication for the Methane Budget	Geophysical Research Letters, 48(16), e2021GL094140	Journal Article	doi:10.1029/2021GL094140	NA18OAR4320123	X		
CIMES	Heneghan R. F., Galbraith E. D., Blanchard J. L., Harrison C., Barrier N., Bulman C., Cheung W., Coll M., Eddy T. D., Erauskin-Extramiana M., Everett J. D, Fernandes-Salvador J. D., Gascuel D., Guiet J., Maury O., Palacios-Abrantes J., Petrik C. M., du Pontavice H., Richardson A. J., Steenbeek J., Tai T. C., Volkholz J., Woodworth-Jefcoats J. A., and Tittensor D. P.	Nov. 2021	Disentangling diverse responses to climate change among global marine ecosystem models	Progress in Oceanography, 198, 102659	Journal Article	doi:10.1016/j.pocean.2021.102659	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	Hsieh T-L, Chang C-Y, Held IM, Zurita-Gotor P	Nov. 2021	Nonlinear Generation of Long Waves and the Reversal of Eddy Momentum Fluxes in a Two-Layer Quasi-Geostrophic Model	Journal of Atmospheric Sciences, 78(11), 3525–3536	Journal Article	doi:10.1175/JAS-D-20-0368.1	NA18OAR4320123	X		
CIMES	Huth, A., Adcroft, A., Sergienko, O.	March 2022	Parameterizing tabular-iceberg decay in an ocean model	Journal of Advances in Modeling Earth Systems, 14(3), e2021MS002869	Journal Article	doi:10.1029/2021MS002869	NA18OAR4320123			X
CIMES	Irrgang, C., Boers, N., Sonnewald, M., Elizabeth A. Barnes, Christopher Kadow, Staneva, J., and Saynisch-Wagner, J.	August 2021	Towards neural Earth system modelling by integrating artificial intelligence in Earth system science	Nature Machine Intelligence, 3, 667–674	Journal Article	doi:10.1038/s42256-021-00374-3	NA18OAR4320123			X
CIMES	Jeevanjee N, Seeley JT, Paynter D, Fueglistaler S	Dec. 2021	An Analytical Model for Spatially Varying Clear-Sky CO2 Forcing	Journal of Climate, 34(23), 9463–9480	Journal Article	doi:10.1175/JCLI-D-19-0756.1	NA18OAR4320123		X	
CIMES	Jeevanjee, Nadir and Linjiong Zhou	March 2022	On the resolution-dependence of anvil cloud fraction and precipitation efficiency in radiative-convective equilibrium	Journal of Advances in Modeling Earth Systems, 14(3), e2021MS002759	Journal Article	doi:10.1029/2021MS002759	NA18OAR4320123		X	
CIMES	Joh, Y., T. L. Delworth, A. T. Wittenberg, X. Yang, F. Zeng, L. Jia, F. Lu, N. Johnson, S. Kapnick, A. Rosati, L. Zhang, C. McHugh, and W. F. Cooke	In-Press	Seasonal-to-decadal variability and predictability of the Kuroshio Extension in the GFDL coupled ensemble reanalysis and forecasting system	Journal of Climate	Journal Article	doi:10.1175/JCLI-D-21-0471.1	NA18OAR4320123	X		
CIMES	Judt, Falko, et al., Linjiong Zhou	June 2021	Tropical Cyclones in Global Storm-Resolving Models	Journal of the Meteorological Society of Japan. Ser. II, 99(3), 579-602	Journal Article	doi:10.2151/jmsj.2021-029	NA18OAR4320123			X
CIMES	Kenigson, J., Adcroft, A., Bachman, S., Castruccio, F., Grooms, I., Pegion, P., Stanley, Z.	March 2022	Parameterizing the Impact of Unresolved Temperature Variability on the Large-Scale Density Field: Part 2	Journal of Advances in Modeling Earth Systems, 14(3), e2021MS002844	Journal Article	doi:10.1029/2021MS002844	NA18OAR4320123			X
CIMES	Khatri, Hemant, Griffies, Stephen M., et al	Sept. 2021	Role of Mixed-Layer Instabilities in the Seasonal Evolution of Eddy Kinetic Energy Spectra in a Global Submesoscale Permitting Simulation	Geophysical Research Letters, 48(18), e2021GL094777	Journal Article	doi:10.1029/2021GL094777	NA18OAR4320123	X		
CIMES	Kou-Giesbrecht S, Malyshev S, Martínez Cano I, Pacala SW, Shevliakova E and Menge DNL	July 2021	A Novel Representation of Terrestrial Nitrogen Cycling and Biological Nitrogen Fixation in GFDL-LM4.1	Biogeosciences, 18(13), 4143–4183	Journal Article	doi:10.5194/bg-18-4143-2021	NA18OAR4320123			X
CIMES	Langford, A. O., Senff, C. J., Alvarez II, R. J., Aikin, K. C., Baidar, S., Bonin, T. A., Brewer, W. A., Brioude, J., Brown, S. S., Burley, J. D., Caputi, D. J., Conley, S. A., Cullis, P. D., Decker, Z. C. J., Evan, S., Kirgis, G., Lin, M., Pagowski, M., Peischl, J., Petropavlovskikh, I., Pierce, R. B., Ryerson, T. B., Sandberg, S. P., Sterling, C. W., Weickmann, A. W., and Zhang	February 2022	The Fires, Asian, and Stratospheric Transport-Las Vegas Ozone Study (FAST-LVOS)	Atmospheric Chemistry and Physics, 22(3), 1707–1737	Journal Article	doi:10.5194/acp-22-1707-2022	NA18OAR4320123		X	
CIMES	Lim H-G, Dunne JP, Stock CA, Ginoux P, John JG, Krasting J	March 2022	Oceanic and Atmospheric Drivers of Post-El-Niño Chlorophyll Rebound in the Equatorial Pacific	Geophysical Research Letters, 49(5), e2021GL096113	Journal Article	doi:10.1029/2021GL096113	NA18OAR4320123	X		
CIMES	Lim H-G, Park J-Y, Dunne J, Stock C, Kang S-H, Kug J-S	May 2021	Importance of Human-Induced Nitrogen Flux Increases in Simulated Arctic Warming	Journal of Climate, 34(10), 3799–3819	Journal Article	doi:10.1175/JCLI-D-20-0180.1	NA18OAR4320123	X		
CIMES	Lin, P., and Y. Ming	April 2021	Enhanced climate response to ozone depletion from ozone-circulation coupling	Journal of Geophysical Research Atmospheres, 126(7), e2020JD034286	Journal Article	doi:10.1029/2020JD034286	NA18OAR4320123	X		
CIMES	Liu X, Stock CA, Dunne JD, Lee M, Shevliakova E, Malyshev S, Milly PCD	Sept. 2021	Simulated global coastal ecosystem responses to a half-century increase in river nitrogen loads	Geophysical Research Letters, 48 (17), e2021GL094367	Journal Article	doi:10.1029/2021GL094367	NA18OAR4320123	X		
CIMES	Loose, Nora, et al., Khatri, Hemant, et al.	February 2022	GCM-Filters: A Python Package for Diffusion-based Spatial Filtering of Gridded Data	Journal of Open Source Software, 7(70), 3947	Journal Article	doi:10.21105/joss.03947	NA18OAR4320123			X
CIMES	MacAyeal, D. R., Sergienko, O. V., Banwell, A. F., Macdonald, G. J., Willis, I. C. & Stevens, L. A.	October 2021	Treatment of ice-shelf evolution combining flow and flexure	Journal of Glaciology, 67(265), 885-902	Journal Article	doi:10.1017/jog.2021.39	NA18OAR4320123			X
CIMES	Martiny AC, Hagstrom GI, DeVries T, Letscher RT, Britten GL, Garcia CA, Galbraith E, Karl D, Levin SA, Lomas MW, Moreno AR	February 2022	Marine phytoplankton resilience may moderate oligotrophic ecosystem responses and biogeochemical feedbacks to climate change	Limnology and Oceanography, 67(S1), S378-S389	Journal Article	doi:10.1002/lno.12029	NA18OAR4320123			X
CIMES	Match, A, S. Fueglistaler	Dec. 2021	Large internal variability dominates over global warming signal in observed lower stratospheric QBO amplitude	Journal of Climate, 34(24), 9823–9836	Journal Article	doi:10.1175/JCLI-D-21-0270.1	NA18OAR4320123	X		
CIMES	Nazarian, R. H., Burns, C. M., Legg, S., Buijsman, M. C., Kaur, H., Arbic, B. K.	Nov. 2021	On the magnitude of canyon-induced mixing	Journal of Geophysical Research: Oceans , 126 (11), e2021JC017671	Journal Article	doi:10.1029/2021JC017671	NA18OAR4320123			X
CIMES	Neel, B., M.A. Erinin, and L. Deike	January 2022	Role of contamination in optimal droplet production by collective bubble bursting	Geophysical Research Letters, 49(1), e2021GL096740	Journal Article	doi:10.1029/2021GL096740	NA18OAR4320123	X		
CIMES	Noh, Kyung Min, Hyung-Gyu Lim, Jong-Seong Kug	May 2021	Zonally Asymmetric Phytoplankton Response to the Southern Annular Mode in the Marginal Sea of the Southern	Scientific Reports, 11, 10266	Journal Article	doi:10.1038/s41598-021-89720-4	NA18OAR4320123			X
CIMES	Oh, Ji-Hoon, Kyung Min Noh, Hyung-Gyu Lim, Emilia Kyung Jin, Sang-Yoon Jun, Jong-Seong Kug	February 2022	Antarctic Meltwater-Induced Dynamical Changes in Phytoplankton in the Southern Ocean	Environmental Research Letters, 17(2), 024022	Journal Article	doi:10.1088/1748-9326/ac444e	NA18OAR4320123			X
CIMES	Riviere, A., W. Mostert, S. Perrard and L. Deike	June 2021	Sub-Hinze scale bubble production in turbulent bubble break-up	Journal of Fluid Mechanics, 917, A40	Journal Article	doi:10.1017/jfm.2021.243	NA18OAR4320123			X
CIMES	Schoof, C. and E. Mantelli	April 2021	The role of sliding in ice stream formation	Proceeedings of the Royal Socety A,47(2248), 20200870	Journal Article	doi: 10.1098/rspa.2020.0870	NA18OAR4320123			X
CIMES	Sergienko O. V.	In-Press	Marine outlet glacier dynamics, steady states and steady-state stability	Journal of Glaciology	Journal Article	doi:10.1017/jog.2022.13	NA18OAR4320123	X		
CIMES	Sergienko O. V. & Wingham, D. J.	February 2022	Bed topography and marine ice sheet stability	Journal of Glaciology, 68(267), 124-138	Journal Article	doi:10.1017/jog.2021.79	NA18OAR4320123	X		
CIMES	Smyth JE, Ming Y	October 2021	Investigating the Impact of Land Surface Characteristics on Monsoon Dynamics with Idealized Model Simulations and Theories	Journal of Climate, 34(19), 7943–7958	Journal Article	doi:10.1175/JCLI-D-20-0954.1	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	Sonnewald, M., and Lguensat, R.	August 2021	Revealing the Impact of Global Heating on North Atlantic Circulation Using Transparent Machine Learning	Journal of Advances in Modeling Earth Systems, 13(8), e2021MS002496	Journal Article	doi:10.1029/2021MS002496	NA18OAR4320123	X		
CIMES	Sonnewald, Maike, Redouane Lguensat, Daniel C Jones, Peter D Dueben, Julien Brajard, and V Balaji	July 2021	Bridging observations, theory and numerical simulation of the ocean using machine learning	Environmental Research Letters, 16(7), 073008	Journal Article	doi:10.1088/1748-9326/ac0eb0	NA18OAR4320123	X		
CIMES	Spingys, C.P., A.C. Naveira Garabato, S. Legg, K.L. Polzin, E.P. Abrahamsen, C.E. Buckingham, A. Forryan, and E.E. Frajka-Williams	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	Su, Y. and J. A. Smith	April 2021	An atmospheric water balance perspective on extreme rainfall potential for the contiguous US	Water Resources Research, 57(4), e2020WR028387	Journal Article	doi:10.1029/2020WR028387	NA18OAR4320123	X		
CIMES	Tittensor D. P., Novaglio C., Harrison C., Heneghan R. F., Barrier N., Bianchi D., Bopp L., Bryndum-Buchholz A., Britten G. L., Büchner M., Cheung W. L., Christensen V., Coll M., Dunne J. P., Eddy T. D., Everett J. D., Fernandes-Salvador J. A., Fulton E. A., Galbraith E. D., Gascuel F., Guiet J., John J. G., Link J. S., Lotze H. K., Maury O., Ortega-Cisneros K., Palacios-Abrantes J., Petrick C. M., du Pontavice H., Rault J., Richardson A. J. Shannon L., Shin Y-J, Steenbeek J., Stock C. A., Blanchard J.	Nov. 2021	Next-generation ensemble projections reveal higher climate risks for marine ecosystems	Nature Climate Change, 11(11), 973–981	Journal Article	doi:10.1038/s41558-021-01173-9	NA18OAR4320123			X
CIMES	Tseng K-C, Johnson NC, Maloney ED, Barnes EA, Kapnick SB	June 2021	Mapping Large-scale Climate Variability to Hydrological Extremes: An Application of the Linear Inverse Model to Subseasonal Prediction	Journal of Climate, 34(11), 4207–4225	Journal Article	doi:10.1175/JCLI-D-20-0502.1	NA18OAR4320123	X		
CIMES	Tseng, K.-C., Johnson, N. C., Kapnick, S. B., Delworth, T. L., Lu, F., Cooke, W., et al.	Sept. 2021	Are multiseasonal forecasts of atmospheric rivers possible?	Geophysical Research Letters, 48(17), e2021GL094000	Journal Article	doi:10.1029/2021GL094000	NA18OAR4320123	X		
CIMES	Vecchi GA, Landsea C, Zhang W, Villarini G, Knutson T	July 2021	Changes in Atlantic Major Hurricane Frequency Since the Late-19th Century	Nature Communications, 12(4054)	Journal Article	doi:10.1038/s41467-021-24268-5	NA18OAR4320123	X		
CIMES	Vergopolan, N. et al.	October 2021	SMAP HydroBlocks, a 30 m satellite based soil moisture dataset for the conterminous US	Scientific Data, 8(264)	Journal Article	doi: 10.1038/s41597-021-01050-2	NA18OAR4320123	X		
CIMES	Wagner CE, Saad-Roy CM, Morris SE, Baker RE, et al.	August 2021	Vaccine Nationalism and the Dynamics and Control of SARS-CoV-2	Science, 373, 6562	Journal Article	doi:10.1126/science.abj7364	NA18OAR4320123			X
CIMES	Winton, M., Bushuk, M., Zhang, Y., Hurlin, B., Jia, L., Johnson, N. C., Lu, F.	In-Press	Prospects for Seasonal Prediction of Summertime Trans-Arctic Sea Ice Path	Journal of Climate	Journal Article	doi:10.1175/JCLI-D-21-0634.1	NA18OAR4320123		X	
CIMES	Xiang, B., Harris, L., Delworth, T. L., Wang, B., Chen, G., Chen, J., Clark, S. K., Cooke, W. F., Gao, K., Huff, J. J., Jia, L., Johnson, N. C., Kapnick, S. B., Lu, F., McHugh, C., Sun, Y., Tong, M., Yang, X., Zeng, F., Zhao, M., Zhou, L., & Zhou, X.	February 2022	S2S Prediction in GFDL SPEAR: MJO Diversity and Teleconnections	Bulletin of the American Meteorological Society, 103(2), E463–E484	Journal Article	doi:10.1175/BAMS-D-21-0124.1	NA18OAR4320123			X
CIMES	Xie, Y., Lin, M., Decharme, B., Delire, C., Horowitz, L. W., Lawrence, D.M., Li, F., Seferian, R.	March 2022	Tripling of Western US Particulate Pollution from Wildfires in a warming climate	Proceedings of the National Academy of Sciences, 119(14), e2111372119	Journal Article	doi:10.1073/pnas.2111372119	NA18OAR4320123	X		
CIMES	Yankovsky, Elizabeth, Sonya Legg, and Robert Hallberg	June 2021	Parameterization of submesoscale symmetric instability in dense flows along topography	Journal of Advances in Modeling the Earth System, 13(6), e2020MS002264	Journal Article	doi:10.1029/2020MS002264	NA18OAR4320123			X
CIMES	Yassin, H. & Griffies, S. M.	February 2022	On the discrete normal modes of quasigeostrophic theory	Journal of Physical Oceanography, 52(2), 243-259	Journal Article	doi:10.1175/JPO-D-21-0199.1	NA18OAR4320123	X		
CIMES	Zahn E, Bou-Zeid E, P.Good S, Katul GG, Thomas CK, Ghannam K, Smith JA, et al.	March 2022	Direct Partitioning of Eddy-Covariance Water and Carbon Dioxide Fluxes into Ground and Plant Components	Agricultural and Forest Meteorology, 315(15), 108790	Journal Article	doi:10.1016/j.agrformet.2021.108790	NA18OAR4320123			X
CIMES	Zeng, Y., Milly, P.C.D., Shevliakova, E., Malyshev, S., van Huijgevoort, M., and Dunne, K.A.	March 2022	Possible Anthropogenic Enhancement of Precipitation in the Sahel-Sudan Savanna by Remote Agricultural Irrigation	Geophysical Research Letters, 49(6), e2021GL096972	Journal Article	doi:10.1029/2021GL096972	NA18OAR4320123	X		
CIMES	Zhang W., Kirtman B., Siqueira L., Clement A., Xia J.	May 2021	Understanding the Signal-to-Noise Paradox in Decadal Climate Predictability from CMIP5 and an Eddying Global Coupled Model	Climate Dynamics, 56(9-10), 2895–2913	Journal Article	doi:10.1007/s00382-020-05621-8	NA18OAR4320123	X		
CIMES	Zhang, G., Murakami, H., Cooke, W. F., Wang, Z., Jia, L., Lu, F., et al.	October 2021	Seasonal predictability of baroclinic wave activity	npj Climate and Atmospheric Science, 4(50)	Journal Article	doi:10.1038/s41612-021-00209-3	NA18OAR4320123			X
CIMES	Zhang, L., Delworth, T. L., Kapnick, S., He, J., Cooke, W., Wittenberg, et al.	March 2022	Roles of meridional overturning in subpolar Southern Ocean SST trends: Insights from ensemble simulations	Journal of Climate, 35(5), 1577–1596	Journal Article	doi:10.1175/JCLI-D-21-0466.1	NA18OAR4320123			X
CIMES	Zhang, W., Kirtman, B., Siqueira, L., Xiang, B., Infanti, J., & Perlin, N.	January 2022	Decadal Variability of Southeast US Rainfall in an Eddying Global Coupled Model	Geophysical Research Letters, 49(1), e2021GL096709	Journal Article	doi:10.1029/2021GL096709	NA18OAR4320123	X		
CIMES	Zhang, Yong-Fei, Bushuk, Mitchell, Winton, Michael, et al.	In-Press	Subseasonal-to-Seasonal Arctic Sea Ice Forecast Skill Improvement from Sea Ice Concentration Assimilation	Journal of Climate	Journal Article	doi:10.1175/JCLI-D-21-0548.1	NA18OAR4320123	X		